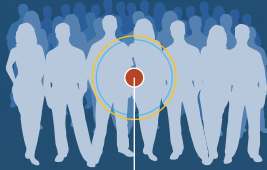


2016 ANNUAL REPORT

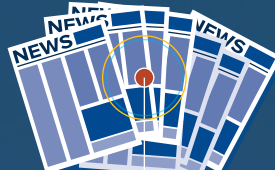


NATIONAL RADIO
ASTRONOMY OBSERVATORY

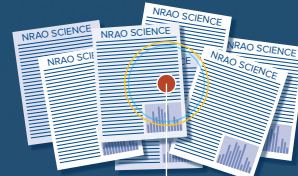
NRAO FACTS & FIGURES



496 EMPLOYEES



43 MEDIA RELEASES



776 REFEREED
SCIENCE PUBLICATIONS

A Suite Of World-Class Astronomical Observatories



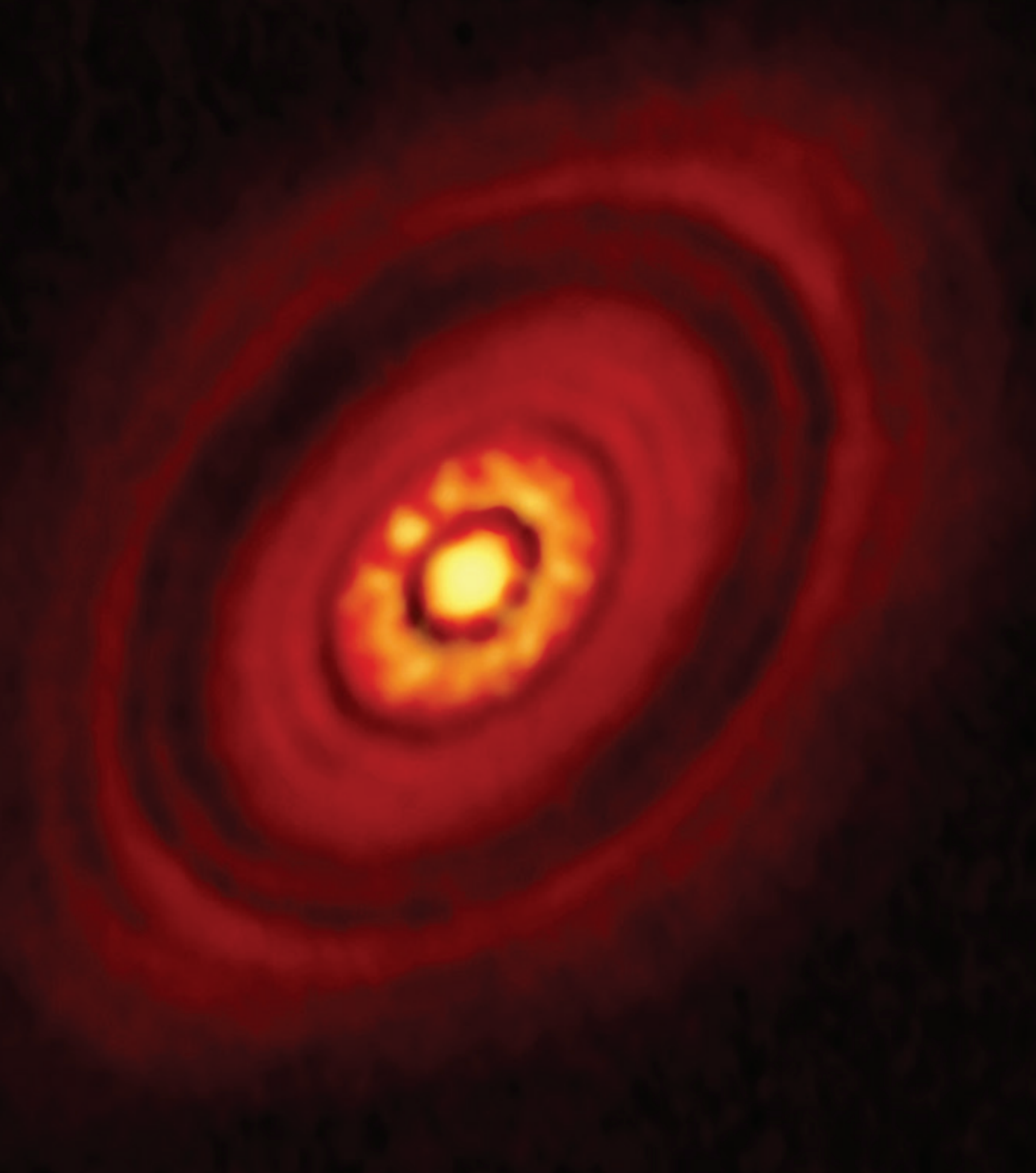


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COVER: Artist impression of the heart of galaxy NGC 1068, which harbors an actively feeding supermassive black hole. Arising from the black hole's outer accretion disk, ALMA discovered clouds of cold molecular gas and dust. This material is being accelerated by magnetic fields in the disk, reaching speeds of 800 kilometers per second. This material gets expelled from the disk and goes on to hide the region around the black hole from optical telescopes on Earth. Essentially, the black hole is cloaking itself behind a veil of its own exhaust. *Credit: NRAO/AUI/NSF; D. Berry / Skyworks*

LEFT: The Karl G. Jansky Very Large Array in central New Mexico. *Credit: J. Hellerman, NRAO/AUI/NSF*



ABOVE: A radio-wavelength composite image of the dusty disk around the young HL Tauri star system that incorporates data from the Atacama Large Millimeter/submillimeter Array and the Jansky Very Large Array. Credit: Carrasco-Gonzalez, et al.; Bill Saxton, NRAO/AUI/NSF



Scientists generated numerous compelling science results and discoveries using the National Radio Astronomy Observatory (NRAO) telescopes in 2016. An impressive 752 peer-reviewed papers were published in scientific journals and 43 NRAO media releases delivered this science to public audiences in North America and around the world. The Atacama Large Millimeter/submillimeter Array (ALMA), the Very Large Array (VLA), Green Bank Telescope (GBT), and Very Long Baseline Array (VLBA) produced transformational science describing the birth of planets and stars, the formation of galaxies in the early Universe, the environments of black holes, and much more. NRAO telescopes are being used by scientists to explore the Universe on all distance scales and across every field of modern astrophysics.

NRAO funding by the U.S. National Science Foundation (NSF) enabled us to achieve the goals we set for ourselves and the Observatory at the start of 2016. Over the past several years, our ability to plan a scientifically compelling program across our instruments and departments and execute it well has been widely praised by the NSF and others. Some factors will always be outside our control – the congressional funding of science, medical costs in the U.S., the global economy – and we are keeping an eye on these as best we can. We are hopeful, for example, that the bipartisan support in the U.S. Congress for NSF and astronomy will continue.

Effective 1 October 2016, Associated Universities, Inc. (AUI) initiated a new ten-year Cooperative Agreement with the NSF for management of NRAO. This new agreement includes fundamental changes to the NRAO structure. The Green Bank research facilities became an independent Green Bank Observatory (GBO), led by Director Karen O’Neil with AUI management oversight; and the VLBA research facilities are now a similarly independent Long Baseline Observatory (LBO), led by Walter Brisken with AUI management oversight. NRAO continues to provide a set of key services to GBO and LBO under this new Cooperative Agreement, and many carefully considered changes were required to establish these relationships. Our experience with these new operations modes in late 2016 has been very positive, and I can report that each of the AUI radio-wavelength observatories – NRAO, GBO, and LBO – are performing well.

Several major initiatives moved strongly forward in 2016 that will drive the NRAO for the next decade and beyond: the creation and ready availability to the community of Science Ready Data Products for all NRAO instruments; the exploration of a next-generation VLA concept (ngVLA); a major VLA infrastructure overhaul; continued innovative development and operations growth for ALMA; a revitalization of the Central Development Laboratory; and a new VLA Sky Survey. We are strongly engaged in crafting our present and future. New ideas, plans, and designs are emerging on multiple fronts, and we are reaching out to our communities to explore the possibilities. The NRAO staff is, as always, a vital part of the Observatory’s success. We remain proud to be a strong and exceptionally capable research organization providing truly state-of-the-art research facilities and tools across the radio spectrum for our colleagues in the international scientific 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 appointment as NRAO Director, 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.



ALMA



VLA

Created in 1956 by the NSF and AUI, the NRAO designs, builds, and operates the world's most capable astronomical telescopes and instruments at radio wavelengths. In 2016, NRAO operated a complementary suite of four 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 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

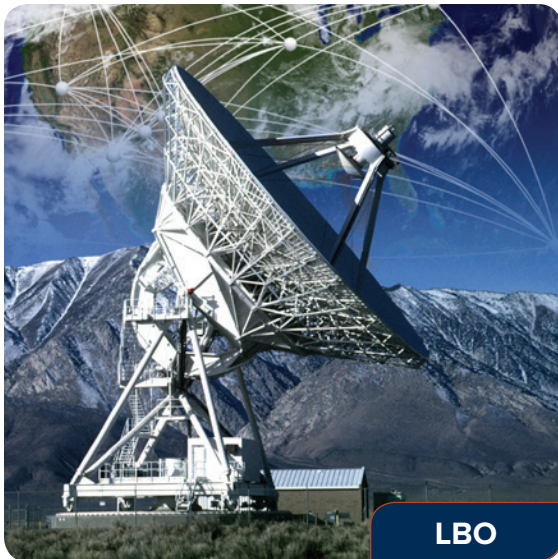
capabilities span wavelengths from 9.6 to 0.3 mm (31 – 950 GHz), a key part of the electromagnetic spectrum for observing the first stars and galaxies, directly imaging planetary formation, and studying the energy output from supermassive black holes in starburst galaxies. The first ALMA Early Science 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 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 the 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 research and development that improves operational NRAO telescopes and helps realize next generation facilities. CDL oversees a science-driven engineering research and development program that supports the community's highest priority science goals.

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.

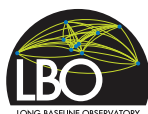
Effective 1 October 2016, AUI initiated a new ten-year Cooperative Agreement with the NSF that includes fundamental changes to the Observatory's structure. Under this new Cooperative Agreement, the Green Bank research facilities became an independent Green Bank Observatory (GBO), led by Director Karen O'Neil with AUI management oversight. Also under this Cooperative Agreement, the VLBA research facilities became a similarly independent Long Baseline Observatory (LBO), led by Director Walter Brisken with AUI management oversight.

As 2016 ends, the NRAO-GBO-LBO telescopes are operating individually, and synergistically with optical, infrared, and X-ray telescopes to open new frontiers across a broad range of modern astrophysics: proto-planetary

disks and extrasolar planet formation; astrochemistry; the early phases of star formation; pulsar physics and nanoHertz gravitational wave limits; molecular gas in high-redshift galaxies; the environments of supermassive black holes; cosmology; and much more.

In addition to research, the NRAO, GBO, and LBO broadly impact science and society via their education and public outreach programs. A diverse NRAO-GBO-LBO program of compelling Science, Technology, Engineering, Art, and Mathematics (STEAM) education programs are introducing more 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-GBO-LBO comprise the nation's core competency in radio astronomy, an invaluable resource for the astronomy and broader 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.

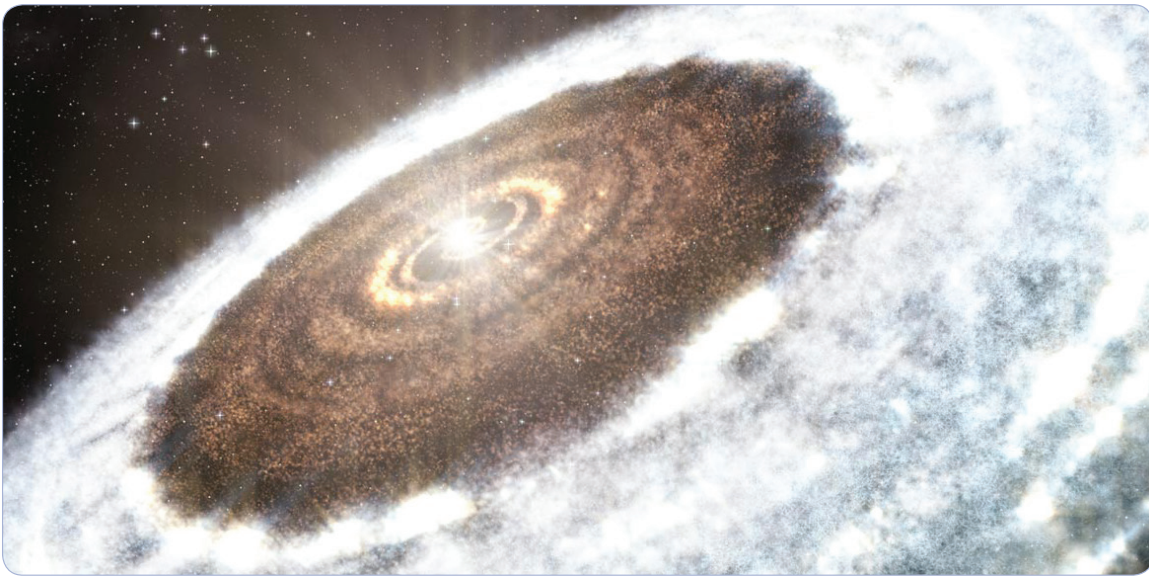
In parallel, the GBT continues to expand in scope, including wide-field continuum and spectroscopic cameras operating at 20 and 90 GHz, while the VLBA remains the premier instrument on the planet for millarcsecond imaging and sub-millarcsecond astrometry. Particularly gratifying has been the demonstration 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 2016.

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

Stellar Outburst Brings Water Snowline into View

A snow-line is the region of a protoplanetary disk at which a volatile molecule reaches its condensation temperature. They play a crucial role in disk evolution by promoting the rapid growth of ice-covered grains. Signatures of the carbon monoxide snow-line, at $T \sim 20$ K, have recently been imaged in the disks surrounding the pre-main-sequence stars TW Hydra and HD163296 at distances of ~ 30 AU from the star. But the water snow-line of a protoplanetary disk, at temperatures of more than 100 deg K, has not been seen, as it typically is less than 5 AU from solar-type stars. Water-ice is important because it regulates dust and planetesimal coagulation efficiency, and the formation of comets, ice giants, and the cores of gas giants. Cieza et al. present ALMA images at 0.03 arcsec resolution (12 AU) of the protoplanetary disk around V883 Ori, a $1.3 M_{\odot}$ protostar undergoing a luminosity outburst owing to a temporary accretion rate increase. The authors found an intensity break corresponding to an abrupt optical depth change at ~ 42 AU, where the elevated disk temperature approaches water's condensation point, and concluded that the outburst has moved the water snow-line. The spectral behavior across the snow-line confirms model predictions that dust fragmentation and the inhibition of grain growth at higher temperatures results in soaring grain number densities and optical depths. As most forming planetary systems are expected to experience outbursts caused by accretion, these results imply that highly dynamical water snow-lines must be considered when developing models of disk evolution and planet formation.



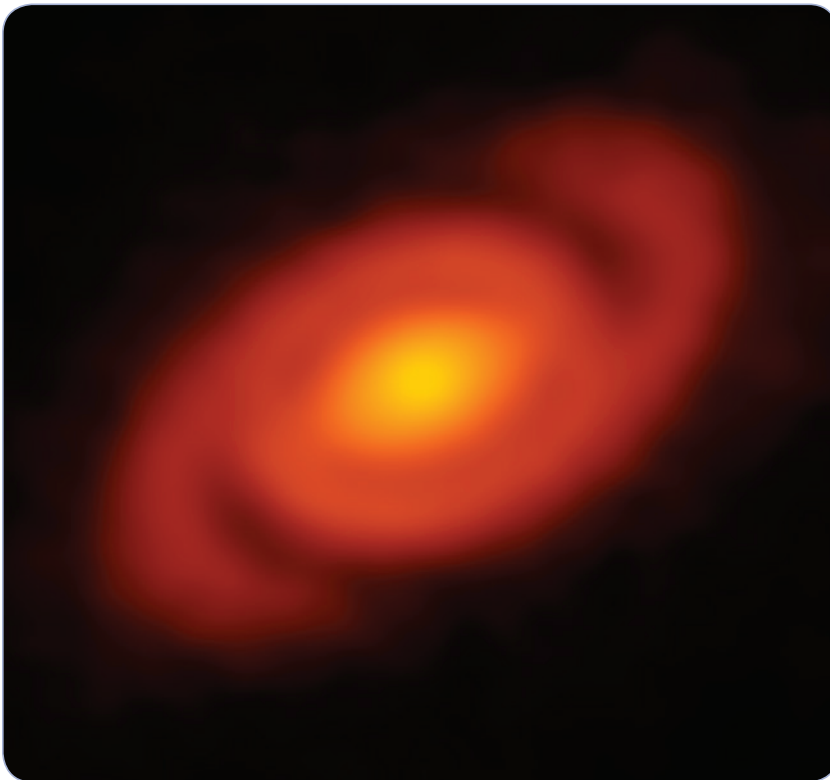
[Above] Artist impression of the water snowline around the young star V883 Orionis, as observed with ALMA. Credit: A. Angelich (NRAO/AUI/NSF).

Science Team: Lucas A. Cieza (Diego Portales), Simon Casassus, (Univ. de Chile), John Tobin (Leiden), Steven P. Bos, (Leiden), Jonathan P. Williams (Hawaii-Manoa), Sebastian Perez (Univ. de Chile), Zhaohuan Zhu (Princeton), Claudio Caceres (Univ. Valparaiso), Hector Canovas (Univ. Valparaiso), Michael M. Dunham (CfA), Antonio Hales (JAO), Jose L. Prieto (Diego Portales), David A. Principe, (Diego Portales), Matthias R. Schreiber (Valparaiso), Dary Ruiz-Rodriguez (Australian National Univ.), and Alice Zurlo (Diego Portales, Univ. de Chile)..

Publication: *Imaging the Water Snow-line During a Protostellar Outburst*, 2016, Nature, 535, 258.

Spiral Arms Embrace Young Star

Gravitational forces are expected to excite spiral density waves in protoplanetary disks, the disks of gas and dust orbiting young stars. However, previous observations that showed spiral structure were not able to probe disk midplanes, where most of the mass is concentrated and where planet formation takes place. Using ALMA, Perez et al. have detected a pair of trailing symmetric spiral arms in the protoplanetary disk surrounding the young star Elias 2-27. The arms extend to the disk outer regions and can be traced down to the midplane. These millimeter-wave observations also reveal an emission gap closer to the star than the spiral arms. The authors argue that the observed spirals trace shocks of spiral density waves in the midplane of this young disk.



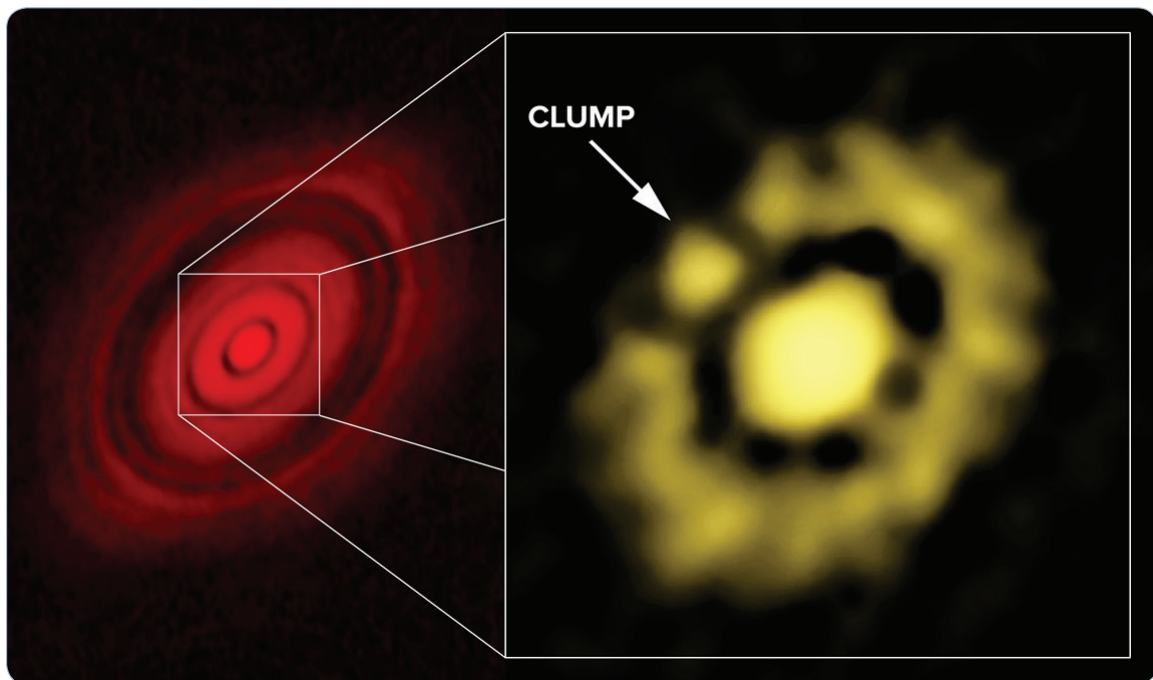
ALMA peered into the Ophiuchus star-forming region to study the protoplanetary disk around the young star Elias 2-27. Astronomers discovered a striking spiral pattern in the disk that is the product of density waves – gravitational perturbations in the disk. Credit: L. Pérez (MPIfR), B. Saxton (NRAO/AUI/NSF), ALMA (ESO/NAOJ/NRAO), NASA/JPL Caltech/WISE Team.

Science Team: Laura M. Pérez (MPIfR), John M. Carpenter (JAO), Sean M. Andrews (CfA), Luca Ricci (CfA), Andrea Isella (Rice), Hendrik Linz (MPIfA), Anneila I. Sargent (Caltech), David J. Wilner (CfA), Thomas Henning (MPIfA), Adam T. Deller (ASTRON), Claire J. Chandler (NRAO), Cornelis P. Dullemond (Heidelberg), Joseph Lazio (JPL), Karl M. Menten (MPIfA), Stuartt A. Corder (JAO), Shaye Storm (CfA), Leonardo Testi (ESO, INAF), Marco Tazzari (ESO), Woojin Kwon (KASSI), Nuria Calvet (Michigan), Jane S. Greaves (Cardiff), Robert J. Harris (Illinois), and Lee G. Mundy (Maryland).

Publication: *Spiral Density Waves in a Young Protoplanetary Disk*, 2016, *Science* 353, 1519.

The VLA View of the HL Tau Disk

The first long-baseline ALMA campaign resolved the disk around the young star HL Tau into axisymmetric bright and dark rings. Despite the young age of HL Tau, these structures have been interpreted as signatures for the presence of proto-planets. Of special interest are the inner parts of disks, where terrestrial planets are expected to form. However, the emission from these regions in HL Tau are optically thick at ALMA wavelengths, preventing the derivation of surface density profiles and grain size distributions. Carrasco-Gonzalez et al. presented the most sensitive images of HL Tau obtained to date with the Karl G. Jansky Very Large Array at 7.0 mm wavelength with a spatial resolution comparable to ALMA. At this wavelength, the dust emission from HL Tau is optically thin, enabling a comprehensive study of the inner disk. The authors obtained a total disk dust mass of $0.001 - 0.003 M_{\odot}$. Their VLA data indicate fast grain growth, fragmentation, and formation of dense clumps in the inner, densest parts of the disk. This research suggests that the HL Tau disk may be in a very early stage of formation, with planets not already formed in the gaps but in the process of future formation in the bright rings.



[Left] ALMA image of HL Tau. [Right] VLA image of HL Tau, showing clump of dust. Credit: Carrasco-Gonzalez, et al.; Bill Saxton, NRAO/AUI/NSF.

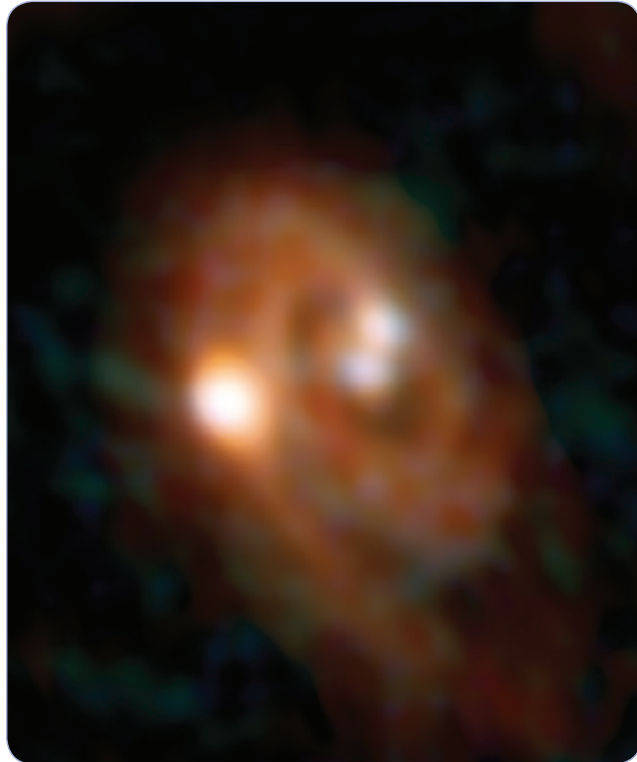
Science Team: Carlos Carrasco-Gonzalez (UNAM), Thomas Henning (MPIfA), Claire J. Chandler (NRAO), Hendrik Linz (MPIfA), Laura Perez (MPIfA, NRAO, MPIfR), Luis F. Rodriguez (UNAM), Roberto Galvan-Madrid (UNAM), Guillem Anglada (CSIC), Til Birnstiel (MPIfA), Roy van Boekel (MPIfA), Mario Flock (JPL), Hubert Klahr (MPIfA), Enrique Macias (CSIC), Karl Menten (MPIfA), Mayra Osorio (CSIC), Leonardo Testi (ESO, INAF), Jose M. Torrelles (CSIC-IEEC), and Zhaohuan Zhu (Princeton).

Publication: *The VLA view of the HL Tau Disk: Disk Mass, Grain Evolution, and Early Planet Formation*, 2016, *Astrophysical Journal Letters*, 821, L16.

Capturing Stellar Fragmentation in Disks

Astronomers believe there are two primary pathways to form binary and multiple star systems: (a) large-scale turbulent fragmentation of cloud cores and filaments; and (b) small-scale fragmentation of a massive protostellar disk due to gravitational instability. While there is evidence for turbulent fragmentation on scales of 1000 AU, evidence for disk fragmentation is limited.

Tobin et al. report on their study of a multiple star system, L1448 IRS3B, which is less than 150,000 years old and includes three stars, all separated by less than 200 AU. ALMA and Jansky VLA observations of the dust and molecular gas in this system reveal a disk with spiral structure surrounding the three protostars. The two protostars near the center of the disk are separated by 61 AU, and a tertiary protostar is coincident with a spiral arm in the outer disk at a separation of 183 AU. The mass of the central pair is $1 M_{\odot}$, the disk has a total mass of $0.30 M_{\odot}$, and the tertiary protostar has a minimum mass of $0.085 M_{\odot}$. The authors demonstrate that the disk around L1448 IRS3B appears susceptible to disk fragmentation at radii between 150 and 320 AU, overlapping with the location of the tertiary protostar, which is consistent with a protostellar disk that recently experienced gravitational instability, yielding one or two stellar companions.



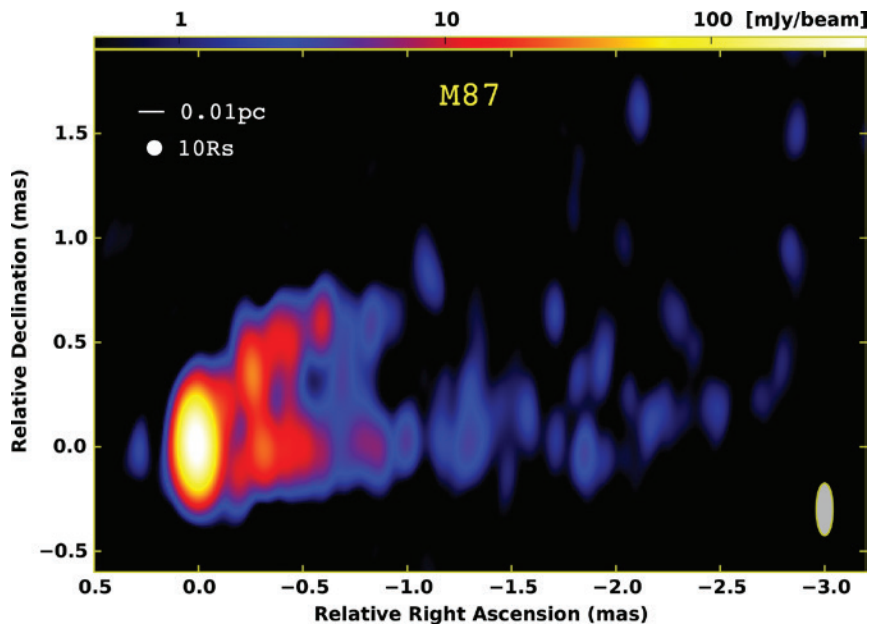
ALMA and Jansky VLA images of the gas and dust in L1448 IRS3B at 1 arcsecond resolution. Credit: ALMA (ESO/NAOJ/NRAO), B. Saxton, NRAO/AUI/NSF

Science Team: John J. Tobin (Oklahoma, Leiden), Kaitlin M. Kratter (Arizona), Magnus V. Persson (Leiden, Onsala), Leslie W. Looney (Illinois), Michael M. Dunham (New York–Fredonia), Dominique Segura-Cox (Illinois), Zhi-Yun Li (Virginia), Claire J. Chandler (NRAO), Sarah I. Sadavoy (MPIfA), Robert J. Harris (Illinois), Carl Melis (UC–San Diego), and Laura M. Pérez (MPIfA).

Publication: *A Triple Protostar System Formed via Fragmentation of a Gravitationally Unstable Disk*, 2016, *Nature*, 538, 483.

Approaching the Schwarzschild Radius

Hada et al. report on high-sensitivity, high-resolution 86 GHz observations of the jet base in the radio galaxy M87, obtained by the Very Long Baseline Array in conjunction with the Green Bank Telescope. The resulting image has a dynamic range exceeding 1500 to 1, resolving and imaging a detailed jet structure to ~ 10 Schwarzschild radii (R_s). The 86 GHz image confirms important jet features known at lower frequencies, a jet base with a wide opening angle, a limb-brightened intensity profile, a parabola-shape collimation profile, and a counter jet. The limb-brightened structure is already well developed at < 0.2 milli-arcsecond ($< 28 R_s$, projected) from the core, where the corresponding apparent opening angle becomes as wide as ~ 100 deg. The subsequent jet collimation near the black hole evolves in a complex manner: there is a constricted structure at tens of R_s from the core, where the jet cross section is locally shrinking. The authors suggest that external pressure support from the inner part of the radiatively inefficient accretion flow may be dynamically important in confining the footprint of the magnetized jet. The authors also present the first 86 GHz polarimetric experiment using VLBI for this source.



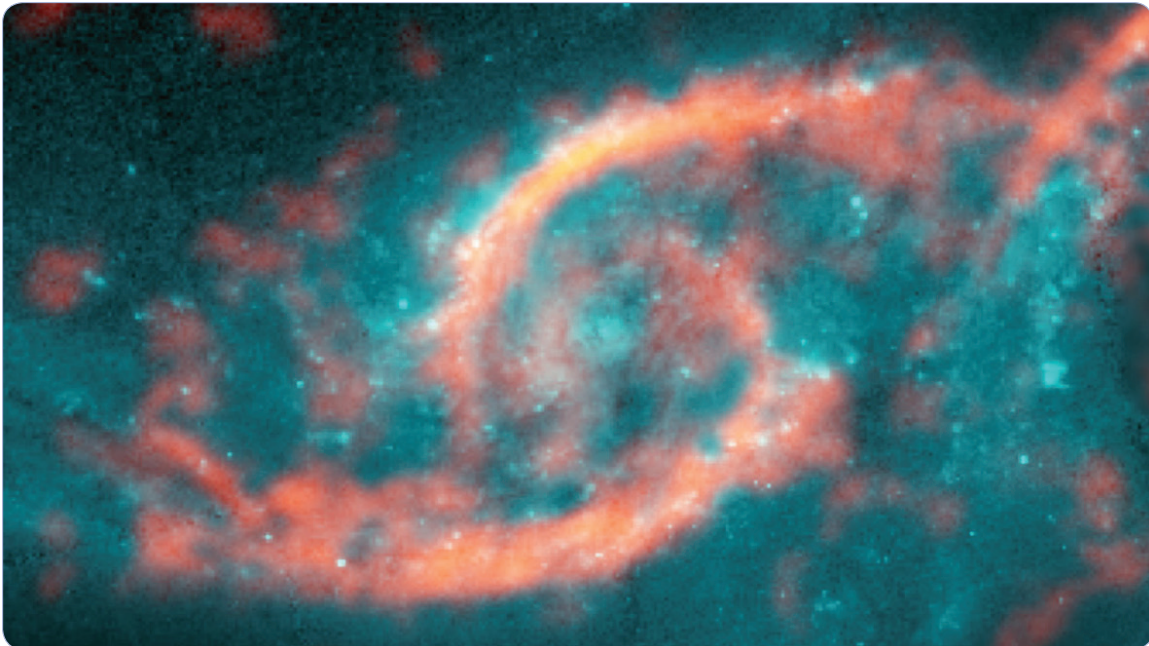
VLBA + GBT 86 GHz false-color total intensity image of the M87 jet. The image is produced by combining the visibility data over the two epochs on 11 & 26 February 2014. The restoring beam is shown in the bottom-right corner. The peak intensity is 500 mJy/beam, the off-source rms noise is 0.28 mJy/beam, where the resulting dynamic range is greater than 1500 to 1. Credit: Kazuhiro Hada et al., 2016 ApJ

Science Team: Kazuhiro Hada (NAOJ, INAF), Motoki Kino (KASI), Akihiro Doi (JAEA), Hiroshi Nagai (NAOJ), Mareki Honma (NAOJ, SOKENDAI), Kazunori Akiyama (NAOJ, Tokyo), Fumie Tazaki (NAOJ), Rocco Lico (INAF, Bologna), Marcello Giroletti (INAF), Gabriele Giovannini (INAF, Bologna), Monica Orienti (INAF), and Yoshiaki Hagiwara (NAOJ, Tokyo).

Publication: *High-sensitivity 86 GHz (3.5 mm) VLBI Observations of M87: Deep Imaging of the Jet Base at a Resolution of 10 Schwarzschild Radii*, 2016, *Astrophysical Journal*, 817, 131.

A Tsunami of Stars & Gas

ALMA observations in the ^{12}CO J=1-0 line of the interacting galaxy pair IC 2163 and NGC 2207 at 2×1.5 arcsec resolution reveal how the encounter drives gas to pile up in narrow, ~ 1 kiloparsec wide, “eyelids” in IC 2163. These two galaxies are involved in a grazing encounter, which has led to the development in IC 2163 of an eye-shaped (ocular) structure at mid-radius, and two tidal arms. The CO data show that there are large velocity gradients across the width of each eyelid, with a mixture of radial and azimuthal streaming of gas at the outer edge of the eyelid relative to its inner edge. The sense of the radial streaming in the eyelids is consistent with the idea that gas from the outer part of IC 2163 flows inward until its radial streaming slows down abruptly and the gas piles up in the eyelids. The radial compression at the eyelids causes an increase in the gas column density by direct radial impact and also leads to a high rate of shear. A linear regression of the molecular column density $N(\text{H}_2)$ on the magnitude of $|\text{dv}/\text{dR}|$ across the width of the eyelid at fixed values of azimuth finds a strong correlation between $N(\text{H}_2)$ and $|\text{dv}/\text{dR}|$. Substantial portions of the eyelids have high velocity dispersion in CO, indicative of elevated turbulence there.



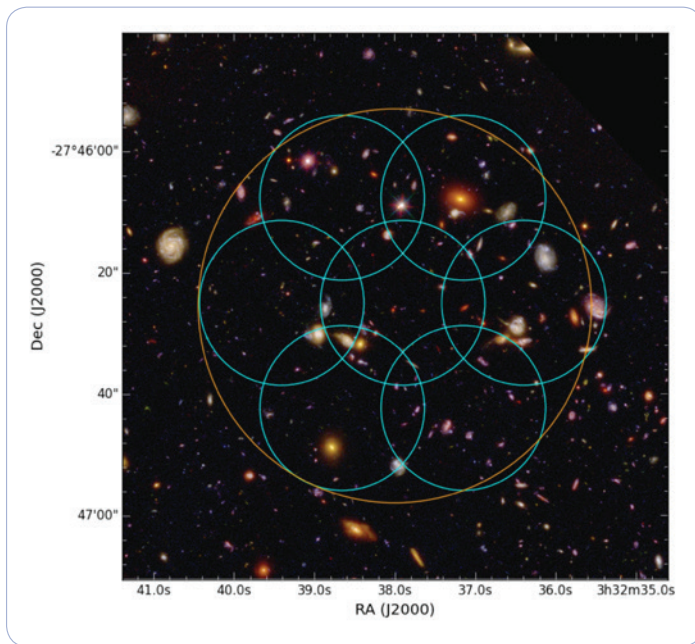
Eyelid-like features bursting with stars in galaxy IC 2163 formed from a tsunami of stars and gas triggered by a glancing collision with galaxy NGC 2207 (a portion of its spiral arm is shown on right side of image). ALMA image of carbon monoxide (orange), which revealed motion of the gas in these features, is shown on top of Hubble image (blue) of the galaxy. Credit: M. Kaufman; B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); NASA/ESA Hubble Space Telescope. Credit: Fabian Walter et al., 2016 ApJ

Science Team: Michele Kaufman (Newton), Bruce G. Elmegreen (IBM Research), Curtis Struck (Iowa State), Debra Meloy Elmegreen (Vassar), Frédéric Bournaud (CEA Saclay), Elias Brinks (Hertfordshire), Stephanie Juneau (CEA Saclay), and Kartik Sheth (NASA).

Publication: *Ocular Shock Front in the Colliding Galaxy IC 2163*, 2016, *Astrophysical Journal*, 831, 161.

A New Era for Cosmological Surveys

Walter et al. present the rationale for and the observational description of the ALMA SPECTroscopic Survey (ASPECS) in the Hubble Space Telescope Ultra-Deep Field (UDF), the cosmological deep field that has the deepest multi-wavelength data available. The goal is to obtain an unbiased census of molecular gas and dust continuum emission in high-redshift ($z > 0.5$) galaxies. The ~ 1 arcminute region covered within the UDF was chosen to overlap with the deepest HST imaging. The observations are full frequency scans in ALMA Band 3 (84–115 GHz) and Band 6 (212–272 GHz) at approximately uniform line sensitivity ($L_{\text{CO}} \sim 2 \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$), and continuum noise levels. The molecular surveys cover the different CO rotational transitions, with essentially full redshift coverage. The [C II] emission line is also covered at redshifts $6.0 < z < 8.0$. A customized algorithm



identifies line candidates in the molecular line scans and quantifies the ability to recover artificial sources from these data. The most likely line identification is constrained based on whether multiple CO lines are detected, and whether optical spectroscopic redshifts and optical counterparts exist. Ten (Eleven) CO line candidates are found in the 3 mm (1 mm) band, and their statistical analysis shows that < 4 of these in each band are likely spurious. Less than one-third of the total CO flux in the low-J CO line candidates are from sources unassociated with an optical / near-infrared counterpart. The data described in this paper are the basis for multiple dedicated studies presented in subsequent papers.

The FWHM of the primary beam (areal coverage) of the 3 mm (orange) and 1 mm (cyan) ALMA observations, overlaid on a three-color HST image from the XDF survey (Illingworth et al. 2013). The circles show the ALMA primary beam of each pointing at the central frequencies of the two scans.

Science Team: Fabian Walter (MPIfA, Caltech, NRAO), Roberto Decarli (MPIfA), Manuel Aravena (Diego Portales), Chris Carilli (NRAO, Cambridge), Rychard Bouwens (Leiden), Elisabete da Cunha (Swinburne, Australian National Univ.), Emanuele Daddi (CEA Saclay), R. J. Ivison (ESO, Edinburgh), Dominik Riechers (Cornell), Ian Smail (Durham), Mark Swinbank (Durham), Axel Weiss (MPIfR), Timo Anguita (Andres Bello, Millennium Inst.), Roberto Assef (Diego Portales), Roland Bacon (Lyon), Franz Bauer (Católica, Millennium Inst., Space Science Inst.), Eric F. Bell (Michigan), Frank Bertoldi (Argelander), Scott Chapman (Dalhousie), Luis Colina (CSIC), Paulo C. Cortes (JAO, NRAO), Pierre Cox (Arizona), Mark Dickinson (Arizona), David Elbaz (CEA Saclay), Jorge González-López (Católica), Edo Ibar (Valparaiso), Hanae Inami (Lyon), Leopoldo Infante (Católica), Jacqueline Hodge (Leiden), Alex Karim (Argelander), Olivier Le Fevre (CNRS), Benjamin Magnelli (Argelander), Roberto Neri (IRAM), Pascal Oesch (Yale), Kazuaki Ota (Cambridge, Kavli), Gergö Popping (ESO), Hans-Walter Rix (MPIfA), Mark Sargent (Sussex), Kartik Sheth (NASA HQ), Arjen van der Wel (MPIfA), Paul van der Werf (Leiden), and Jeff Wagg (SKA)

Publication: *The ALMA Spectroscopic Survey in the Hubble Ultra Deep Field: Survey Description*, 2016, *Astrophysical Journal*, 833, 67.

Earth–space interferometry with RadioAstron

Earth–space interferometry with RadioAstron provides the highest direct angular resolution ever achieved in astronomy at any wavelength. RadioAstron detections of the classic quasar 3C 273 on interferometric baselines up to 171,000 km suggest brightness temperatures exceeding expected limits from the inverse-Compton catastrophe by two orders of magnitude. The authors show that at 18 cm, these estimates most likely arise from refractive substructure introduced by scattering in the interstellar medium. They use the scattering properties to estimate an intrinsic brightness temperature of 7×10^{12} K, which is consistent with expected theoretical limits, but which is ~ 15 x lower than estimates that neglect substructure. At a wavelength of 6.2 cm, the substructure influences the measured values appreciably but gives an estimated brightness temperature that is comparable to models that do not account for the substructure. At 1.35 cm, the substructure does not affect the extremely high inferred brightness temperatures, in excess of 10^{13} K. The authors also demonstrate that for a source having a Gaussian surface brightness profile, a single long-baseline estimate of refractive substructure determines an absolute minimum brightness temperature, if the scattering properties along a given line of sight are known, and that this minimum accurately approximates the apparent brightness temperature over a wide range of total flux densities.



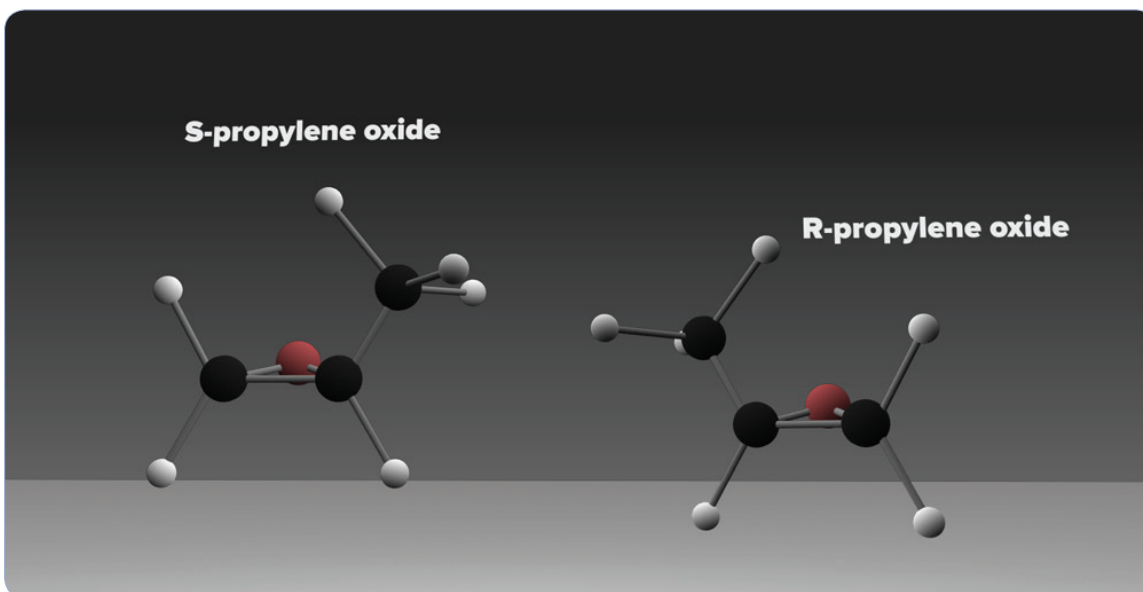
Artist rendering of the orbiting RadioAstron satellite, the farthest element in an array of radio antennas that combine to form the highest resolution instrument in all of astronomy. Credit: Lavochkin Association.

Science Team: Michael D. Johnson (CfA), Yuri Y. Kovalev (Lebedev, MPIfR), Carl R. Gwinn (UC-Santa Barbara), Leonid I. Gurvits (VLBI ERIC, Delft), Ramesh Narayan (CfA), Jean-Pierre Macquart (ICRAR, CAASTRO), David L. Jauncey (CSIRO, ANU), Peter A. Voitsik (Lebedev), James M. Anderson (Helmholtz-Zentrum), Kirill V. Sokolovsky (Lebedev, Moscow State), and Mikhail M. Lisakov (Lebedev).

Publication: *Extreme Brightness Temperatures and Refractive Substructure in 3C273 with RadioAstron*, 2016, *Astrophysical Journal Letters*, 820, L10.

Life's First Handshake: Chiral Molecule Detected

Life on Earth relies on chiral molecules – species that are not superimposable on their mirror images. This manifests itself in the selection of a single molecular handedness, or homochirality, across the biosphere. The authors present the astronomical detection of a chiral molecule, propylene oxide ($\text{CH}_3\text{CHCH}_2\text{O}$), in absorption toward the Galactic Center, the first complex organic chiral molecule detected in interstellar space. The research was undertaken primarily with the Green Bank Telescope (GBT) as part of the *Prebiotic Interstellar Molecular Survey*. Additional supporting observations were taken with the Parkes radio telescope in Australia. Propylene oxide was detected in the gas phase in a cold, extended molecular shell around the embedded, massive protostellar clusters in the Sagittarius B2 star-forming region. Complex organic molecules form in interstellar clouds like Sagittarius B2 in several ways. The most basic pathway is through gas-phase chemistry, in which particles collide and merge to produce ever more complex molecules. Once organic compounds as large as methanol (CH_3OH) are produced, however, this process becomes much less efficient. To form more complex molecules, such as propylene oxide, astronomers believe thin mantles of ice on dust grains help link small molecules into longer and larger structures. These molecules can then evaporate from the surface of the grains and further react in the gas of the surrounding cloud.



The S (Latin for sinister, left) and R (Latin for rectus, right) versions of the chiral molecule propylene oxide, which was discovered in a massive star-forming region near the center of our Galaxy. This is the first detection of a chiral molecule in interstellar space. Credit: B. Saxton (NRAO/AUI/NSF).

Science Team: Brett A. McGuire (NRAO, Caltech), P. Brandon Carroll (Caltech), Ryan A. Loomis (Harvard), Ian A. Finneran (Caltech), Philip R. Jewell (NRAO), Anthony J. Remijan (NRAO), and Geoffrey A. Blake (Caltech).

Publication: *Discovery of the interstellar chiral molecule propylene oxide ($\text{CH}_3\text{CHCH}_2\text{O}$), 2016 Science, 352, 1449.*

U.S. RADIO-MILLIMETER-SUBMILLIMETER FUTURES

The NRAO is organizing a series of three conferences for the astronomy community to broadly discuss and make key decisions regarding 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 second conference in this series – “Futures 2” – was held 3-5 August 2016 at the Renaissance Harborplace Hotel in Baltimore, Maryland with 135 scientists in attendance from U.S. and international universities, observatories, and laboratories representing virtually every field of astrophysics.



The Futures I conference held 15-17 December 2015 was structured around key science themes that reflect community priorities identified in the *New Worlds, New Horizons* Astro2010 Decadal Survey that require RMS observations and facilities. Futures I yielded a compelling definition of the transformational science that interests the community and motivates the exploration of the scope and feasibility of the future RMS instrument and technique options.

The executive Organizing Committee (OC) formed and convened by NRAO, AUI, and the Kavli Foundation to define and guide the three-event Kavli Conference Series continued from Futures I, and comprised

- 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)

Sessions at Futures 2 broadly discussed potential RMS Flagship and Small/Midscale initiatives associated with the next-generation Very Large Array (ngVLA), a Hydrogen Epoch of Reionization Array (HERA), the Cosmic Microwave Background (CMB), and pulsars. Flagship options are major investments with widespread community benefit and support that would require funding by or on a scale comparable to the National Science Foundation (NSF) – Major Research Equipment and Facility Construction program. Small/Midscale initiatives are investments that might be funded via the NSF Mid-Scale Initiative Program.

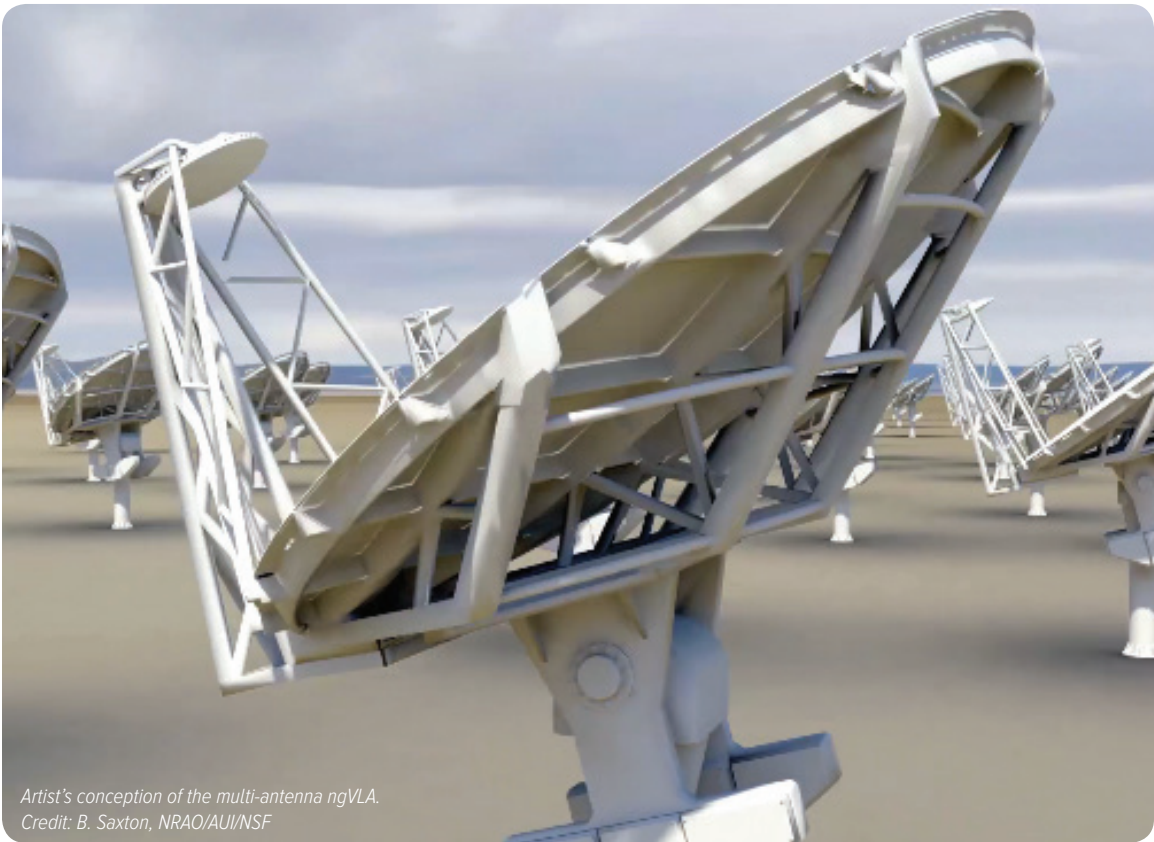
The ngVLA session at Futures 2 began with presentations on the general concept for the instrument, the transformational science to be done with it, and the technical challenges and choices to be addressed in its design. Breakout sessions were held to discuss and debate science cases and drivers on topics such as receiver bands, baseline lengths, and array configurations. The session culminated with the announcement of an ngVLA Community Studies program designed to facilitate community contributions to the instrument design, a call for nominations for membership on the ngVLA Science Advisory Council, and the preliminary announcement of an ngVLA science conference to be held in mid-2017.

Strong and compelling science cases were presented at the CMB and pulsar sessions of the Futures 2 conference. The strategy for developing HERA and detecting the Epoch of Reionization was also presented.

Information regarding Futures III – including the conference website and registration information – will be available in early 2017 at the NRAO science website and will be publicized via the NRAO electronic newsletter (eNews), NRAO Announcements series, and the NRAO / AUI exhibits at the American Astronomical Society meeting in Grapevine, Texas, 3-7 January 2017. The Futures III conference is expected to be held in August 2017 at a location on the U.S. west coast, in California.



Above: Futures II, NRAO Director Tony Beasley's plenary presentation, 3 August 2016. Below: Artist's conception of the multi-antenna next generation VLA (ngVLA). Credit: Bill Saxton, NRAO/AUI/NSF.



*Artist's conception of the multi-antenna ngVLA.
Credit: B. Saxton, 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; and
- Education and Public Outreach (EPO) programs and Diversity initiatives.



Photos by Pablo Carrillo

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 support for 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.

Science Operations

The program for Early Science Cycle 2 carryover and Cycle 3 observations at the Joint ALMA Observatory in Chile continued into 2016 from the previous year, and concluded on 30 September. Cycle 4 science operations were then initiated and continued through the end of the year and into 2017, as planned. New capabilities announced in March 2016 Cycle 4 Call for Proposals became operational on the array, enabling astronomers to address the exciting science targeted by proposals submitted in April 2016.

NORTH AMERICAN ALMA OPERATIONS

Cycle 4 Call for Proposals

The ALMA Cycle 4 proposal submission process opened on 22 March 2016 with a submission deadline on 21 April 2016. Several new proposal types and observing modes were offered in Cycle 4, including:

- Large Programs
- Millimeter-wavelength VLBI proposals
- Atacama Compact Array (ACA) stand-alone observing
- Solar observing, and
- Spectral line polarization.

Large programs were defined as those proposals that attempt to address strategic scientific issues and that request 50 observation hours or more with either the 12-m Array or the ACA in stand-alone mode. Millimeter-wavelength VLBI proposals were accepted for Band 3 (84-116 GHz) and Band 6 (211-275 GHz). Such programs were also required to submit a proposal to the appropriate VLBI telescope network. Cycle 4 proposals were also accepted for ALMA interferometric and single-dish observations of the Sun at selected frequencies in Bands 3 and 6. Polarization proposals were restricted to observing compact sources in Bands 3, 6, or 7, with linear polarization as the only accepted observing mode.

Multiple NRAO Live! workshops were organized at North American institutions by the NAASC in advance of the Cycle 4 proposal deadline to provide users with the knowledge they need to carry out cutting-edge scientific research using NRAO facilities, including ALMA. NRAO Live! events are free, one to two day workshops designed in cooperation with host institutions across North America. These events include science talks, an introduction to submillimeter interferometry, and hands-on workshops designed to assist attendees in proposal preparation, observation planning, and data reduction for ALMA Cycle 4.



The JAO received 1571 proposals from the international community by the Cycle 4 submission deadline. The proposals were reviewed during a meeting in Vienna, Austria, 19-24 June, by a review committee that consisted of 18 ALMA Review Panels (ARPs), each with eight Science Assessors. The panels were distributed across five scientific categories:

1. Cosmology and the high redshift universe (4 panels)
2. Galaxies and galactic nuclei (4 panels)
3. ISM, star formation and astrochemistry (4 panels)
4. Circumstellar disks, exoplanets and the solar system (4 panels)
5. Stellar evolution and the Sun (2 panels).

Science Assessors were selected on the basis of scientific specialization while having the regional affiliation of the ARP members closely match the nominal ALMA regional shares of observing time. The 18 ARP Chairs for Cycle 4 served on the ALMA Proposal Review Committee (APRC), together with the APRC Chair, Anneila Sargent.

The JAO created an observing queue and assigned a priority grade to each proposal after considering the APRC scientific rank, the observing time share for each region, and scheduling feasibility to avoid oversubscribing configurations and LST ranges.

The Cycle 4 proposals demonstrated considerable interest in the newly available observing modes. ALMA received more than two dozen large proposals, nearly two dozen Very Long Baseline Interferometry proposals, and more than four dozen solar proposals.

On 22 March, NRAO released a Call for Proposals for 1mm Very Long Baseline Interferometry (VLBI) using the phased output of the ALMA and the Event Horizon Telescope (EHT) during ALMA Cycle 4. The Event Horizon Telescope Consortium (EHTC) comprised the Submillimeter Array, the James Clerk Maxwell Telescope, the Submillimeter Telescope, the Atacama Pathfinder Experiment, the South Pole Telescope, the Large Millimeter Telescope Alfonso Serrano, the IRAM 30m telescope, and an antenna from the Northern Extended Millimeter Array.



An overview of phased ALMA and the EHT, additional technical information supporting proposal preparation, and instructions for proposal submission were provided at the Call website. Up to 5% of ALMA Cycle 4 observing time was potentially available for VLBI, shared between 1mm and 3mm. A proposal had to be submitted to request phased ALMA by the ALMA Cycle 4 proposal deadline. In addition, the same proposal had to be submitted in response to the NRAO 1mm VLBI Call for Proposals. The submission deadline for 1mm VLBI proposals was 28 April 2016.

North American ALMA Development Program

Ongoing Development Projects

The first North American ALMA Development Program cycle began in FY2012. Three projects were funded. One Project, a fiber optic project, was ongoing in 2016. The OSF – AOS – Santiago fiber optic link became fully functional and operating pursuant to a temporary permit. The project is being held open for administrative purposes only while the final operating permit is being processed by the Chilean Ministry of National Assets (Ministerio de Bienes Nacionales.)

The second North American ALMA Development Program cycle began in FY2014. Five of eight project proposals were funded. Three of the projects (operating on no-cost, contract extension) completed at the conclusion of FY2016. Two of the Projects are ongoing and also operate on a no-cost contract extension. The following three Cycle 2 projects completed at the conclusion of FY2016.

ALMA Data Mining Toolkit (ADMIT) – University of Maryland

The ALMA ADMIT software runs within the framework of Common Astronomy Software Applications (CASA) and the archive. The ADMIT software: (1) creates basic data products for the ALMA archive, (2) creates a software infrastructure system for ADMIT tools to run in CASA on the user's local machine, (3) provides a graphical user interface for inspecting data products, (4) provides selected new tools for mining data cubes. The ALMA archive supports the ingestion and serving of ADMIT Basic Data Products and CASA supports distribution of ADMIT software as an add-on package.

NORTH AMERICAN ALMA OPERATIONS

Next Generation ALMA Image Viewer (CARTA) – University of Alberta

Cube Analysis and Rendering Tool for Astronomy (CARTA) is the next generation visualization tool for ALMA. The project combined the strengths of two major visualization efforts (CASA viewer and the CyberSKA Image Viewer) to provide an extensible tool that meets the needs of the observatory for the foreseeable future. It provides a tool that uses server-side visualization technology to provide portable, responsive views of large ALMA data sets. This dramatically expands the ability for users to effectively explore the ALMA archive.

Expansion of the Central Local Oscillator (LO) Article to Five Subarrays – NRAO

This project procured and tested all the required modules and equipment to complete Photonic LO subarray five. The complete chain was tested in Charlottesville before shipment, installation, and commissioning of the subarray at the AOS Technical Building. The completed system was integrated into the current software control system.



Photos by Pablo Carrillo

Ongoing Development Studies

The third North American ALMA Development Program cycle began in FY2015. Seven of fifteen study proposals were funded. No project proposals were solicited. The start date of the Cycle 3 Studies was delayed until Q2 FY2016 due to a temporary suspension of FY2015 ALMA Development activities while a new Cooperative Agreement was finalized between the National Science Foundation (NSF) and Associated Universities, Incorporated (AUI). The following Cycle 3 Studies are ongoing.

Pulsars, Magnetars, and Transients with Phased ALMA – Cornell University

This study will define pulsar phasing and data modes using the ALMA Phasing Project and will develop software for resampling and reformatting into Flexible Image Transport System format for use in pulsar and transient search and timing pipelines. Test data is being analyzed in the time-frequency domain relevant for studies of compact objects, and characterized with respect to data integrity and signal quality. Test observations on pulsars, if available, will be used to ground truth the system. The final reports will describe software, data results, and the next steps needed to fully develop a system that can be offered for general use.

Feature Extraction & Visualization of ALMA Data Cubes – University of Utah

The availability of large data cubes produced by telescopes like the ALMA is leading to new data and visual analysis challenges as scientists explore and compare data cubes at ever increasing resolutions. Approaches that offload the majority of the analytic tasks to the human cognitive system do not scale well with large datasets due to the limited human input bandwidth. This study uses a multidisciplinary approach to address the problem of effective visualization of ALMA data cubes. By using the notion of a contour tree from topological data analysis (TDA), the overall data load will be reduced in a mathematically robust manner. The visualizations will be designed to be intuitive, informative, and interactive and the visual analysis will preserve and present structures within the data to support scientifically meaningful analytic tasks. The study addresses the following research issues: 1) data transformation, 2) feature extraction, 3) feature exploration, and 4) feature comparison.

Digital Correlator and Phased Array Architectures for Upgrading ALMA – Smithsonian Astrophysical Observatory

The technologies used in the present ALMA correlator are a decade old. Using current technology, this study will improve bandwidth, spectral resolution and integrate native features such as phased array recording for VLBI and pulsar work. Provision of electrical power to ALMA is not from the Chilean national grid and is proving to be expensive. This same upgrade may substantially reduce the power requirements and size of the ALMA correlator. This study will examine alternative paths whereby the ALMA correlator can be upgraded. A conceptual design, including recommendations on the specifications and technologies, and estimates of schedule and cost is being developed. This will serve as the basis for follow-on work building the next generation combined correlator and phased array system for ALMA.

Advanced Materials and On-Wafer Chip Evaluation for 2nd Generation ALMA – University of Virginia

This study is investigating the suitability of an alternative materials deposition technology to realize high-energy gap, novel, all NbTiN Superconductor Insulator Superconductor (SIS) mixer devices needed for optimal 2nd generation Band 9 and Band 10 receivers and to realize a future Band 11 receiver. An existing tool is being used in a set of room temperature deposition experiment, to optimize NbTiN films, optimize AlN films and study/optimize the NbTiN/AlN/NbTiN interfaces (surface roughness, morphology, lattice constant). These experiments will be repeated with hot deposition conditions where the elevated temperatures will yield both higher energy gap NbTiN material and offer the powerful epitaxial deposition variable of wafer temperature that can be used to better match the lattice constant of the AlN to the NbTiN layers. A parallel effort is underway to develop an all-wafer SIS device I-V electrical characteristic screening technique, the objective being the quick evaluation of devices, matching of similar device characteristics in a mixer, and definition of a feasible path toward populating receiver arrays with suitable mixer elements.

NORTH AMERICAN ALMA OPERATIONS

Extensions and Enhancements to the ALMA Phasing System – MIT Haystack Observatory

The ALMA Phasing Project (APP) provides the hardware and software necessary to coherently sum the signals of up to 61 ALMA antennas in Bands 3 or 6 and record the resulting data stream in Very Long Baseline Array Data Interchange Format (VDIF). This phasing capability permits ALMA to function as the equivalent of a single large-aperture mm/submm dish; the resultant collecting area is sufficient to boost the sensitivity of global Very Long Baseline Interferometry (VLBI) experiments at mm and submm wavelengths by an order of magnitude. This study is evaluating four aspects of this capability with intent to enhance and expand the capabilities of the ALMA Phasing System (APS) beyond those delivered by the APP Phase 1. Specifically, the four topics of investigation are: (1) extension of the phasing capabilities to Band 7; (2) development of correlation techniques to compensate for the mismatch in sampling rates between ALMA and other VLBI stations; (3) optimization of ALMA baseband delay application to avoid unnecessary decorrelation losses; and (4) exploration of data reduction and analysis pathways for experiments utilizing phased ALMA data.

Improving the Calibration of Atmospheric Spectral Features – NRAO

The atmospheric calibration of ALMA science data is currently performed with the correlators operating in a coarse spectral resolution mode known as Time Division Mode, with the effect that the line profile of atmospheric line features, primarily ozone, are not fully resolved in the calibration data. As a result, their effect is not fully removed in the calibrated science data. Such data may be misinterpreted by non-experts as features in the target. This study is investigating a method to reduce or eliminate these features using the online software module TelCal. The method involves reading the total power data recorded from the baseband total power processors and using it to compute and apply a 3-bit quantization correction to the raw FDM data prior to the calculation of the receiver temperature and system temperature spectra. The study will determine the performance improvements needed for online TelCal to handle the increased computation load, and determine whether a processor upgrade will be necessary to institute this improved algorithm as standard for Frequency Division Mode observations.

Spectral Resolution and Bandwidth Upgrade of the ALMA Correlator – NRAO

This study is developing the means, and determining the integration consequences, cost, and labor requirements, for increasing the spectral resolution of the 64-antenna ALMA correlator by a factor of eight. Present resolution modes (specifically, Correlator Modes 25 and 31) achieve frequency resolution adequate for resolving the narrowest thermal lines known at 100 GHz, but are inadequate for that purpose in Band 1 (35-52 GHz). Higher resolution is needed at the lowest frequencies, Bands 1 and 2, which will soon come on line, since narrow line widths in these bands require narrower frequency bins, and at present are insufficiently resolved. The higher resolution can be traded for higher sensitivity by using twice-Nyquist sampling and 4-bit correlation. These modes exist in the present correlator, but high-level software to support them has never been developed. The increased sensitivity of the twice-Nyquist, 4-bit mode in the upgraded correlator would be equivalent to the sensitivity increase resulting, for some types of observations, from adding approximately 6 or 8 antennas to the current 50 12-m main array or to a 64-antenna array, respectively. A preliminary design, construction timeline, and cost estimates, along with simulations of parts of the design, are in work.

Development Cycle 4

A solicitation for Development Cycle 4 Studies (only) was released on 01 March 2016 and awarded on 30 July 2016. Six of fifteen study proposals were funded and are currently underway:

Cleaning Up Interactive Cleaning – University of Alberta

This study is developing a new interactive cleaning tool based upon the tools created by the CARTA project. The new tool will interface with the CASA clean/tclean tasks using the dbus communication protocol, and will provide a simple messaging interface between computational processes. This interface is already used by the CASA viewer and does not require redeveloping any software within CASA. The interactive clean tool itself will be a specifically designed layout of the CARTA tool built for the creation and manipulation of clean masks. A graphical user interface is being designed to visualize the critical information in the image for cleaning and to manipulate the masks efficiently. Users will also be able to control the algorithmic parameters of the clean task through the tool.

Total Power Map to Visibilities (TP2VIS) – Stony Brook University

This study is developing a software tool, referred to as TP2VIS, that implements the joint-deconvolution of ALMA 12m, 7m, and Total Power (TP) array data on the CASA platform. Combining data from the ALMA arrays is a critical driver for a number of scientific topics, namely those that probe size scales of extended and compact structures simultaneously. This study gives ALMA users an immediate access to joint deconvolution. TP2VIS is being built using the existing CASA toolkit and is based on the successful implementation of the same TP2VIS joint-deconvolution method on the MIRIAD software platform for CARMA and the Nobeyama 45m telescope. The work includes extensive tests of tasks in the CASA toolkit, the development of the CASA-based tool (TP2VIS) and visualization tool, tests of TP2VIS with simulation data of known flux distributions, tests of TP2VIS with ALMA archival data, and preparation of a user manual.



Photo by Pablo Carrillo

Diversifying the Scientific Applications of the ALMA Phasing System – MIT Haystack Observatory

This study is in enhancing and expanding the capabilities of the ALMA Phasing System (APS) for future ALMA Observing Cycles – without any modifications to ALMA hardware. Software modifications will improve the method for the application of baseband delays and are specific to the control interfaces used by the ALMA VLBI Observing Mode (VOM). Minor changes are being made to the communication protocol between the Correlator Control system and TelCal software. These changes add capability while leaving existing software intact and unchanged. The overall outcomes of this study will enhance the flexibility of the APS and help to significantly diversify the science applications of this new capability.

Prototype Dual-Linear 2SB Block and Single-Polarization Balanced 2SB Block – National Research Council - Canada

This study is designing, fabricating, and evaluating two prototype blocks: (1) a dual-linear polarization double-sideband block assembly, and, (2) a single polarization balanced 2SB block assembly. Prototype #1 explores possible improvements in image rejection, narrowband noise temperature, and integration. Prototype #2 extends the results further to evaluate the added advantages of a balanced receiver, namely reduced signal reflections and LO sideband noise. Measurements will be completed using a spare ALMA Band 3 receiver cartridge and test set currently available at NRC Herzberg.

Development of 2nd Generation SIS Receivers – NRAO

This study continues the development of the next generation of SIS receivers for ALMA Bands 6 and 10, with the goal of lower receiver noise temperatures, flat across the full radio frequency (RF) band and over a 4-12 GHz Intermediate Frequency (IF). For Band 6, the goal is to develop elemental mixers with wider RF bandwidth using Nb/Al-AlN/Nb SIS junctions. These will be used in a balanced sideband-separating configuration to reduce the contribution of residual LO sideband noise to the receiver noise temperature. For Band 10, the goal is to develop a highly reproducible sideband-separating receiver using Nb/Al-AlN/Nb SIS junctions with high critical current density. This will potentially improve the observing speed in Band 10 by as much as a factor of four. For both Bands 6 and 10, balanced IF amplifiers will be used to minimize interaction between mixer and amplifier without the additional loss of a wideband IF isolator. This study continues work supported under earlier ALMA development studies. If successful, several of the proposed developments will be applicable to second receivers in all the higher-frequency ALMA bands which use SIS mixer receivers.

Digital Back End Antenna Article – NRAO

This study is evaluating the design and feasibility of a Digital Back End Antenna Article (DBEAA). The DBEAA will ultimately replace the existing legacy article with a simplified, robust, and flexible set of digital hardware. Capabilities, limits, and risks of current technologies to digitize and deliver the entire current 8 GHz dual-polarization IF signals produced by the Front End receivers are being identified. Two key technical concerns are: the feasibility of using a high-speed, 3-bit, 24 GHz sampler; and the performance of a Digital Signal Processor (DSP) filter at full ALMA data rates. Neither the high sampling rate nor the DSP processing design have been demonstrated in hardware within the Observatory. With the capabilities understood, the study will develop an implementation plan towards an array-ready product that can double the processed bandwidth to 16 GHz dual-polarization IFs or 32GHz of a single IF. The DBEAA will provide the same functions as the present Back End equipment while also enabling future enhancements. This path will integrate with other Front End and Correlator development projects, keeping ALMA at the forefront of millimeter and submillimeter wavelength astronomy.

Half a Decade of ALMA Conference



Half a Decade of ALMA conference attendees. Credit: Brett McGuire.

The *Half Decade of ALMA: Cosmic Dawns Transformed* conference was held 20-23 September 2016 in Indian Wells, California, USA with 215 attendees. The 68 invited and contributed talks were compelling and are online at <https://osf.io/view/ALMA5Yrs/>. Abstract books for the talks and the 123 posters are available at the conference website, <http://go.nrao.edu/ALMA5Years>. Together these constitute the published output of the conference.

The meeting was followed by a short workshop on plans proposed by East Asia for a new total power correlator, and a stimulating symposium for postdoctoral researchers. Details of the postdoctoral symposium are also available at the conference website.



Photos by Pablo Carrillo

NORTH AMERICAN ALMA OPERATIONS

From the Historical Archives



[Left to right] Bill Harris (NSF), Hugh Van Horn (NSF), and NRAO Director Paul Vanden Bout at the 16,500 foot Millimeter Array (MMA) Chilean Andes site that became the Atacama Large Millimeter/submillimeter Array (ALMA) site. In the Fall 1997 Point Source, the NRAO internal newsletter, prompted by Congressional approval of the NSF Year 1998 budget, which included design and development funding for the MMA, the late Bob Brown wrote:

“Further partnership and cooperative involvement in the MMA is very likely. The NSF would like to see the MMA done as a partnership between their agency (through the NRAO) and another governmental agency or an international partner. Discussions, some quite far along, are being held with both the Japanese National Astronomical Observatory and the European Southern Observatory. These may lead to the MMA being done collaboratively and being expanded well beyond the scale of the project that we have been imagining heretofore. Such partnerships, should they come to pass, will have little effect on our near-term development plans but perhaps profound effects on the long-term evolution of the MMA project.”

ALMA Ambassadors Postdoctoral Program

The ALMA Ambassadors Postdoctoral Program (http://go.nrao.edu/alma_ambassadors) was created in 2016 to provide training and a \$10,000 research grant to postdoctoral researchers interested in expanding their ALMA/interferometry expertise and sharing that knowledge with their home institutions through the organization of ALMA Cycle 5 proposal writing workshops.

The NAASC sponsored selected postdocs to travel to NAASC headquarters in Charlottesville, Virginia for three days in February 2017 to receive in depth training in topics related to ALMA proposal writing – interferometry basics, ALMA science capabilities, recent ALMA headlines, use of the Observing Tool – as well as guidance with speaking on these topics. The postdocs returned to their home institutions with the knowledge and skills to host a local day-long proposal writing workshop – similar to an abbreviated version of Community Day and NRAO Live! events from previous observing cycles. Workshops took place in February or March 2017 in advance of the Cycle 5 ALMA proposal deadline in April 2017.

All talk materials, supplies, and infrastructure for the workshops are provided by the NAASC. A \$10,000 grant is offered in support of the selected postdocs' independent research programs. Postdocs with some radio or sub-millimeter interferometry experience are preferred.

NAASC Workshop on Molecular Gas in Galactic Environments



The NRAO – North American ALMA Science Center (NAASC) organized a science workshop titled *Molecular Gas in Galactic Environments*, 4–7 April 2016 in Charlottesville, Virginia, USA.

The spectral line sensitivity and spectral grasp of ALMA have resulted in the identification and imaging of more than 40 molecules outside the Milky Way. This international Workshop focused on the character of the molecular gas in the varied environments in which these molecules are found beyond our Galaxy and brought together ALMA, VLA, and GBT users and potential users of future facilities – a next-generation VLA, the James Webb Space Telescope, the Thirty Meter Telescope, etc. – to consider what capabilities or upgrades to these instruments might best facilitate the study of extragalactic molecules.

Major topics of discussion at this NAASC Workshop included:

- Exploring the relationship between molecular distributions and physical processes in galaxies
- Investigating the roles of molecular variation in extreme metallicity environments
- Examining the existence and cause of isotopic gradients within galaxies
- Scrutinizing variations in molecular excitation, both rotational and vibrational
- Seeking evidence for and causes of molecular abundance gradients
- Identifying molecules useful as probes of nuclear infall and outflow
- Determining the prospects of molecules as probes of black hole masses.

NORTH AMERICAN ALMA OPERATIONS

ALMA at the National Radio Science Meeting

The U.S. National Committee (USNC) of the International Union of Radio Science (URSI) held its annual meeting in Boulder, Colorado 6-9 January 2016. As with previous USNC-URSI meetings, the 2016 program included a wide range of subjects that were directly and indirectly relevant to radio astronomy.

The URSI Commission J (Radio Astronomy) sessions included:

- Emerging Instrumentation and Techniques
- SKA Technical Development
- Digital Developments
- New Telescopes, Techniques, and Observations
- Timing and Transients
- Atacama Large Millimeter/submillimeter Array: Systems and Science



In addition to the numerous NRAO scientists who presented during the Commission J sessions, a dedicated ALMA session featured a cross-section of scientists from the user community, including the following speakers and presentations.

- *Atacama Large Millimeter/submillimeter Array (ALMA): Status & Development*, Pierre Cox (Joint ALMA Observatory)
- *The ALMA Phasing System: A New Capability for High Angular Resolution & High Sensitivity Science*, Michael Hecht (MIT Haystack Observatory)
- *Observing the Sun with the ALMA: A New Tool for Solar Physics*, Timothy S. Bastian (NRAO)
- *Exploring the Solar System with ALMA*, Arielle Moullet (NRAO)
- *Volatiles in Protoplanetary Disks & the C/N Budgets of Terrestrial Worlds*, Geoffrey Blake (Caltech)
- *Witnessing the Formation of Stars & Planets with ALMA*, Laura Perez (MPIfR Bonn)
- *Unraveling the Mysteries of Star & Planet Formation with ALMA*, Doug Johnstone (NRC Herzberg)
- *Spectral Observations of Star Formation with ALMA*, James Di Francesco (NRC Herzberg)
- *Getting the Most Out of Your ALMA Data with ADMIT: The ALMA Data Mining Toolkit*, Leslie Looney (University of Illinois)
- *Probing Massive Star Cluster Formation with ALMA*, Kelsey Johnson (University of Virginia)
- *Galaxy Evolution Across Cosmic Time: The Important Role of ALMA*, Caitlin Casey (University of Texas)
- *Detecting Dark Matter Subhalos with ALMA Observations of Gravitationally Lensed Galaxies*, Yashar Hezaveh (Stanford)



Photo by Pablo Carrillo

NEW MEXICO OPERATIONS



Karl G. Jansky Very Large Array

The Karl G. Jansky Very Large Array is a radio telescope with unprecedented sensitivity, frequency coverage, and imaging capabilities. A suite of modern wide-bandwidth receivers, a digital data transmission system, and a Wideband Interferometric Digital Architecture (WIDAR) correlator combine to provide superb spectral resolution and unmatched continuum sensitivity at frequencies from 1 to 50 GHz. The VLA provides the centimeter-wavelength radio complement to ALMA and the next generation instruments coming online over the next few years, with the following capabilities:



- Operation at any frequency between 1.0 and 50 GHz, in addition to 58-84 MHz and 220-500 MHz.
- Unprecedented continuum sensitivity with up to 8 GHz of instantaneous bandwidth per polarization, 64 independently tunable sub-band pairs, each providing full polarization capabilities.
- Up to 65,536 spectral channels, adjustable frequency resolution from 2 MHz to sub-kHz, and extensive capabilities to allocate correlator resources with a planned increase to up to 4,194,304 spectral channels.
- VLA phased array mode for pulsar observations or Very Long Baseline Interferometry with the VLBA or as an element in the HSA.
- Dynamic scheduling based on weather, array configuration, and science requirements. Calibrated visibilities and reference images of calibrators for quality assurance automatically produced, with all data products archived.
- Calibration of all data acquired on the telescope through a dedicated pipeline currently optimized for Stokes I continuum science, with planned expansions to include polarization and spectral line science projects, as well as imaging.

VLA Sky Survey Pilot

The Very Large Array Sky Survey (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, and will begin in 2017, pending successful achievement of the design phase milestones. The total VLA telescope time required for the survey is ~5400 hours, or ~900 hours per configuration cycle.



With the decision in late 2015 to proceed with VLASS, a 200-hr pilot in the recently commenced VLA B-configuration of semester 2016A, has been approved, with the first observations starting June 2016. This pilot survey will inform VLASS implementation and

NEW MEXICO OPERATIONS

operational issues associated with the full survey as input to design reviews, while at the same time providing the community with early VLASS-type data products. The pilot will be observed in as similar a mode to the full VLASS as possible, including:

- S-band (2-4 GHz), 1024 x 2 MHz channels
- VLA B-configuration, 2.5-arcsec resolution
- On-The-Fly (OTF) mosaics scanning at 3.31 arcmin/sec in right ascension, at constant declination
- Net mapping speed ~ 20 deg²/hr, 4-hr scheduling blocks covering 80 deg² (10° x 8° tiles)

Some areas will be covered with three passes to provide a similar sensitivity as that expected from three epochs of the full VLASS (70 microJy/beam), while others will be observed with a single pass (120 microJy/beam) to maximize sky coverage. The pilot will cover key galactic and extragalactic fields that have good multi-wavelength ancillary data, as well as covering areas of sky with good prior radio observations for technical validation of the OTF mosaicking observing mode. The total area to be covered will be ~ 2500 deg², and will include:

VLASS Pilot Fields, 3 passes (70 microJy/beam):

- Galactic Plane fields: Galactic Center, Cygnus, Cepheus
- Extragalactic fields: Cosmological Evolution Survey, Sloan Digital Sky Survey (SDSS) Stripe 82, Chandra Deep Field South

VLASS Pilot Fields, 1 pass (120 microJy/beam):

- SDSS South Galactic Cap / FIRST southern sky for declination > 0 deg
- SDSS North Galactic Cap fields: Great Observatories Origins Deep Survey – North, Elais-N1, Lockman Hole, H-ATLAS North, Bootes

Raw visibility data will be immediately available through the NRAO archive under project code TVPILOT. Data products (calibrated visibility data, images) will be made available after undergoing quality assurance.

NRAO encourages community participation via the following VLASS Science Working Groups as we define and refine the operational aspects of the pilot survey:

- Extragalactic Working Group
- Galactic Working Group
- Transients Working Group
- Polarization Working Group
- EPO Working Group
- Survey Implementation Working Group
- NRAO Data Products, Archiving and Enhanced Data Products Working Group

Assistant Director for New Mexico Operations

Mark McKinnon became the permanent NRAO Assistant Director for New Mexico Operations in mid-December.

McKinnon came to Socorro in the 1980s to begin his Astronomy Masters and Ph.D. degrees, after an engineering career in the oil industry. He became a Jansky Fellow, and following that moved to Green Bank as an assistant scientist, and eventually Deputy Assistant Director during the Green Bank Telescope construction. In that role, he led the team that conducted the first-light observations with the new telescope.



Back in Socorro, McKinnon was the New Mexico Deputy Assistant Director and Project Manager for the Expanded Very Large Array Project between 2006-2010, and led that team to create the highly successful Jansky Very Large Array. From 2010-2014 he was the North American ALMA Project Manager, and subsequently led the Square Kilometre Array Dish Consortium during a long-term visit to Australia.

McKinnon has been critically involved at the highest levels of most major NRAO accomplishments over the past two decades. Mark has been the interim Assistant Director for New Mexico Operations for the past year, during which many excellent science results emerged from the VLA and the Very Long Baseline Array, and he helped oversee the complex transition to create the Long Baseline Observatory.

15th Synthesis Imaging Workshop



Attendees at the 15th Synthesis Imaging Workshop.

The 15th Synthesis Imaging Workshop was held 1-8 May 2016 in Socorro, New Mexico. Most of the workshop was held at the Workman Center on the campus of the New Mexico Institute of Mining and Technology (NMT). The data reduction tutorials were partially held at the NRAO Domenici Science Operations Center in Socorro. The Workshop featured four days of lectures, two days of data reduction tutorials, and an afternoon of observation preparation tutorials. Other events included a reception, workshop dinner, hikes of the Magdalena Mountains and the Bosque del Apache, and a popular tour of the VLA.

NEW MEXICO OPERATIONS

Workshop attendance included 136 scientists from 15 countries. Over half the participants were graduate students; scientific and engineering staff, postdocs, undergraduates, and faculty also attended.

The students spent one afternoon learning the important considerations for observing and how to prepare for VLA and ALMA observations. There were also two full days of data reduction tutorials. Participants could choose tutorials using VLA, VLBA, Long Wavelength Array (LWA), and/or ALMA data. The datasets and a guide to reducing them via the Common Astronomy Software Applications (CASA) package are online.

5th VLA Data Reduction Workshop



The 5th VLA Data Reduction Workshop was held 14-18 March 2016 to assist observers with the challenges of VLA Data Reduction posed by the increased flexibility and complexity of the instrument. NRAO staff provided lectures on various topics of interest, and allowed participants to reduce some of their own data with local expert staff in attendance for consultation.

This was an advanced workshop, unlike the NRAO Synthesis Imaging Workshops, and was not intended for those who are new to radio interferometry. Prior experience with AIPS, CASA, or MIRIAD was required.

From the Historical Archives

In June 1974, John Payne (back to camera), Mike Balister, and Ken Kellermann (at right) consider the four-frequency Cassegrain receiver and feed assembly, with optics designed by Peter Napier, that was the prototype system for the VLA and was also used for the VLBA. It was a new and innovative concept, first developed by the Jet Propulsion Laboratory for use on their Deep Space Network antennas, where the four feeds were offset from the electrical axis and could be illuminated by rotating the asymmetric subreflector. Here it is



being installed for testing on the 140-Foot antenna in Green Bank. After installation of the Cassegrain cabin on the 140-Foot Telescope, the system was integrated and evaluated by Chuck Brockaway and Tom Dunbrack.

Coexisting with Radio Frequency Interference

NRAO hosted *RFI 2016: Coexisting with Radio Frequency Interference*, in Socorro, New Mexico 17–20 October 2016. This is latest in a series of international meetings discussing radio frequency interference (RFI) and RFI mitigation for passive sciences – radio astronomy and remote sensing.

Following the previous successful workshops held in Bonn (Germany 2001), Penticton (Canada, 2004), and Groningen (The Netherlands, 2010), RFI 2016 brought together researchers, engineers and users from all radio science disciplines to consider how RFI affects their respective fields, to develop mitigation strategies, and to foster cooperation and collaboration. Attention was given to the impact of new and future sources of RFI, spectrum management challenges, and new technology developments.

Real-time, Commensal Fast Transient Searches

While the Expanded Very Large Array project produced dramatic improvements in sensitivity and frequency coverage, its legacy may be defined by the introduction of powerful and flexible digital signal processing. The power and flexibility of the VLA correlator makes it uniquely capable of doing a broad range of science today and growing to do the science of tomorrow.



One exciting pursuit for the VLA is the study of Fast Radio Bursts (FRBs), a new class of millisecond radio transient. FRBs seem to come from far outside our galaxy, which would make them unusually luminous and novel probes of the intergalactic medium. As the most sensitive centimeter-wavelength radio interferometer, the VLA will revolutionize this field with its ability to precisely localize sources to identify multi-wavelength counterparts (e.g., a host galaxy). Previously, our group has demonstrated that potential with the introduction of “fast imaging,” a new concept for using the VLA as a high speed camera. Now, we are expanding on that concept with the construction of realfast, a 24 / 7 fast transient survey system at the VLA.

The core of realfast is a 32-node, Graphics Processing Unit-accelerated compute cluster that will perform real-time transient searches on millisecond timescales as data are received at the VLA, before averaging the data for archive storage. Real-time processing will allow us to rapidly identify transients and trigger recording of data for those brief moments when a transient candidate is detected. Triggered data recording reduces the data flow by orders of magnitude and makes it feasible to observe continuously. We will integrate this system with a duplicate high-speed data stream to turn each VLA observation into a fast transient survey, ultimately encompassing thousands of hours per year.

Realfast will be supported by a three-year grant from the NSF Advanced Technologies and Instrumentation program, and developed in close collaboration with NRAO staff. Transient alerts and associated data products will be made public. This will make the VLA into a transient survey machine and help connect the public to our understanding of the rapidly changing sky.

Next Generation Very Large Array

Radio astronomy is playing a leading role in opening new discovery space, imaging the earliest phases of planet and star 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, and testing the fundamental laws of physics and cosmology.

Inspired by dramatic discoveries from the VLA and ALMA, the community and NRAO have initiated discussion of a future facility at short centimeter wavelengths that will enable a major step in imaging thermal emission from the cosmos at milliarcsecond resolution: a next generation Very Large Array (ngVLA). The year 2016 has seen rapid progress in the ngVLA science case and technical requirements, and the ngVLA is an integral part of the broader astronomy community discussion of future science opportunities and instrumentation.

ngVLA Project Scientist

Eric Murphy was appointed in 2016 to the position of ngVLA Project Scientist. In this role, Eric is responsible for the development of the ngVLA science case and its science requirements. He serves as the primary liaison between the NRAO and the astronomy community to ensure inclusive engagement in the development of the ngVLA science case and design. He also works with the ngVLA technical teams in translating science requirements into high level technical requirements.



Eric transferred to the ngVLA from the NAASC, where he was a member of the Data Services and Archive Team. He was an active participant in the astronomy community as a co-chair of the Governing Council for the VLA Sky Survey, chair of the ngVLA Galaxy Ecosystems Science Working Group (SWG), and a core member of the SKA Extragalactic Continuum SWG. Prior to joining NRAO, Eric was a research scientist at Caltech and a postdoctoral fellow at Carnegie Observatories and the Spitzer Science Center. He received his PhD in Astronomy from Yale University. His research interests include galaxy formation and evolution, star formation, cosmic ray propagation, and magnetic fields.

Next Generation VLA Workshop at the AAS

The NRAO organized a day-long workshop on 4 January 2016 – immediately prior to the AAS meeting in Kissimmee, Florida – to continue and enlarge on community discussions regarding the scientific motivation and technical concept for the ngVLA.

This Workshop updated the community on progress toward the ngVLA concept throughout 2015 and fostered broad discussion of the science case and technical challenges for such an array. The program included:

1. Invited presentations of current scientific drivers for the ngVLA
2. Contributed science talks that expand the ngVLA science case
3. Discussion of the technical requirements and challenges emerging from the science program
4. Discussion of ngVLA synergies with other science facilities, such as ALMA, James Webb Space Telescope, High Definition Space Telescope, Square Kilometre Array, and Thirty Meter Telescope.

Community Studies

As part of the process of building towards a concept for a ngVLA, the NRAO launched an ngVLA Community Studies program in 2016, allowing members of the scientific and engineering communities to become major contributors to this effort. Twenty-five scientific and technical ngVLA Community Studies have been approved. Each of these studies will be carried out over the next year to help define a final design concept to be brought to the Astro2020 Decadal Survey.

All accepted Community Studies efforts will document their findings as part of a peer-refereed journal article or ngVLA Memo, and present their progress and final results at the ngVLA science conference in June 2017. Consequently, NRAO will financially support each study at a modest level to help offset travel expenses to present the results, as well as for page charges from publications that result from the study. NRAO is able to provide funding at a more significant level for ten of the accepted proposals.

Table 1: Approved Science Studies

PI (affiliation)	Proposal Title
Geoffrey Bower (ASIAA)	Galactic Center Pulsars with the ngVLA
Caitlin Casey (University of Texas at Austin)*	Cold Gas in the Early Universe
Shami Chatterjee (Cornell University)*	A NANOGrav Study of Gravitational Wave Astronomy with the ngVLA
Alessandra Corsi (Texas Tech University)*	Cosmic Explosions and Collisions in the ngVLA Era
Andrea Isella (Rice University)*	Imaging Planet Formation with the ngVLA
Garrett Keating (SAO)	Exploring the Cosmic History of Molecular Gas with Intensity Mapping
Adam Leroy (Ohio State University)	Assessing the Suitability of Proposed ngVLA Designs for Surface Brightness Science
Brett McGuire (NRAO)	The Detectability of Interstellar Molecules with the ngVLA
Kristina Nyland (NRAO)	Revolutionizing Radio AGN Science with the ngVLA
Rachel Osten (STScI & JHU)*	Quantifying the ngVLA's Contribution to Exo-Space Weather
Jorge Pineda (JPL)	Composition of the Interstellar Medium
Vikram Ravi (Caltech)*	Centimeter-Wavelength Observations of Compact-Object Cataclysms
Keren Willacy (JPL)	Protoplanetary Disk Chemistry as a Probe of Planet Formation

*Requested and approved for additional funding.

Table 2: Approved Technical Studies

PI (affiliation)	Study Title
Roger Angel (University of Arizona; REhnu, Inc.)	A New Approach to Inexpensive Radio Dishes
Joe Campbell (UVa)*	High-Power, High-Speed Photodiodes
Larry D'Addario (Caltech/JPL)	Advanced Cryocooling Technologies
Matt Fleming (Minex Engineering Corp.)*	Proposal for Antenna Mount Study
David Frayer (GBO)	Short Spacing Requirements for the ngVLA
Brian Jeffs (BYU)*	Advanced Spatial Filtering Methods for RFI Mitigation at the ngVLA
Jeroen Koelmeij (LaserLaB and VU Amsterdam)	Sub-Nanosecond Time Accuracy and Frequency Distribution through White Rabbit Ethernet
Dean Chalmers (NRC Herzberg)	Offset Gregorian Antenna
Lewis Knee (NRC Herzberg)	ngVLA Receivers
Michael Rupen (NRC Herzberg)	The Scientific Drivers and Technical Requirements for the ngVLA Correlator
Stefano Spagna (Quantum Design Inc.)*	Smart Energy Cryocooler Technology for the ngVLA
Greg Taylor (UNM)	Exploring Low Frequency Options for the ngVLA: Providing a Path to a Next Generation LOw Band Observatory (ngLOBO)
David Woody (Caltech/Owens Valley Radio Observatory)	Impact of Fast Switching on Telescope Design

*Requested and approved for additional funding.

Science Advisory Council

The NRAO solicited nominations in 2016 for membership to the Science Advisory Council (SAC) for the ngVLA. The SAC is the interface between the scientific community and NRAO, providing feedback and guidance directly to the ngVLA Project Office on issues that affect the scientific design for a U.S. led, next-generation centimeter-to-millimeter wave interferometer, most likely to be centered around the VLA site in the Plains of San Agustin in New Mexico.

ngVLA Science Advisory Council

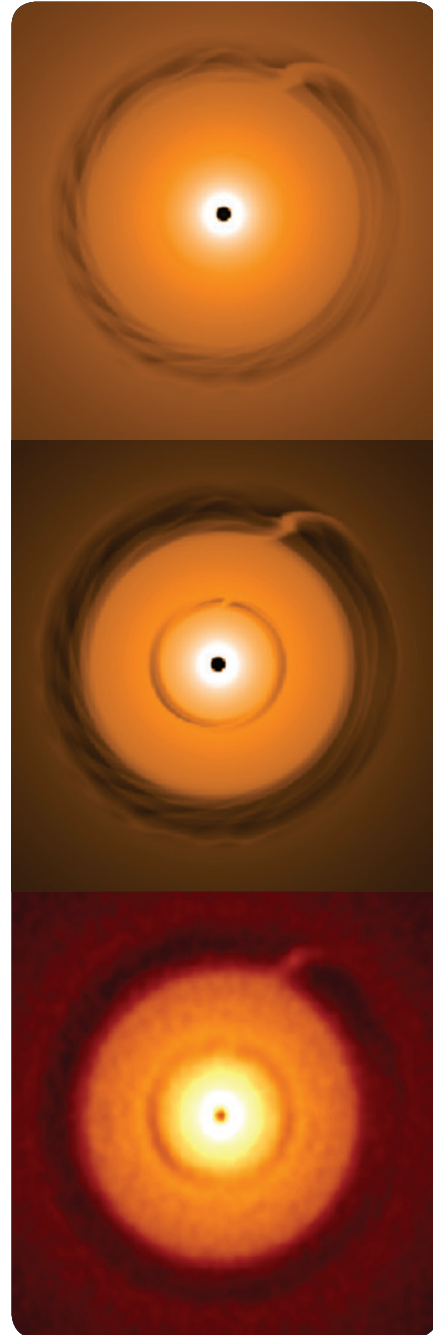
Alberto Bolatto	University of Maryland (Co-Chair)
Shami Chatterjee	Cornell University
Caitlin Casey	University of Texas at Austin
Laura Chomiuk	Michigan State University
Danny Dale	University of Wyoming
Imke de Pater	University of California, Berkeley
Mark Dickinson	National Optical Astronomy Observatory
James Di Francesco	National Research Council – Canada
Gregg Hallinan	California Institute of Technology
Andrea Isella	Rice University (Co-Chair)
Kotaro Kohno	University of Tokyo
Shri Kulkarni	California Institute of Technology
Cornelia Lang	University of Iowa
Joseph Lazio	NASA – Jet Propulsion Lab
Adam Leroy	Ohio State University
Laurent Loinard	Universidad Nacional Autónoma de México
Thomas Maccarone	Texas Tech University
Brenda Matthews	National Research Council – Canada
Rachel Osten	Space Telescope Science Institute
Mark Reid	Harvard-Smithsonian Center for Astrophysics
Dominik Riechers	Cornell University
Nami Sakai	Rikagaku Kenkyūsho
Fabian Walter	Max-Planck-Institut für Astronomie
David Wilner	Harvard-Smithsonian Center for Astrophysics

Ex-Officio Member

Eric Murphy NRAO (ngVLA Project Scientist)

Terrestrial Zone Planet Formation

A 1 Myr protoplanetary disk at 140 pc hosts a Jupiter and a Saturn mass planet at 12 and 6 AU, respectively. **[Top]** Because of the high optical depth within 10 AU, model emission above 50 GHz reveals only the outermost planet, while **[Center]** the model emission below 50 GHz reveals both planets. **[Bottom]** A simulated ngVLA observation of the 25 GHz disk emission at 10 milli-arcseconds (1 AU) resolution detects both planets. Isella et al. 2015.



Technical Advisory Council

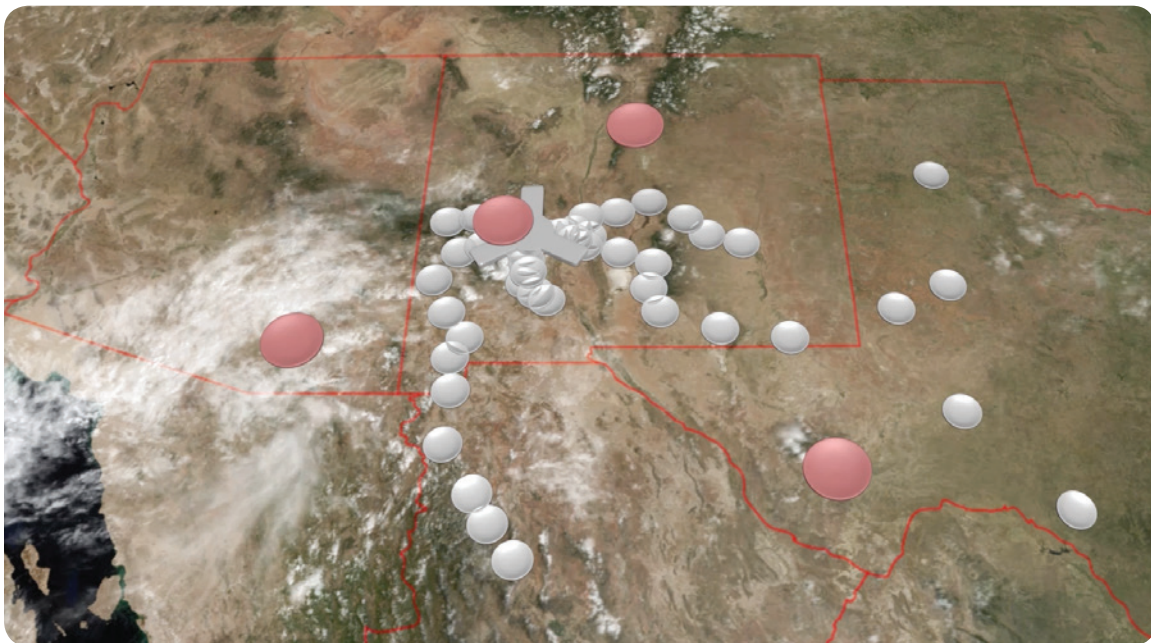
The NRAO solicited nominations in 2016 for membership to the Technical Advisory Council (TAC) for the ngVLA. Selections were made by the NRAO Director and the ngVLA Project Office, in consultation with NRAO Advisory Committees. The ngVLA TAC acts as the interface between NRAO and engineering and computing experts within the radio astronomy community, providing feedback and guidance as the Observatory moves towards a final design for a next-generation centimeter-to-millimeter wave interferometer centered around the VLA site on the Plains of San Agustin in New Mexico.

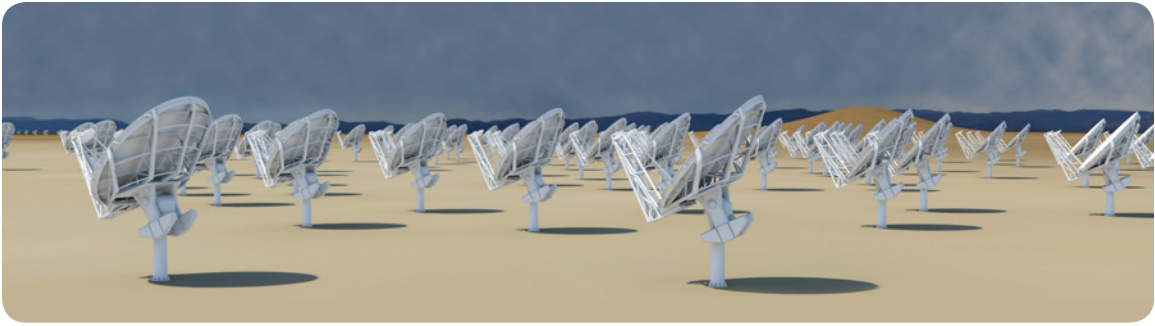
ngVLA Technical Advisory Council

Sarah Church	Stanford University
Larry D'Addario	NASA – Jet Propulsion Lab
Sean Dougherty	National Research Council – Canada
Mark Gurwell	Harvard-Smithsonian Center for Astrophysics
Andy Harris	University of Maryland
Tetsuo Hasegawa	National Astronomical Observatory of Japan
Jeff Kantor	Large Synoptic Survey Telescope
Stan Kurtz	UNAM
James Lamb (co-chair)	California Institute of Technology
Michael Rupen	National Research Council – Canada
Melissa Soriano (co-chair)	NASA – Jet Propulsion Lab
Sander Weinreb	California Institute of Technology

Ex-Officio Members

Rob Selina	NRAO (ngVLA Project Engineer)
Barry Clark	NRAO (Emeritus)





*Artist's conception of the multi-antenna ngVLA.
Credit: B. Saxton, NRAO/AUI/NSF*

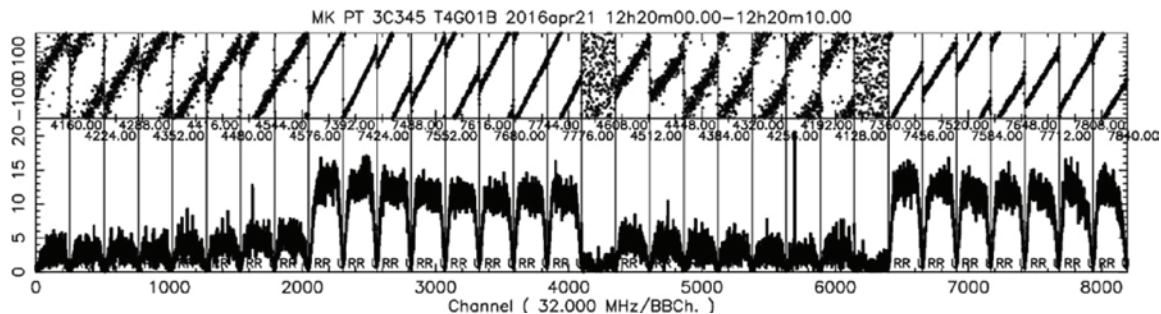
Very Long Baseline Array

The Very Long Baseline Array (VLBA) is an interferometer of ten identical 25-meter antennas with baseline lengths up to 8600 km – Mauna Kea, Hawaii to St. Croix, Virgin Islands – controlled remotely from the Domenici Science Operations Center in Socorro, New Mexico. The array can be scheduled dynamically, taking into account predicted weather conditions across the array.

Ten discrete observing bands are available, ranging from 90 cm to 3 mm wavelength (300 MHz to 96 GHz). Signals received at each antenna are sampled, processed digitally, and recorded on fast, high capacity recorders. The recorded data are sent from the individual VLBA stations to the Science Operations Center, where they are combined in a software-based correlator system.

The VLBA's continuum sensitivity can be extended significantly when combined with the phased VLA, the Robert C. Byrd Green Bank Telescope, and the William E. Gordon Telescope in Arecibo, Puerto Rico, and the Max-Planck-Institute for Radio Astronomy telescope in Effelsberg, Germany. Together, these facilities form the High Sensitivity Array (HSA), available to astronomers by submission of a single proposal.

4 Gbps Mode Demonstration



32 base-band channels, each 32 MHz wide, correlated on the Pie Town to Mauna Kea baseline. [Top] Phase as a function of frequency, with the slope indicating a typical residual delay (~ 20 nanosec). [Bottom] Amplitudes vary due to the structure of 3C345 as a function of baseline length (measured in wavelengths) which span nearly a factor of two across the observing bands (4160 to 7840 MHz). Note channels are not in a natural order and two "non-channels" (17th and 25th) provide no useful data.

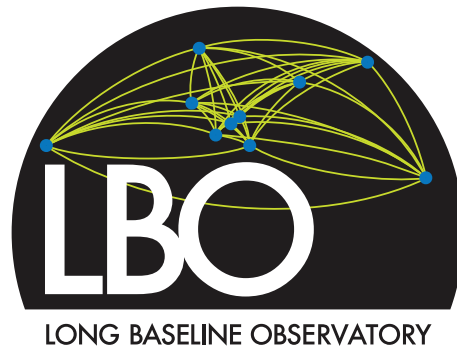
Starting in 2008, new digital electronics and recorders were installed on the VLBA as part of ongoing efforts to improve the array's sensitivity. The instrument's usable bandwidth was increased from 64 MHz per polarization, to 256 MHz with the most restrictive limitation being throughput of the Mark5C recorders. A 4 Gbps capability was demonstrated in a test using the Pie Town and Mauna Kea antennas on 21 April 2016. Two ROACH Digital Back Ends using the Polyphase Filter-Bank personality, each fed a separate Mark5C recorder (see Figure).

A second four-station test was performed 23 May 2016. Tests were performed in a non-operational mode (hand-created files and hand-configured instrumentation). The cost and effort to make this operational across the VLBA is being evaluated with possible roll-out of this new capability over the next year or two.

While doubling the bandwidth would be a welcome improvement for almost all VLBA continuum science, it is especially attractive to 3mm Very Long Baseline Interferometry (VLBI) observations, where short atmospheric coherence times require high sensitivity, and where several other antennas comprising the Global Millimeter VLBI Array (GMVA) either already have or are developing similar capabilities. The GMVA is coordinated by the Max Planck Institute for Radio Astronomy and has been supporting the VLBA in testing and through contribution of recorder resources.

Long Baseline Observatory Launch

On 1 October 2016, the Very Long Baseline Array (VLBA) separated from the NRAO facilities suite and was placed into the Long Baseline Observatory (LBO). This transition financially separated the VLBA from the VLA, though the LBO will continue to work closely with NRAO to ensure continuity of services and efficient operations. To avoid confusion, the research facility will continue to be called the VLBA, but the VLBA will be managed and operated by the LBO. Walter Brisken is in the inaugural LBO Director.



A key goal in the creation of the LBO, and migration of the VLBA into the LBO, has been minimal change to the user experience. Users saw the first impact of the separation at the 1 August 2016 NRAO Call for Proposals, where VLBA proposals were solicited separately from those for VLA and the Green Bank Telescope (GBT). As time progresses, other changes will become apparent, including the creation of a new Internet domain, <https://www.lbo.us>.

Perhaps the largest changes to the VLBA as part of its transition into the LBO are new opportunities for technical improvements, such as the installation of new receivers, and further increasing the system bandwidth through new electronics and data transmission equipment.

A necessary consequence of the new partnerships that are enabling continued VLBA science operations is a reduction in time openly available to the VLBA community. The magnitude of impact is not yet precisely known, though a reduction of up to 50% is possible. Available VLBA science operations time will continue to be awarded under an Open Skies policy: the highest-rated science observing proposals will continue to be awarded time, regardless of proposer affiliation. The HSA, a VLBI array consisting of the VLBA antennas, the phased VLA, the GBT, Arecibo, and Effelsberg, will continue to be offered at upcoming calls for proposals with the same Open Skies policy, as will global VLBI with the European VLBI Network and the GMVA.



WEST VIRGINIA OPERATIONS



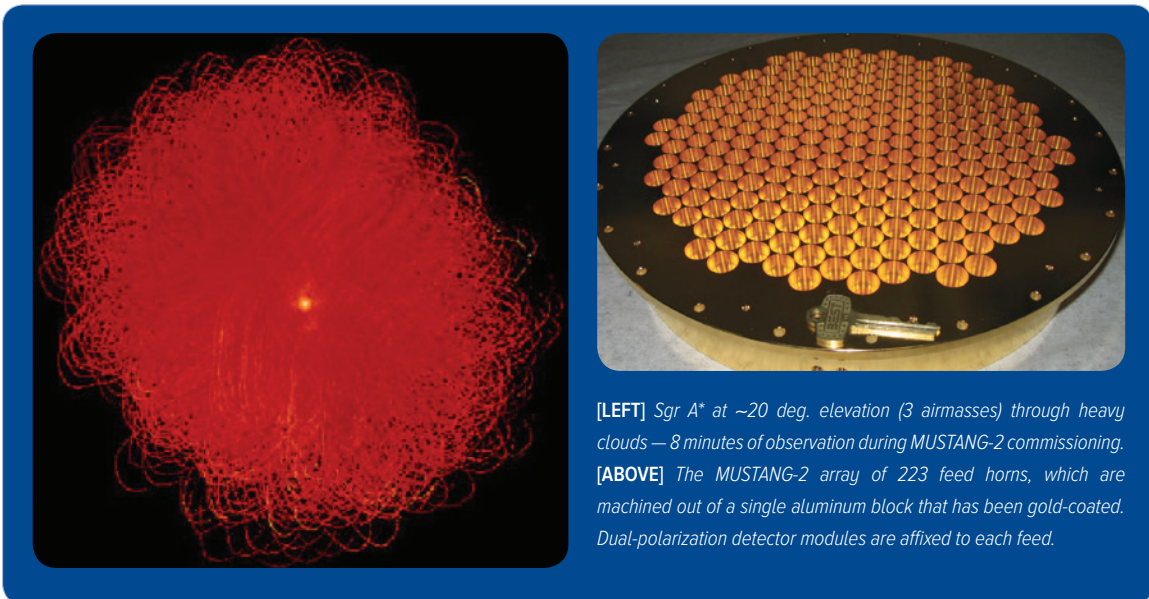
The Green Bank Telescope (GBT) is the premier single-dish radio telescope operating at centimeter and millimeter wavelengths. Its enormous 100-meter diameter collecting area, unblocked aperture, and excellent surface accuracy provide unmatched sensitivity across the telescope's full 0.1-116 GHz (3.0m-2.6mm) operating range. The GBT has a suite of detectors optimized for spectroscopy, pulsar observations, continuum, and VLBI. Located in the National Radio Quiet Zone, the GBT benefits from a low radio-frequency interference environment.

The single focal plane of the GBT is ideally suited for multi-pixel radio cameras; it serves as the wide-field imaging complement to ALMA and the VLA. Its operation is highly efficient, and it is used for astronomy ~6500 hours every year, with ~2000 hours per year available for high frequency science. It is scheduled dynamically to match project needs to the available weather.

Part of the scientific strength of the GBT is its flexibility and ease of use, allowing for rapid response to new scientific ideas. The GBT is regularly reconfigured with new and experimental instrumentation, adopting the best technology for any scientific pursuit. The facilities at the Green Bank site are also used for other scientific research, for many programs in education and public outreach, and for training students and teachers.

MUSTANG-2 First Light

The MUSTANG-2 camera achieved first light on 23 May 2016 at the GBT. MUSTANG-2 consists of an array of 211 feed horns outfitted with Transition-Edge Superconducting bolometers, read out by a microwave resonator multiplexer. The detectors are cooled to 300 mK to improve their sensitivity. With a larger, 4 arcminute diameter field-of-view and more numerous, more sensitive detectors than its precursor, MUSTANG-2 enables unprecedentedly detailed study of phenomena from dust in our own Galaxy to the Sunyaev-Zel'dovich Effect in the most distant galaxy clusters. After a brief evaluation period the receiver returned for GBT science observations.



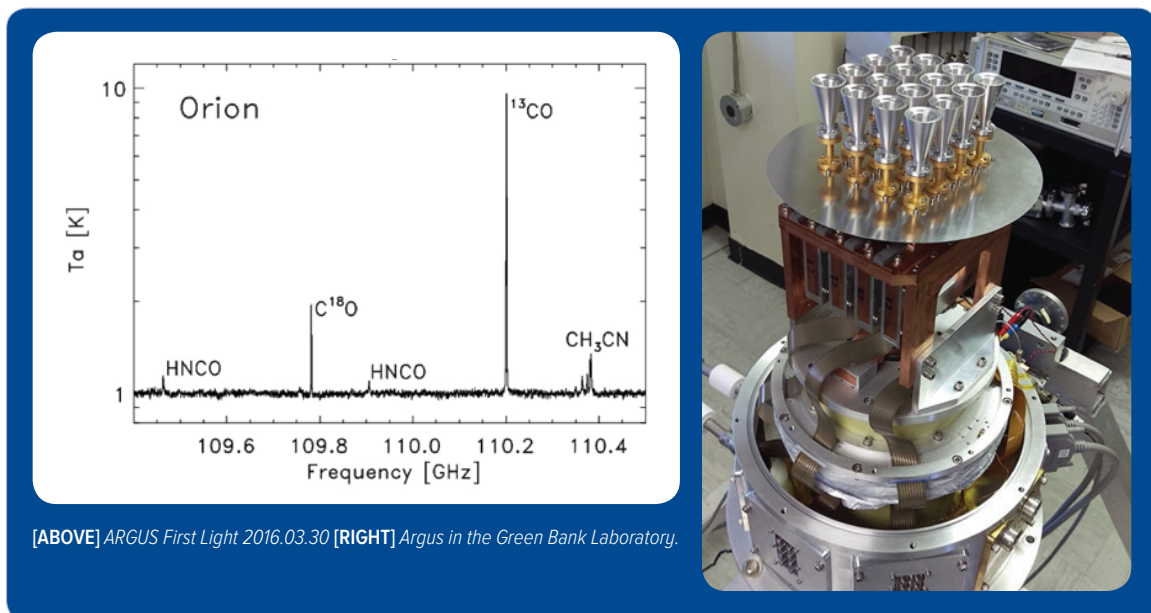
[LEFT] *Sgr A* at ~20 deg. elevation (3 airmasses) through heavy clouds — 8 minutes of observation during MUSTANG-2 commissioning.*
[ABOVE] *The MUSTANG-2 array of 223 feed horns, which are machined out of a single aluminum block that has been gold-coated. Dual-polarization detector modules are affixed to each feed.*

Argus First Light

The Argus 16-element W-band focal plane array obtained first light with the GBT on 30 March 2016, marking the first time GBT observed above 100 GHz. The spectrum in the Figure is from two, 30-second On-Off scans of the Orion star-forming complex and is a combination of data from the eight beams of Argus that were fully connected.

These test observations targeted the ^{13}CO and C^{18}O lines near 110 GHz. The data have been plotted on a log-scale to show the faint spectral features along with the bright ^{13}CO line, and the temperature scale is only an approximation. After commissioning, Argus will be available for shared-risk observations within its operational frequency range of 80-116 GHz.

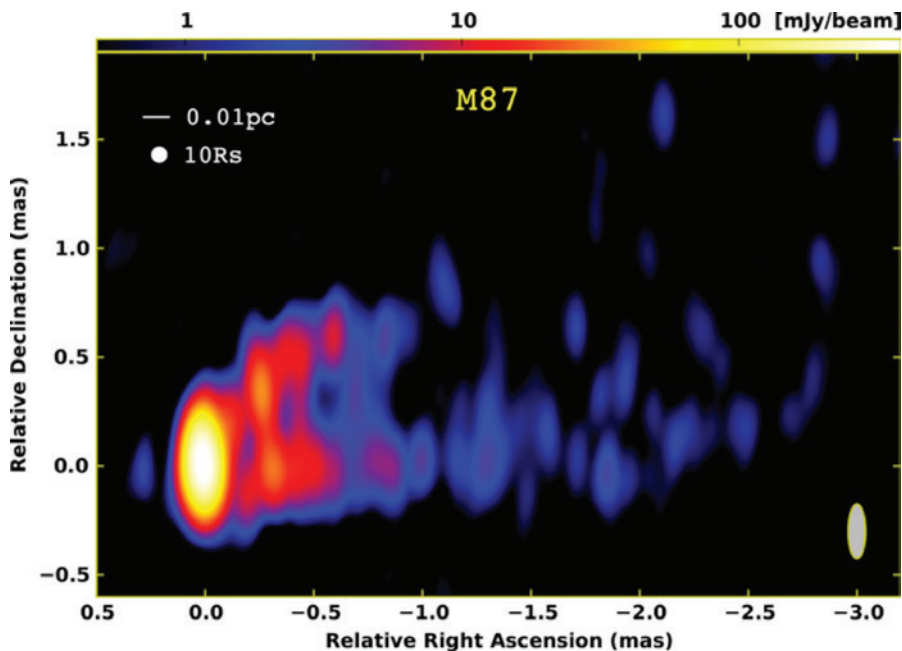
Argus is a collaboration of Stanford University (Principal Investigator, Sarah Church), Caltech, NASA-JPL, University of Maryland, University of Miami, and NRAO.



First VLBI results from the GBT at 3mm

The first publication using the GBT for VLBI measurements at 85 GHz has just appeared. Hada et al. combined eight VLBA antennas with the GBT to study the relativistic jet emanating from the central black hole of the galaxy M87. The large collecting area of the GBT, together with a new NRAO wide-band recording system, produced an image of unprecedented quality, with a dynamic range 10x greater than previous M87 images in this band. The sensitivity of the GBT allowed for detection of correlated flux densities below 100 mJy on the longest baseline.

These M87 observations resolve details of the jet formation and collimation structure to ~ 10 Schwarzschild radii (R_s). The jet has an opening-angle near the black hole as wide as 100 degrees, the broadest opening angle in any astrophysical jet. A limb-brightened structure is already well developed at $< 28R_s$ and a complicated jet launch shape at $< 100R_s$ indicates



This (VLBA+GBT) 86 GHz false-color total intensity image of the M87 jet was produced by combining the visibility data from 2014 Feb 11 and Feb 26. The restoring beam is at bottom-right. The peak intensity is 500 mJy/beam.

multiple collimation stages. Some polarized features are observed near the jet base with a fractional polarization up to ~20%, the highest value ever seen on parsec-to-subparsec scales of this jet.

These results show that the GBT is a powerful addition to our astronomical capabilities for high-resolution measurements in the 3mm band.

Reference: *High-sensitivity 86 GHz (3.5 mm) VLBI Observations of M87: Deep Imaging of the Jet Base at a Resolution of 10 Schwarzschild Radii*, Kazuhiro Hada (NAOJ, INAF), et al., 2016, ApJ, 817, 1

Breakthrough Listen Workshop

The Breakthrough Listen Project and the Green Bank Observatory (GBO) sponsored the Breakthrough Listen North American Community Workshop 5-6 October 2016 at the GBO in Green Bank, West Virginia, USA.

The Breakthrough Listen Initiative was launched 20 July 2015 at the Royal Society in London, U.K., with a charge to conduct the most comprehensive and sensitive search for advanced life. Observations are currently being conducted at radio and optical wavelengths, in part using the GBT from 0.3 - 100 GHz. The Breakthrough Listen North American Community Workshop discussed the goals, strategies and capabilities of the Breakthrough Listen Project, including commensal and ancillary science opportunities, and explored the search for extraterrestrial intelligence in the modern era.



Green Bank Observatory Launch

On 1 October 2016, the NRAO Green Bank facilities, including the 100m GBT, were separated from the NRAO facility suite and into a new organization – the GBO. The transition resulted in changes in the financial and staffing structure, as well as a new website. GBO and NRAO staff worked throughout the process to ensure a seamless transition for visitors and scientists using the GBO instruments and facilities. Karen O’Neil is the inaugural GBO Director.



One of the most visible changes for those familiar with the Green Bank facility is the new GBO website, <http://greenbankobservatory.org>. All GBO information will be migrated to this new website, including information about visitor programs, site visits, telescope information, and links to the GBT proposal submission tool.

One of the most significant changes for most scientists will be in the NSF-funded Open Skies access to the GBT. As NSF funding for Open Skies science on the GBT decreases, the GBT observing time available for Open Skies proposals will also decrease.

Information specific to scientists wishing to use the GBT will be migrated to the new website throughout 2017, and links on the NRAO science website will be updated accordingly. To keep the process as straightforward as possible for the scientific community, scientists interested in applying for the NSF funded Open Skies time on the GBT will continue to apply through the NRAO Proposal Submission Tool.

A celebration of the launching of the GBO took place in Green Bank, West Virginia on 8 October 2016.



SCIENCE SUPPORT & RESEARCH



Telescope Time Allocation: Semester 2016B



A total of 326 new proposals were received by the 1 February 2016 submission deadline for the Semester 2016B NRAO Call for Proposals. A record number of proposals was received for the Global 3mm VLBI Array (GMVA) as a result, in part, of the participation of ALMA (Cycle 4) for the first time. In aggregate, the proposals covered a broad spectrum of modern research in astronomy and astrophysics.

The proposals were reviewed for scientific merit by eight Science Review Panels (SRPs) and for technical feasibility by NRAO staff. These reviews were completed in March 2016 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 18-19 April 2016 at NRAO in Green Bank, WV. The TAC consists of the SRP chairs and was charged with recommending a science program for Semester 2016B to the NRAO Director. The recommended program was reviewed and approved on 13 May 2016.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 18 May 2016. A TAC report containing information for proposers and observers, including statistics and telescope pressure plots, was released the same day. The approved science program was posted to the NRAO science website. For each approved proposal in the science program, the Proposal Finder Tool enables access to its authors, title, abstract, and approved NRAO hours.

Telescope Time Allocation: Semester 2017A



A total of 207 new proposals were received for the 1 August 2016 submission deadline for the VLA Semester 2017A Call for Proposals. The oversubscription rate (by proposal number) was 2.5 and the proposal pressure (hours requested over hours available) was 1.9. A number of large, time-critical (triggered), and multi-observatory proposals were received.

SCIENCE SUPPORT AND RESEARCH

The proposals were reviewed for scientific merit by eight SRPs and for technical feasibility by NRAO staff. These reviews were completed in early October 2016 and then considered by the TAC at a face-to-face meeting on 17-18 October 2016 at NRAO in Charlottesville, Virginia. The TAC – comprising the eight SRP chairs – was charged with recommending a science program for Semester 2017A to the Observatory Director. The recommended program was reviewed and approved on 2 November 2016.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 10 November 2016, and a TAC report containing information for proposers and observers, including statistics and telescope pressure plots, was released the same day. The approved science program for the VLA was posted to the NRAO science website. The authors, title, abstract, and scheduled hours for each approved proposal can be accessed from the Proposal Finder Tool.

Assistant Director of Science Support and Research

Lewis Ball arrived at NRAO – Charlottesville on 10 October 2016 to take on the important role of Assistant Director of Science Support and Research, succeeding Tim Bastian. Lewis was the ALMA Deputy Director between 2010 and 2013, during which time he was also an NRAO employee. Lewis oversaw the exciting transition of ALMA from construction to operations, and the delivery of ALMA Early Science through Cycles 0 and 1. Between 2013 and 2016, Lewis was the Director of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) division of Astronomy and Space Science (CASS), the Australian analog of NRAO, delivering radio astronomy facilities to Australian and overseas astronomers, including the Parkes Radio Telescope, the Australia Telescope Compact Array, and the new Australian SKA Pathfinder (ASKAP).



NRAO Astronomer Awarded Major AAS Prize



The American Astronomical Society (AAS) awarded its prestigious 2016 George Van Biesbroeck Prize to Dr. Rick Perley, an NRAO Astronomer based in Socorro, New Mexico. The Van Biesbroeck Prize honors a living individual for long-term extraordinary or unselfish service to astronomy, often beyond the requirements of his or her paid position. The AAS recognized Perley for his “tireless and unrelenting career-long service to the global astronomical community.” Perley was presented with his prize at the AAS meeting in January 2017.

The award cited Perley’s contributions “to the design, commissioning, and optimization of the world’s premier radio telescope, the Very Large Array, and its recent reinvention as the Karl G. Jansky Very Large Array (VLA).” The citation notes that Perley’s efforts have been central to every major improvement in the VLA over that facility’s more than 35-year history.

Arriving at NRAO as the first postdoctoral research fellow at the VLA in 1977, Perley led efforts that produced some of the first iconic images that demonstrated the capabilities of that telescope. In 1984, he founded a semiannual synthesis imaging school to teach astronomers from around the world how to effectively use the VLA. The AAS citation calls that school the “gold standard” of such training, and it has been emulated around the world.

Perley was NRAO's Project Scientist for the decade-long VLA Expansion Project, completed in 2012, that transformed the VLA into a vastly more powerful scientific tool by bringing its electronic systems back to the state-of-the-art. Noting those efforts, along with his enthusiastic advocacy for the VLA and radio astronomy, the AAS called him "the driving force behind one of the most powerful and productive telescopes in the world, at any wavelength, for close to four decades."

Perley received bachelor's and master's degrees in physics from the University of British Columbia and his Ph.D. in astronomy from the University of Maryland, with the late Bill Erickson as his graduate advisor. He has worked at NRAO since 1977.

Perley is the third NRAO astronomer from Socorro to receive the Van Biesbroeck Award. Dr. Eric Greisen received the award in 2005, and Dr. Barry Clark was the recipient in 1991.

2016 Jansky Lectureship: Professor Jacqueline H. van Gorkom



AUI and NRAO awarded the 2016 Karl G. Jansky Lectureship to Professor Jacqueline H. van Gorkom of Columbia University in New York City. The Jansky Lectureship is an honor established by the trustees of AUI to recognize outstanding contributions to the advancement of radio astronomy.

Professor van Gorkom is a longtime radio astronomer, specializing in studies of neutral hydrogen, the most abundant element in the Universe. Her observations have focused on the distribution and dynamics of hydrogen in and around nearby galaxies of varied types and in widely different environments, and how the gas affects the evolution of the galaxies. She currently leads an important Very Large Array observing project aimed at learning how these properties change over time by observing hydrogen at greater cosmic distances.

She received her Ph.D. in astronomy from the Kapteyn Astronomical Institute in the Netherlands, and was a postdoctoral fellow at the NRAO, and worked at the Raman Research Institute in India and Princeton University before joining the faculty at Columbia in 1988. She currently is Rutherford Professor of Astronomy at Columbia, and previously has served as Chair of the Department of Astronomy and Director of Graduate Studies.

Professor van Gorkom's awards include a NSF Faculty Award for Women, a Miller Visiting Professorship at the University of California, Berkeley, a Da Vinci Professorship at the Kapteyn Institute, and election as a Corresponding Member of the Royal Dutch Academy of Sciences. In addition, she has served on the visiting committees of the National Optical Astronomy Observatory and several radio observatories; on advisory committees for the VLA Upgrade Project; on the board of ASTRON, the Dutch National radio astronomy observatory; and on the SKA site selection advisory committee. She also has served on the scientific organizing committees of several astronomical symposia and on numerous proposal review boards for a variety of observatories and funding agencies.

As Jansky Lecturer, van Gorkom presented open lectures at NRAO facilities in Charlottesville, VA, and Socorro, NM.

This was the 51 Jansky Lectureship. First awarded in 1966, it is named in honor of the man who, in 1932, first detected radio waves from a cosmic source. Karl Jansky's discovery of radio waves from the central region of the Milky Way started the science of radio astronomy.

2016 Jansky Fellowships

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 to candidates with interest in radio astronomy research, instrumentation, computation, and theory. Prior radio experience is not required. Multi-wavelength projects leading to a synergy with NRAO instruments are encouraged.

Three new Jansky Fellows joined the NRAO in the fall of 2016.

Laura Fissel, an incoming Jansky Fellow at NRAO in Charlottesville, completed her Ph.D. at the University of Toronto and was previously a Center for Interdisciplinary Exploration and Research in Astrophysics Fellow at Northwestern University. Laura studies the magnetic field of our Galaxy, in particular, the role that magnetic fields play in star formation. She also works on the development of balloon-borne telescopes that operate above most of the Earth's atmosphere and can be used to make detailed maps of the magnetic fields in our Galaxy.



Adam Ginsburg, an incoming Jansky Fellow at NRAO in Socorro, received his Ph.D. from the University of Colorado, working with John Bally on the Bolocam Galactic Plane Survey. His research is focused on millimeter and radio observations of high-mass stars forming within high-mass clusters and on using molecular lines as probes of physical conditions in dense gas. He has experience using Arecibo, the GBT, the VLA, and ALMA.

Jackie Villadsen, an incoming Jansky Fellow at NRAO in Charlottesville, completed her Ph.D. at Caltech in 2016. She uses radio spectroscopy of stellar flares to search for extrasolar space weather events such as coronal mass ejections and stellar aurorae. She uses the VLA and the VLBA and has worked on a team developing the Starburst Project, a stellar radio burst spectroscopy facility at the Owens Valley Radio Observatory.



Robert L. Brown Award for an Outstanding Doctoral Dissertation

The NRAO and Associated Universities, Inc. (AUI) are pleased to announce that Dr. Adele Plunkett is the recipient of the 2015 Robert L. Brown Award for an Outstanding Doctoral Dissertation. Dr. Plunkett was recognized for her study of molecular clouds that serve as the incubators of clusters of new stars. Her work showed outflows being launched during the stellar birth process that impact their nearby siblings – a result that extends the classical view of isolated star formation to the far more common situation when families of stars are born together. The Award – a \$1,000 check and framed certificate – was presented in Charlottesville on 21 April 2016, after which Dr. Plunkett presented a colloquium on her research.



Dr. Adele Plunkett

The Award is administered by NRAO and AUI on behalf of Robert (Bob) Brown’s colleagues, family, and friends, and is given each year to a recent doctoral degree recipient in the United States whose dissertation is substantially based on new observational data obtained at any NRAO facility and is considered to be of an exceptionally high scientific standard.

Visit the Award website for additional information: <https://science.nrao.edu/opportunities/student-programs/brown-award>.

Grote Reber Fellows

The Grote Reber Doctoral Research Program at NRAO is jointly sponsored by the Observatory and by universities who want their Ph.D. students to have a concentrated exposure to research in radio astronomy, instrumentation, or computational techniques in astrophysics. The fellowship term is typically two years, during which the student works at one of the NRAO sites to complete their thesis research under the supervision of an NRAO scientist or engineer. Reber Fellows are paid a stipend and have access to NRAO computing resources, and are also encouraged to attend one scientific meeting per year to present their Ph.D. research. In 2016, three Reber Fellows gave outstanding dissertation talks at the January meeting of the American Astronomical Society.

Loreto Barcos-Muñoz, a student at the University of Virginia, presented her research on “A High Resolution, Unobscured View of the Active Regions in (Ultra) Luminous Infrared Galaxies from a VLA 33 GHz Survey.” Loreto has worked with Aaron Evans (UVA/NRAO) and Adam Leroy (Ohio State), among others.

Kristen M. Jones, also from the University of Virginia, gave a talk at the AAS on her work with Mark Lacy (NRAO) and Danielle Nielsen (UW-Madison) on “The Environments of Obscured Quasars.”

Bridget McEwen, a student at the University of New Mexico in Socorro, presented her thesis work on “Characterizing Supernova Remnant and Molecular Cloud Interaction Sites Using Methanol (CH₃OH) Masers,” a project she has undertaken with Ylva Pihlstrom (UNM) and Lorant Sjouwerman (NRAO).

An NRAO Summer Student's Experience

Sinclair Manning first came to the attention of NRAO astronomer Aaron Evans when she applied for a Research Experiences for Undergraduates (REU) summer internship in 2012. That summer at NRAO headquarters in Charlottesville, Virginia, provided Manning with her first glimpse into the world of research, and what it was like to be a professional astronomer.

Manning's summer experience also coincided with the nascent steps toward the development of NRAO's National Astronomy Consortium (NAC) program: an internship program designed to attract underrepresented students to astronomy and related fields and build long-term mentoring relationships that lead to successful academic and professional careers.



Manning found that while the learning curve was steep, her 10-week internship at NRAO as a rising junior was a very positive experience and solidified her decision to pursue a career in astronomy. The experience was so positive for both Manning and Evans that she returned to NRAO for a second summer in 2013, and was part of the 2014 NAC cohort at the University of Wisconsin–Madison (a NAC partner).

Now an astronomy graduate student at the University of Texas-Austin, Manning credits Aaron Evans and her advisor at Howard University (a NAC partner), Marcus Alfred, with providing research opportunities and important, ongoing mentoring support. Manning reports that Evans wrote letters of recommendations for REUs, graduate school applications, and, most recently, her NSF Graduate Research Fellowship application.

The long-term mentoring assistance by Evans and Alfred highlighted for Manning the value of the NAC program's mentoring model in a field that does not feature a large number of people from underrepresented backgrounds. Their example has encouraged Manning to serve as a mentor with the NAC and a new summer research initiative at the University of Texas-Austin. Manning is working with Dr. Caitlin Casey on understanding the formation and evolution of dusty star-forming galaxies at high redshift. She will be conducting a large-scale morphological analysis of $z \sim 1-3$ obscured galaxies and then using this analysis to distinguish between AGN and starburst-driven radio emission.

January AAS Presentations by NRAO Summer Students

Numerous NRAO summer students who conducted research with NRAO scientists in the summer 2015 presented the results of their work at the 2016 AAS meeting in Kissimmee, Florida. The session number for each paper is indicated.



Tuesday, 5 January 2016

135.01 *Formaldehyde in Absorption: Tracing Molecular Gas in Early-Type Galaxies.* **Niklaus M. Dollhopf; Jennifer Donovan Meyer.**

141.05 *Probing Solar Wind Turbulence Using JVAS and VLA Calibrator Sources.* **Sarah Betti.**

141.20 *Chemistry of the Upper Atmosphere of Neptune.* **Elizabeth Nance.**

Wednesday, 6 January 2016

241.03 *The Optimization of GBT Pulsar Data for the GBNCC Pulsar Survey.* **Ashlee N. Gordon.**

241.06 *Shedding Light on the Eclipses of PSR 1748-2446A.* **Christopher Bochenek; Paul Demorest.**

243.22 *Searching for Super Massive Binary Black Holes in the VLBA Calibrator Survey.* **Brittney C. High; Alison B. Peck; Anthony J. Beasley.**

243.38 *Jansky VLA Imaging of Heavily Obscured, Luminous Quasars at Redshifts[~]2.* **Adam Trapp; Carol J. Lonsdale; Palavi Patil.**

249.07 *Applying the Principles of Systems Engineering and Project Management to Optimize Scientific Research.* **Adria J. Peterkin.**

249.08 *The Value of Methodical Management: Optimizing Science Results.* **Linnea Saby.**

Thursday, 7 January 2016

302.06 *Characterizing Supernova Remnant and Molecular Cloud Interaction Sites Using Methanol (CH₃OH) Masers.* **Bridget McEwen; Ylva Pihlstrom; Lorant Sjouwerman.**

341.02 *Studying Star Formation in the Central Molecular Zone using 22 GHz Water and 6.7 GHz Methanol Masers.* **Matthew Rickert; Farhad Yusef-Zadeh; Juergen Ott; David S. Meier.**

341.05 *GBT Search for HI Clouds Tracing the Nuclear Wind of the Milky Way.* **Kevin C. Harrington; Felix J. Lockman; Naomi M. McClure-Griffiths.**

341.06 *Widespread Hot Ammonia in the Central Kiloparsec of the Milky Way.* **Tierra Candelaria; Elisabeth Mills; David S. Meier et al.**

341.09 *Estimating Circumnuclear Disk temperatures using ALMA data.* **Kevin Gima; Elisabeth A. Mills; Viviana A. Rosero et al.**

341.14 *Probing Metallicity across the Milky Way Disk with the VLA.* **Jonathan Barnes; Dana S. Balser; Trey Wenger.**

342.26 *CSS Object Found in Galaxy Merger 1015+364 at 2.3 and 8.5 Hz.* **Antonio J. Porras; Sarah Burke-Spolaor.**

346.01 *[NII] 205 μ m Line Emission Detection in High Red-shift Galaxies.* **Michelle Nowling.**

346.05 *The Circumnuclear Starburst Ring in NGC 1097.* **Beverly Thackeray-Lacko; Sabrina Stierwalt; Kartik Sheth.**

346.09 *Star Formation Rate in The Solar Neighborhood and Beyond.* **Bridget Kajitesi; Amanda L. Heiderman.**

346.15 *The Spatial Distribution of Large and Small Dust Grains in Transitional Disks.* **Elizabeth Gutierrez; Laura M. Perez.**

347.05 *Physical Conditions in the Molecular Gas of the Local Group Dwarf Starburst, IC 10.* **Lauren E. Bittle; Kelsey E. Johnson; Adam Leroy et al.**

349.18 *A 6 GHz Synoptic Survey of the COSMOS Deep Field with the JVLA.* **Joseph R. Sink; Steven T. Myers.**

The image features a server rack on the left side, with multiple rows of server units. Each unit has a perforated metal front panel. Several blue indicator lights are visible, some of which are illuminated. To the right of the rack, there is a vertical column of blue lights, some of which are blurred. In the foreground on the right, a server component is visible, but it is heavily blurred, showing a yellowish-gold color. The overall lighting is dim, with the primary light sources being the indicator lights.

DATA MANAGEMENT AND SOFTWARE

The Data Management and Software (DMS) department made key contributions to the NRAO in 2016. The new NRAO archive interface was developed and underwent two rounds of internal testing. Pipeline capabilities were enhanced, notably via the further development and initial commissioning of imaging capabilities, but also including operational improvements such as automatic invocation for ALMA, and Quality Assurance (QA) parameters and displays for the VLA. The ALMA Systems group supported Cycle 3 observing, while preparing the capabilities needed for later cycles. As ALMA continued to move into routine operations, the emphasis shifted 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 very high data rate Versatile Green Bank Astronomical Spectrometer (VEGAS). NRAO made its computing facilities available to the external community through direct cluster access, and for ALMA and the VLA made progress towards delivering a reprocessing user interface. CASA High Performance Computing (HPC) and parallelization facilities were validated for in-house pipeline operations and external users. DMS will continue to investigate and roll-out common cross-observatory technologies and services, such as access to Cloud computing resources. A Science Ready Data Products review is planned for 2017.

Scientific Information Services

The Scientific Information Services (SIS) division is matrixed into the Computing and Information Services (CIS) division. This enables sharing of skilled SIS resources for telescope-supporting science responsibilities and general Information Technology support. In 2016, there were five major functional groups in SIS.

Computing Operations (NAASC, New Mexico, Green Bank)

These three site-centric groups support day-to-day telescope operations and data delivery to the archive. They ensure that telescope capability development projects are appropriately staffed, with resources being assigned based on commitments and timelines defined within the PMD and at the site. Project and milestones for these resources are tracked under the appropriate telescope support sections.

Archive and Cluster Processing

This group supports the production archive, parallel processing clusters, and user storage resources needed in support of pipeline processing and science data analysis. It defines the operational model for these shared resources and works closely with the Software Division. This group ensures sufficient storage is provisioned to keep up with observations, and within the budget envelope.

Science Computing Infrastructure

This group provides technology-driven Computer Engineering support and is tasked with delivering the next generation of data processing solutions, working in cooperation with the Software Division, CDL, and external cyberinfrastructure partners, such as the National HPC centers. This group is responsible for escalations from Archive and Cluster Processing and CIS in the event of systematic performance issues with the production infrastructure.

Wide-Area Networking

This science data capacity driven group is responsible for provisioning the long-haul, high-bandwidth connectivity to deliver reliable throughput for observation data delivery. Operational support for commodity circuits are handed off to Computing and Information Services (CIS) once a network service has been accepted into production.

External Cyber Resource Utilization

Science Computing Infrastructure initiated a pilot program in 2016 for automated processing on external computing resources, in preparation for normal pipeline processing operations. An initial allocation of time on Amazon Web Services provided valuable insight into running a large number of parallel pipeline processing jobs, as well as providing a wide array of system configurations, for probing CASA performance versus cost. This will be used to budget for capacity needed for the VLA Sky Survey and obviate the need for substantial additional computing infrastructure at NRAO.

ALMA System Software

NRAO is responsible for delivering software to the Joint ALMA Observatory (JAO) as part of the Integrated Computing Team (ICT) that is staffed by personnel from all three ALMA Executives and the JAO. In North America, some work is also conducted by the National Research Council – Canada for the ALMA Archive Subsystem. The bulk of the work done at NRAO by the ALMA System Software group is categorized as Offsite Maintenance and Repair. The ALMA System Software group is responsible, for example, for the NRAO software (though not firmware) contribution to the ALMA Phasing Project. Because ALMA has been moving into full science operations, the focus during 2016 was on improving operational stability. This effort was largely successful, resulting in a low proportion of operational issues being attributed to software.

In 2016, the NRAO ALMA System Software group contributed to multiple ICT tasks and priorities, including the Control / Correlator software that controls and monitors all ALMA equipment (excluding the Atacama Compact Array correlator), interprets the scheduling blocks, and forms the bulk data and auxiliary data for the post-observing and Archive systems. This includes many online Graphical User Interfaces (GUIs) and the NRAO contributions to the ALMA Phasing Project. The ALMA System Software group is also responsible for the dynamic scheduling-ranking software, manual and queued observing modes, scheduling GUIs, and an offline planning mode. This team also contributes to overall ICT management, software testing, and makes additional contributions to various operations GUIs.

The spring 2016 release of the ALMA System Software group improved operations support, implemented 90-degree phase switching, created a detailed plan for upgrading the Real-Time Operating System, and provided additional control and correlator enhancements required by the JAO.

VLA / VLBA System Software

In 2016, the VLA / VLBA system software functional priorities were 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. New system software capabilities for Semesters 2016A and 2016B included support for VLA pulsar observing commissioning, VLA fast data dumps, and VLA triggered observations. The development and deployment of the VLBA monitor data stream replication software was completed in 2016.

Facing page: The ALMA Correlator is installed in the AOS Technical Building. Photos by C.Padilla NRAO/AUI/NSF.



GBT System Software

GBT system software functional priorities are defined by West Virginia Operations within resource limits provided by DMS. Green Bank Operations previously used a web application to log and report on detailed GBT usage. The application used obsolete technology, was undocumented, and was not supported by any GBT employee. This system was replaced in 2016 by a new one providing the same features and appearance and utilizing the same technology used by all GB web applications.

Pulsar modes were implemented in the VEGAS spectrometer in 2016. The annual GBT monitor and control system software release occurred in fall 2016, consolidating system patches made over the preceding two years, validating the revision control system, and pruning obsolete subsystems.

The capabilities and use cases of the GBT Pipeline were improved in 2016. Working with the GBT Scientific Staff, DMS developed a prioritized list of improvements for expanding the role of the GBT Pipeline. These improvements included a new imager to remove the dependence on AIPS, expansion of the pipeline to include additional mapping use cases, and improved reliability.

Pipeline testing with the Pittsburgh Supercomputing Center continued during 2016.

Next Generation Archive System

Due to the nature of the Green Bank Telescope, and the legacy of historical observations from the other instruments at the site, the Green Bank archive had been file-system based. DMS upgraded the version of the Next Generation Archive System (NGAS) in 2016 and transitioned the Green Bank archive data into the NGAS architecture already leveraged for the other NRAO instruments, including ALMA. The NGAS software infrastructure underlying the archive was reviewed and a report of recommendations created. Work was started in 2016 on refactoring ingestion programs and on creating a standard for archive deployment.

NRAO Archive & Reprocessing

The prototype software for the new NRAO Archive (Phase 1) and reprocessing interface was updated based on user feedback, and a Phase 2.0 was delivered for further testing in 2016. Phase 2.0 included authentication and authorization capabilities, a simplified query interface, and an integrated view of all telescopes, including ALMA. It also delivered the ability to reprocess data via the CASA package from both NRAO and ALMA archives via methods seen as consistent by users. Phase 2.0 will be released for testing to a sub-committee of the NRAO Users Committee, and their input will help guide the development of Phase 2.5 that will be released to users in 2017.

Common Astronomy Software Applications

The Common Astronomy Software Applications (CASA) package is being developed by NRAO, the European Southern Observatory (ESO), the NAOJ, and Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). CASA supports the offline reduction and analysis of ALMA and Jansky VLA data, and is fully scriptable. Full



support is provided for ALMA and VLA, but almost any data that can be written in uvfits format can be imported and reduced in CASA.

Versions 4.5, 4.6, and 4.7 of the CASA package were released by the development team in February, May, and October 2016, respectively. These releases supported Pipeline improvements for the VLA, with the version 4.5 release additionally focusing on ALMA priorities for Cycle 3. The development plan was informed by our ongoing experience with the VLA and ALMA, the CASA Users Committee, and the CASA Science Steering Committee. The CASA 4.7 release included the pipeline for ALMA Cycle 4 and an updated VLA pipeline.

A CASA reliability initiative was initiated in 2016 to better understand what users want in terms of reliability and to outline related efforts, such as expanding test coverage, moving beyond regression testing to an automated module-level test capability, investigating test coverage metrics, producing a software quality improvement plan, and incorporating standards development for continuous integration.

Performance improvement through parallelization was implemented in the CASA releases. User adoption of this capability has been slow and DMS is working to simplify and make it more robust, in order to improve its uptake.

The CASA Pipeline continued to evolve in 2016 as ALMA moved towards full science operations, with patches developed and released throughout the period. A major release was delivered in late 2015 to coincide with ALMA Cycle 3. Reference imaging was released to the ALMA project in early 2016.

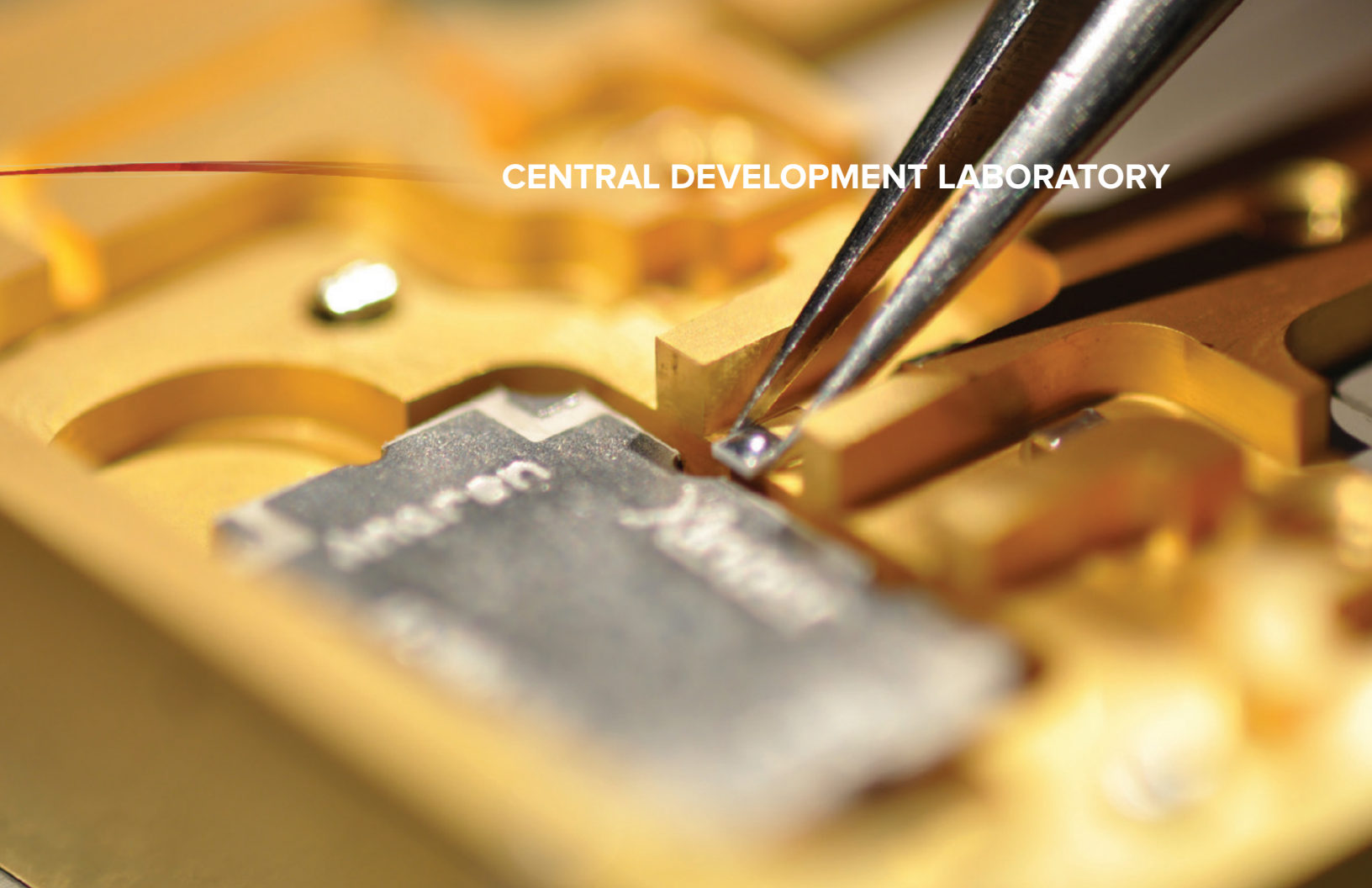
The Cube Analysis and Rendering Tool for Astronomy (CARTA) – a new visualization tool designed for ALMA, the Jansky VLA, and radio telescopes of the future, such as the Square Kilometre Array – and the ALMA Data Mining Toolkit (ADMIT) were delivered and accepted.

Proposal & Observing Tools

The Proposal Submission Tool (PST) was updated to support required functionality for the NRAO Semester 2016B and 2017A Calls for Proposals. The Proposal Handling Tool was updated to support required functionality for the Time Allocation Committee (TAC) meetings and the Observation Preparation Tool (OPT) for the VLA was updated to support new instrumental capabilities during each observing semester. The OPT updates included support for commissioning, including Resident Shared Risk Observing (RSRO) observations, and once commissioned, for general observing. Updates for commissioning occurred in the semester prior to when they are needed for general observing.

The Tool Redesign project reviewed the design of the Observatory's user-facing tools, including the PST, PHT, and OPT. 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 would be a productive way to make the toolset both more functional and easier to use. The tools were reviewed and a high-level design created in 2016. A decision was made to start by modifying the PST to address the highest-priority user requests and, in parallel, create a detailed plan for future development based on a logical partitioning of the tools' functions and a modern user interface.

CENTRAL DEVELOPMENT LABORATORY



The mission of the NRAO Central Development Laboratory (CDL) is to support the evolution of NRAO's existing facilities and to provide the technology and expertise needed to build the next generation of radio astronomy instruments. During 2016, work and progress continued in the areas of low-noise amplifiers, millimeter and sub-millimeter detectors, optics and electromagnetic components including feeds and phased arrays, digital signal processing, integrated receiver development, and other new receiver architectures.

Repair, Maintenance, Production & Support

CDL production and support activities for 2016 are described in the following sections.

Millimeter and Sub-millimeter Detectors

A large number of mixer-preamplifiers were refurbished in 2016, but no new mixers were qualified for use in Band 6 cartridge repair work. Some passive amplifiers and heterostructure field-effect transistors (HFETs) obtained after the ALMA construction components were exhausted had cryogenic parameters that were not part of the product specifications. This rendered the existing design unable to consistently meet ALMA specifications. Rather than devote additional effort to re-optimize the Microwave Integrated Circuit (MIC) based "chip and wire" amplifier design, alternatives were explored. A Monolithic Millimeter-wave Integrated Circuit (MMIC) cryogenic amplifier from the Low Noise Factory was identified as a drop-in replacement for the mixer preamplifier, and an initial batch of ten units were ordered. The gain response of the MMIC amps is flatter than the MIC versions, so equalizers were designed to pre-distort the gain slope to compensate for existing equalizers in latter stages of the receivers. Initial test results show promising mixer-preamplifier performance suitable for cartridge repair work. Significant progress was made in identifying and qualifying an alternate path to build compliant mixer-preamplifiers while producing sufficient devices to meet the ALMA offsite hardware support needs to keep up with the necessary Band 6 cartridge maintenance work.

Low Noise Amplifiers

The CDL Amplifier Group continued to produce replacement amplifiers and/or repair amplifiers for NRAO telescopes: 33 amplifiers were delivered, including two for testing of the ALMA Band 2 prototype receiver cartridge. Also, four prototype Band 2 MMIC amplifiers from the Cahill Radio Astronomy Laboratory were fully evaluated. A contract for CDL to manufacture 160 amplifiers for full production of Band 1 cartridges was signed.

Electromagnetics

Extensive cross-polarization measurements on the ALMA Band 2 optics design were carried out at the Green Bank Anechoic Chamber range. Measurements were done with the lens in the appropriate position and orientation with respect to the feed horn. The 15 K and the 110 K infrared (IR) filters were introduced one at a time and measurements repeated. These tests concluded that the IR filter contribution to cross-polarization performance was negligible at the measurement frequencies. The sharp polarization efficiency dips versus frequency measured in the ALMA test cryostat were attributed to narrow band interactions with the 15 K IR filter, and are expected to be remedied by the eventual removal of the redundant 15 K IR filter.

Digital Signal Processing

The Digital Signal Processing group provided support to the ALMA correlator group in Chile. Additional support was provided via the two-antenna correlator in Charlottesville. Support was also provided to the software group that writes and maintains the correlator software using the Charlottesville two-antenna correlator as a test bed.

Research and Development

CDL research and development activities for 2016 are described below.

Millimeter and Sub-millimeter Detectors

The crisis in funding to support the superconducting circuits foundry at University of Virginia Microfabrication Laboratory (UVML) came to a head in 2016. UVML is the sole U.S. fabricator of superconducting circuits with the characteristics needed for the millimeter and sub-millimeter wavelength detectors essential to the maintenance and improvement of the ALMA receivers. In April 2016, NRAO convened an expert panel, composed of many of the most senior experts in the superconducting mm/sub-mm receiver design and fabrication community, to review the NRAO/UVML partnership. The panel was charged with examining the performance of this collaborative effort over the past five years, as well as plans for the next five years, and to advise the NRAO on the continuation of this effort. The panel concluded that funding of UVML was essential to the continuing health of ALMA, and stressed the importance of completing the efforts underway to expand the CDL millimeter receiver group. The NSF approved funding for UVML for the next five years, subject to annual program performance reviews by NRAO. Searches were made for a millimeter/sub-millimeter research engineer, an engineer, and a high-level technical specialist with expertise in this field.

The design of a superconducting IF hybrid that will be useable in second generation receivers for all ALMA bands has been completed. UVML completed the photomask layout and a fabrication/testing design iteration cycle was scheduled. The CDL SIS group is continuing to evaluate new SIS mixer designs for ALMA Band 6 that will offer improved performance and for Band 8 (385-500 GHz), the latter utilizing new UVML Niobium/Aluminum-Aluminum Nitride/Niobium (Nb/Al-AIN/Nb) junctions.

After eight and half years of work, the Institute of Electrical and Electronic Engineers (IEEE) Standard 1785.2-2016 for waveguide interfaces above 110 GHz was published in September 2016. The new standard includes the NRAO-developed ring-centered flange.

Low Noise Amplifiers

Research on the general noise properties of microwave Field Effect Transistors (FET) transistors and amplifiers in all technologies [including Complementary Metal Oxide Semi-Conductor (CMOS)] resulted in a paper – *On the Dependence of FET Noise Model Parameters on Ambient Temperature* – which has been accepted for the 2017 Institute of Electrical and Electronics Engineers Microwave Theory and Techniques Society (IEEE MTT) Radio and Wireless Week Conference. A review of measurements and analyses concerning the limits on the maximum desirable instantaneous SIS receiver bandwidth, which is limited by IF amplifier bandwidth, was given in an ALMA Memo #60, *On the Instantaneous SIS Receiver Bandwidth*.

Two other papers were published with the ALMA Band 1 Consortium: *The Atacama Large Millimeter/sub-millimeter Array (ALMA) Band 1 receiver*; and *Band 1 receiver front-end cartridges for Atacama Large Millimeter/submillimeter Array (ALMA): design and development toward production*.

Electromagnetics

The design of a feed horn and phase-shifter for an improved 35-50 GHz VLA receiver was completed. Due to lack of funds, a prototype was not fabricated, and further work on this receiver was shelved. Design of a turnstile junction orthomode transducer to cover the 67-95 GHz range of an ALMA "Band 2+" receiver was completed. The development work carried out for the optics of the ALMA Band 2 prototype receiver was reported on at the 2016 International Union of Radio Science (URSI) Asia-Pacific Radio Science Conference in August 2016 in a paper titled *ALMA Band 2 Optics - Design, Constrains, Prototype and Measurements*.

Digital Signal Processing

During 2016, the Digital Signal Processing Group focused on detailed planning to upgrade the ALMA baseline correlator. The group received a study grant from the ALMA Development Program to provide a detailed plan for upgrading the ALMA baseline correlator, doubling its bandwidth and increasing its resolution by a factor of eight. A Very High Speed Integrated Circuit Hardware Description Language (VHDL) description of an integrated circuit needed for the upgrade was completed and simulated to verify correctness. A system design and description was completed, and designs of four of the five cards required for the upgrade were completed. A draft schedule and budget estimate were also completed. A test card to check correlator cable bandwidth was designed, and a study of the effects of truncation in the ASIC design was completed.

Final deliverables were completed for the Smart Network Analog to Digital Converter Processor (SNAP) project, including a detailed mechanical design for a radio-frequency interference (RFI) case, final schematic, printed circuit board drawings, thermal testing, RFI testing, and a final report on thermal and RFI tests. SNAP modules are intended for data acquisition and transmission in the Hydrogen Epoch of Reionization Array (HERA) project, and other members of the Collaboration for Astronomy Signal Processing and Electronic (CASPER) community have expressed interest in the module.

Integrated Receiver Development

Integrated receiver development efforts in 2016 focused on extending the unformatted serial link concept by synchronizing parallel data streams, and in exploring new and more efficient ways of calibrating the Digital Orthomode Transducer (DOMT).

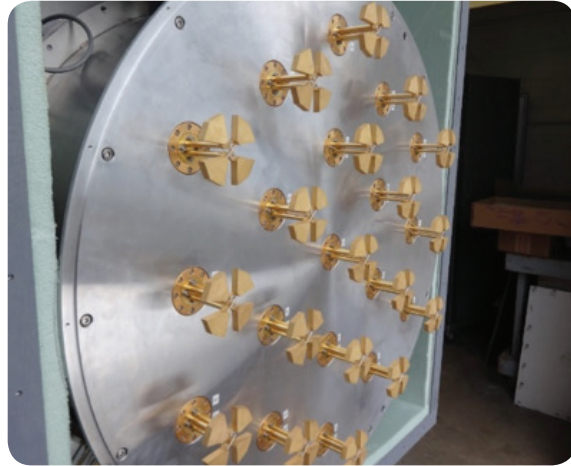
Efforts to synchronize parallel data streams on unformatted serial links operating at 2.5 Gbps using first in, first out (FIFO) buffering were successful. This early success led to new innovations with regard to separation of interleaved In-Phase and Quadrature (I and Q) data on such a link, as well as rapid prototyping of faster links in support of broader bandwidths. Second-generation reflectionless filter topologies have also been tested successfully, again leading to new innovations and a third-generation of even more sophisticated topologies, for which patent applications have been filed.

It was noted in the NRAO Program Operating Plan (POP) that the outcome of experiments regarding DOMT calibration might lead to alternative approaches being pursued, and a quasi-optical wire-grid calibration scheme has now become the preferred approach. It was stated in the POP that a higher-frequency front-end would eventually be required for this experiment, and this is now under development. The effort has been somewhat delayed, however, as the personnel needed to complete the polarization software are still heavily over-subscribed supporting ALMA maintenance and Phased Array Feed (PAF) development.

Phased Array Feeds

In 2016, the Phased Array Feed (PAF) Research and Development (R&D) work was focused on construction and test of a new L-band Phased array receiver for the GBT. Almost all of the prior generation of PAF instrumentation was redesigned and improved, including Low Noise Amplifiers, Dipoles, Cryostat, Digital Downconverter, Photoreceiver Cards, and Reconfigurable Open Architecture Computing Hardware 2 (ROACH2) Firmware.

PAF progress this year included construction completion, firmware completion, system testing, and tests on the GBT. The new hardware provides a significant improvement in available bandwidth (150 MHz) and in the noise temperature of each channel ($T_{\text{noise}} < 20$ K). Further telescope testing revealed that the low noise amplifiers and digital downconverters worked well, the end-to-end connectivity was stable and reliable, and the software, firmware, and data acquisition flow performed well.



PAF cryostat and crossed dipoles.

Two problems remain that have prevented the lowest ($T_{\text{sys}}/\text{efficiency}$) metric from being realized: (1) a systematic effect has limited the beamforming; and (2) there is a spurious instability in the digital link. Research on these issues is continuing.

PAPER – HERA – DARE

CDL's involvement in three low-frequency collaborations continued. Spare and refurbished components have been delivered to the Precision Array for Probing the Epoch of Reionization (PAPER) site in South Africa. All milestones associated with the Hydrogen Epoch of Reionization Array (HERA) feed development and antenna structure have been achieved. The antenna and front-end electronics for Dark Ages Radio Explorer (DARE) have been extensively refined as a result of the electromagnetic modeling using Computer Simulation Technology and prototype measurements. The improved design is being incorporated into the new DARE mission proposal.

ALMA Band 2 Prototype

The goal of this project was to design and build an operating Band 2 prototype receiver using MMIC based Cryogenic Low Noise Amplifiers (CLNAs); the MMIC contract was intended to be structured to procure a sufficient supply of MMICs that could be used in a follow-on construction phase.

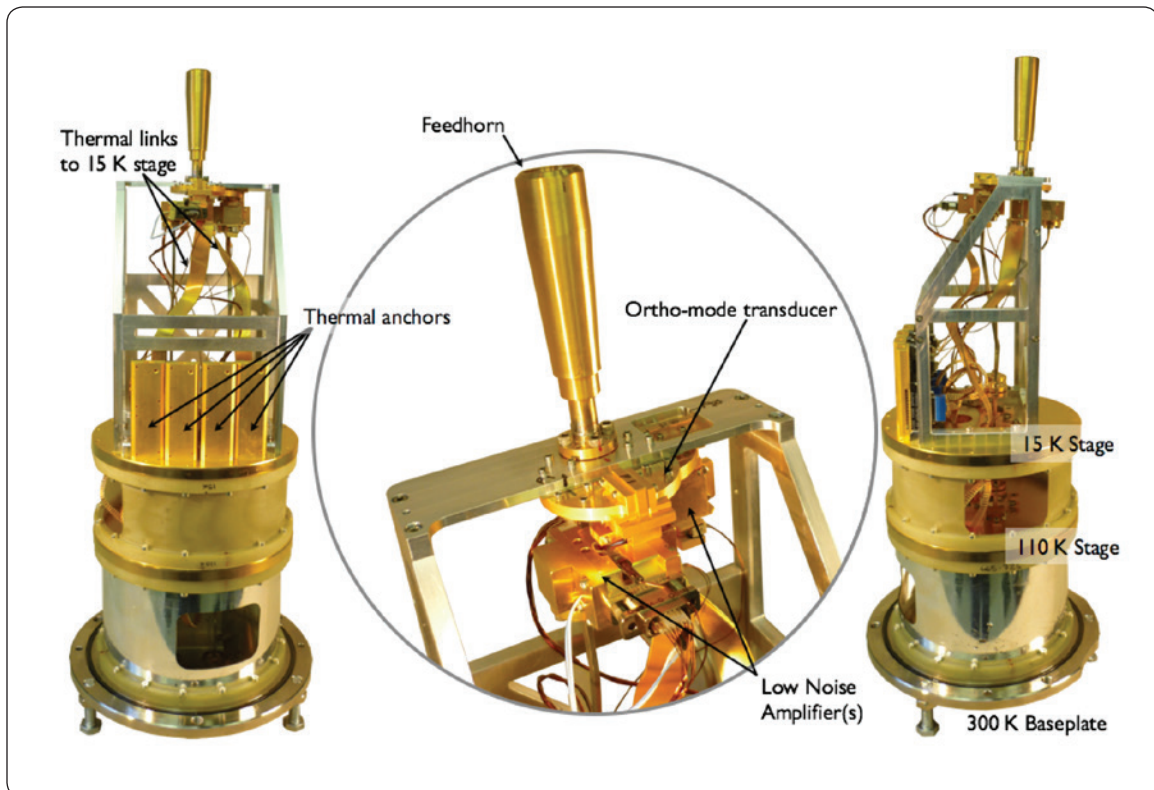
At the outset of the project, the two-year development timeline was recognized as tight, as it had to accommodate the development – design, fabrication and construction – of new 35 nm InP MMIC-based low noise amplifiers (LNAs) and the construction of a new receiver. It was decided to construct the receiver prototype using NRAO/CDL MIC based “chip and wire” E-band CLNAs while MMIC development by Caltech's Cahill Radio Astronomy Laboratory (CRAL) proceeded under a project

subcontract. Following this plan, the first ALMA Band 2 receiver – cold cartridge, local oscillator, IF down converter – was constructed and evaluated. Evaluation of this first iteration of the receiver cartridge provided a platform to diagnose and resolve problems with the hardware and develop the software suite to test and fully qualify the receiver.

Although delayed by the contracting process, the CRAL MMIC development effort culminated with a successful Northrup Grumman Corporation (NGC) wafer run, which produced four good wafers. All four wafers were probed at room temperature and two were selected for follow-up cryo probing and device selection for constructing CLNAs. The completed CLNAs were evaluated – showing excellent 20-25 K noise temperature values on the prototype amplifiers – and the prototype Band 2 receiver cartridge was subsequently upgraded with these CLNAs and re-evaluated.

The measured receiver noise temperatures are fairly flat versus frequency, and the average value of 44 K is close to the calculated value based on the optics configuration along with the measured performance of the amplifiers. The ALMA optics specifications were generally met by the prototype, with the exception that there are dips in polarization efficiency at specific frequencies that fall slightly below the 99.5% specification value. These are attributed to an interaction of the 15 K IR filters with the horn aperture—an effect also seen on some other ALMA bands. The optimal solution is the eventual removal of the redundant 15 K IR filters in the ALMA cryostat.

A one year, no-cost extension was granted to provide sufficient time for CRAL to evaluate all of the fabricated device variants and to complete a follow-on wafer run that incorporates all selected designs. This will ensure a sufficient quantity of MMICs for an eventual construction phase.



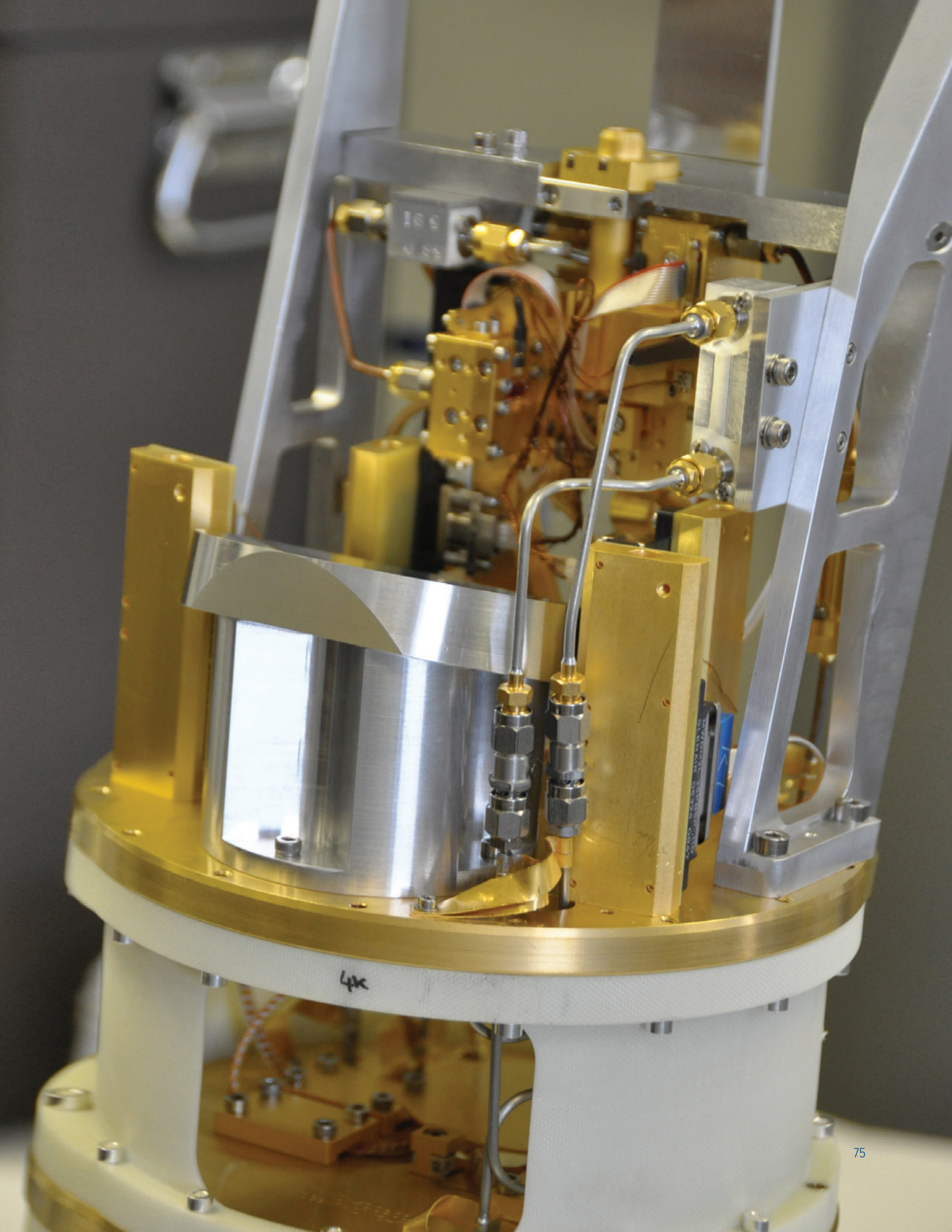
Fully assembled Band 2 prototype cartridge with details of the horn-OMT arrangement (inset).

From the Historical Archives

In June 1996, NASA contracted with NRAO to design and build amplifiers for the MAP, later renamed the Wilkinson Microwave Anisotropy Probe (WMAP) after David Wilkinson, a pioneer in the study of cosmic background radiation. The WMAP satellite mapped the background sky in five spectral bands with an angular resolution of 0.3 degrees and sensitivity of 20 micro-Kelvins/pixel over a nine-year mission (Sep 2001 – Aug 2010). These measurements have helped determine rigorous constraints on the origin, content, age, and geometry of the Universe. The cooled amplifiers developed by Marian Pospieszalski using Hughes Research Laboratories high electron mobility transistors were vital to this success. The critical step was the development in 1995 by the CDL of an amplifier with a center frequency of 80 GHz that satisfied all mission requirements. The MAP amplifiers represented a significant step forward in low-noise amplifier design and performance. The MAP team produced 120 space-qualified amplifiers covering five frequency bands: 20-25, 28-37, 35-46, 53-69, and 82-104 GHz. The team produced these over several years, and the entire CDL celebrated on 23 October 1999 when the last of these these amplifiers were shipped.



The NRAO Microwave Anisotropy Probe (MAP) team in 1996 [Left to Right]: John Webber, Ed Wollack, Nancyjane Bailey, Bill Lakatosh, Skip Thacker, and Marian Pospieszalski. Other MAP team participants, not in this photo: Tod Boyd, Ron Harris, Greg Morris, Gerry Petencin, Bill Wireman, Tony Marshall, Garnett Taylor, Matt Dillon, and Vince Summers.



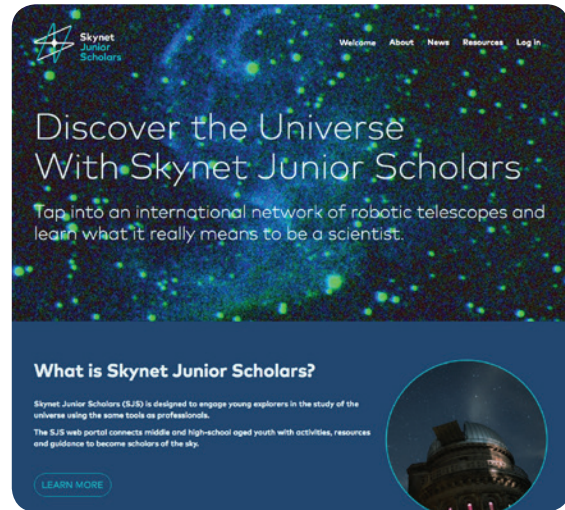
EDUCATION & PUBLIC OUTREACH



Education and Public Outreach (EPO) created exemplary programming in communities where NRAO resides as well as with serving a larger national audience through national workshops, social media and the popular press.

STEM Education & Outreach

Major initiatives included Skynet Junior Scholars (SJS) a NSF-funded project. In its final year of funding, SJS completed a more user-friendly redesign of its website, expanded its curriculum, held two onsite and two online workshops and launched a self-paced online workshop model for sustainability of the program. SJS gives out-of-school providers, including teachers with astronomy clubs, 4H Leaders, etc., access to optical telescopes and the Green Bank 20 Meter Radio Telescope through the web portal (<https://skynetjuniorscholars.org>) for queue-based data collection. As the project wraps up under the grant, 1400+ children have accessed the telescopes for observing projects. The program was described at the 4H national convention, and there was great interest in making an SJS exploration the 4H national science project in 2017.



Anticipating the separation of Green Bank from NRAO, a three-dish instructional interferometer was refurbished in partnership with New Mexico Tech at their Etscorn Observatory campus. Curriculum will be developed for these student instruments and pilot programs launched in 2017 to determine the feasibility of expanding teacher and student training.

The Green Bank teacher and student programs continued with overnight student groups using the 40-Foot Telescope, guided tours, hosting local science fairs, and participation in the Earth Space Science Passport workshop. Outreach included the Pocahontas County Math Field Day and multiple Elderhostel courses.

Charlottesville took the lead on NRAO attending the USA Science and Engineering Festival, the Astronomy on the National Mall Star Party, and AAS EPO Live events, radio broadcasts on Wake-Up Call, 94.7 FM.

VLA Student and Outreach Programs included Starlab lessons in Rio Rancho and Albuquerque, hosting events for the Enchanted Skies Star Party, Spring and Fall Open Houses, first Saturday tours each month, and providing access to scientists through events like Science Club Connection Skype chats with NRAO astronomer Dale Frail.

Chilean Teacher/Student Programs and Outreach included participation in 100 Hours of Astronomy, Galilean Nights, Galileo Teach Training Program workshop with Faculty of Education and Institute of Astrophysics from Pontificia Universidad Catolica de Chile, and public talks about ALMA and radio astronomy. A concerted effort was made to revive the Sister Cities program, with eight students and five teachers participating in a cultural exchange between schools in San Pedro de Atacama, Chile, and Magdalena, New Mexico. After visits to each other's countries in this first year, efforts are being made to include STEM activities in the second year.

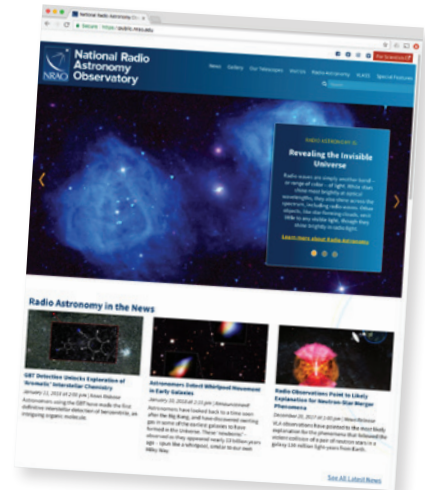
News & Public Information

A total of 67 press products, 42 press releases, 22 announcements, and three tip sheets were produced by EPO in FY2016. Social Media reached ~1000 people daily with 66,000+ followers.

Three news stories garnered special attention:

1. **Today Show** featured the radio free zone around Green Bank:
<https://www.today.com/video/in-green-bank-w-va-wi-fi-and-cellphones-are-illegal-and-life-goes-on-611469379592>.
2. **CNN's Great Big Story:** A Telescope So Powerful, It Can See Into the Past
<https://www.youtube.com/watch?v=5mliMXdEaLs>.
3. **Discover Magazine** chose the detection of chirality of molecules in space as one of the top 100 science stories of 2016. It will be featured in the January 2017 issue.

Progress was made in 2016 on the new WordPress NRAO public web site with the initiation of the coding and implementation of new designs with a friendlier user interface. Interactive features were expanded on the current public website, adding more role model videos, the Milky Way Explorer, ALMA Explorer, and Orion Explorer.



From the Historical Archives

The Visitor Center at the VLA was dedicated on 16 April 1983, with exhibits, slide shows, and instructions for a self-guided walking tour designed to educate the public and to excite people about science, astronomy, and NRAO. Over the years, the slide show became a video, which has changed multiple times. The current version is an award-winning video narrated by Jodie Foster. The building has had several interior remodels and has expanded to include a gift shop. Many visitors have come through the doors, with an average of up to 22,000 in recent years.



In this image from the dedication, Assistant Director Ron Ekers introduces guests and speakers at the dedication ceremony. [Left to right] Ekers, AUI Board President Robert Hughes, former New Mexico Governor Bruce King, unidentified, unidentified, State Senator James Martin, New Mexico Tech Professor of Mineral Engineering Catherine T. Aimone-Martin, Alice King, and another unidentified person.

The RadioSky Mobile App

The NRAO is bringing a whole new view of the cosmos – as seen at radio wavelengths – right to your mobile device. Intriguing views of the invisible Universe, and much more, are part of NRAO’s new, free iOS app, called RadioSky. RadioSky shows how familiar celestial objects, along with objects invisible to even the most advanced optical telescopes, look when viewed with NRAO’s world-class research radio telescopes. You can browse an all-sky map and choose objects to explore through NRAO’s powerful radio eyes, learning fascinating details about each of these objects.



The app features an introduction to radio astronomy, information about NRAO and about each of our telescopes, along with streaming videos with behind-the-scenes virtual tours of our facilities and explanations by the astronomers who use them.

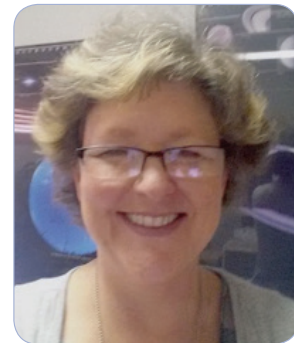
Also included are instructions on how to build your own “itty-bitty radio telescope” from an old satellite dish. Once you’ve built this educational tool, the app guides you through a series of hands-on experiments that illustrate the basics of radio observations. The experiments include observing the Sun, detecting the radio waves coming naturally from your own body, and finding geosynchronous satellites in the sky.

RadioSky is a valuable resource for educators, experimenters, and anyone interested in the Universe and how it works. Download this free iOS app from the App Store: <https://itunes.apple.com/us/app/radiosky/id1115228545>.

NRAO EPO Assistant Director

Suzanne Gurton became the next NRAO Assistant Director for Education & Public Outreach (AD – EPO), effective 21 September 2016, succeeding Tania Burchell who led the NRAO EPO team and program as interim AD – EPO over the past year.

Suzanne received a B.S. in astronomy from the University of Arizona and studied Science Curriculum and Instruction at the University of North Carolina – Chapel Hill while completing the Morehead Internship in Planetarium Operations. From 1984–2000, Suzanne gained experience via astronomy education and outreach positions she held at Griffith Observatory (Astronomical Lecturer), the University of Colorado (Production Supervisor), the American Museum of Natural History (Astronomical Writer/Producer), and Santa Fe Community College (Planetarium Director).



Suzanne Gurton

Since September 2000, Suzanne has been Education Manager and, more recently, Director of Education for the Astronomical Society of the Pacific (ASP), a recognized leader in astronomical education and public outreach. Suzanne has been a key contributor to the strategic direction and success of the ASP, crafting an innovative portfolio of science education programs, including many with national reach and impact. The ASP education programs led by Suzanne have delivered scientific insight and professional development to diverse audiences, including science museum educators, amateur astronomers, museum directors, interpretive park rangers, 4H leaders, and the science-attentive public. Suzanne also brings to NRAO an impressive record of success in obtaining major grant funding from the NSF and NASA.

MANAGEMENT & ADMINISTRATION



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, Education and Public Outreach, and Science Support & Research.

Phil Jewell continued as Assistant Director for the North America (NA) ALMA department. 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 the NRAO Deputy Director.



The New Mexico Operations department, based in Socorro, was led by **Mark McKinnon**, who transitioned in December 2016 from an interim to a permanent assignment as Assistant Director: New Mexico Operations. 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, until 1 October 2016, when the VLBA transitioned into the Long Baseline Observatory (LBO). Walter Brisken is the Director of the LBO.

The NRAO West Virginia Operations department formally became the Green Bank Observatory (GBO) on 1 October 2016, and no longer appears on the NRAO organization chart. Karen O'Neil is the Director of the GBO.

Assistant Director **Lewis Ball** led the Science Support & Research (SSR) department, effective 10 October 2016, succeeding Tim Bastian. 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 and Socorro.



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 PM department strives 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-term strategic goals; and compile deliverables.

Suzanne Gurton arrived in Charlottesville as the NRAO Assistant Director for the Education & Public Outreach department on 21 September 2016, succeeding Tania Burchell who led the EPO team and program for the first nine months of the year. 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 inform the science-interested public about the Observatory, its facilities, and the latest technical and scientific achievements of its users and staff.



MANAGEMENT & ADMINISTRATION



The Data Management and Software (DMS) department led by Assistant Director **Brian Glendenning** manages data archiving at NRAO, including access, distribution, provisioning, and operations. 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 build the next generation of radio astronomy instruments. The CDL team, led on an interim basis by **William Randolph**, accomplishes this through development of the enabling technologies: low-noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components, including feeds and phased arrays.

Based in Charlottesville and led by Associate Director **Steven Geiger**, the Administration Service department provides the 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** continued to jointly lead the Human Resource (HR) department that supports the needs of the Observatory U.S. and international staff. Giles is the HR Manager and Diversity Officer; 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 ALMA. Led by Assistant Director, **Paulina Bocaz**, OCA provides ALMA with legal, payroll, and travel support, and provides the legal and institutional support for numerous contracts and procurements for ALMA Operations in Chile.

The Office of Diversity & Inclusion (ODI) is led by Program Manager **Lyndele von Schill**. 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, the NSF and other key external stakeholders. The NRAO Chief Scientist, **Chris Carilli**, also reports to the Director.



Kwok-Yung (Fred) Lo: 1947-2016

It is with great regret that we report the death of Kwok-Yung (Fred) Lo on 16 December 2016. Fred was an eminent scientist who led the NRAO as its Director and Distinguished Astronomer September 2002 – May 2012, an important decade during which the NRAO and its international partners realized the construction and initiation of science operations with ALMA. Fred also led the NRAO while the Expanded Very Large Array (EVLA) project was built and completed – on time, to specification, and under budget – enabling the rebirth of the 1970s-era VLA as the much more capable Karl G. Jansky Very Large Array. During his tenure as Director, the Green Bank Telescope and the Very Long Baseline Array also made extraordinary progress in their scientific capabilities and productivity. Fred's vision and leadership were vital to each of these major NRAO technical and scientific successes.

Born in 1947 in Hong Kong, Fred arrived in the United States in 1965 to attend the Massachusetts Institute of Technology, from which he obtained a B.S. and a Ph.D. in Physics in 1969 and 1974, respectively. He joined the California Institute of Technology in 1974 as a Research Fellow in Radio Astronomy, and in 1976, took up a position at the University of California, Berkeley as a Miller Fellow. Two years later, Fred returned to Caltech where he held research and teaching positions until, in 1986, he became a Professor of Astronomy at the University of Illinois at Urbana-Champaign and served as Astronomy Department Chair from 1995–1997. Immediately prior to coming to the NRAO, Fred joined the Academia Sinica in Taipei, Taiwan in 1997 as Director of its newly formed Institute of Astronomy and Astrophysics, and was appointed Professor of Physics at the National Taiwan University in 1998.



Fred was an accomplished radio astronomer and physicist whose research impacted international scientific progress across multiple fields. His interests ranged from mega-masers to star formation, starbursts, the Galactic Center, and cosmology. Fred made the first millimeter-wave interferometric map of carbon dioxide emission from an external galaxy and in 1986, he and Mark Claussen were the first to suggest that luminous water maser emission in external galaxies is circumnuclear, affiliated with active galactic nuclei, and could serve as very high resolution probes of the centers of galaxies. These keen insights led eventually to the Megamaser Cosmology Project that is now accurately measuring the expansion rate of the Universe and that will yield a direct test of the standard cosmological model and meaningfully constrain the nature of dark energy; Fred was one of the driving intellects in the project.

Fred's vision for radio astronomy and NRAO lie at the center of the Observatory's plans for the future, and his guidance will be greatly missed. His force of character and remarkable intellect made him a notable leader in astrophysics, across many arenas and decades.

Diversity & Inclusion

The NRAO Office of Diversity & Inclusion (ODI) supports NRAO in achieving its core mission goals by increasing staff diversity and inclusion across the Observatory, developing and implementing programs to improve the recruitment, retention, and success of under-represented and under-served students and staff members, and fostering a work environment that is inclusive of all individuals. In 2016, the ODI Director worked closely with the HR, EPO, and SSR departments to develop and maintain programs that affect the NRAO workforce, broader impact efforts, new and ongoing pipeline initiatives, and the internal NRAO culture and climate.



2016 NAC IV Annual Workshop, September 9-11, Washington, DC

The ODI is supported by an Advisory Board composed of the Assistant Directors for Human Resources, New Mexico Operations, Education & Public Outreach, Program Management, Central Development Laboratory, Science Support & Research, Office of Chilean Affairs, and the GBO Director, together with ODI Program Managers serving as ex officio members. The Advisory Board met each quarter in 2016 to review ODI activities and to provide advice regarding implementation of activities across the Observatory.

National Programs

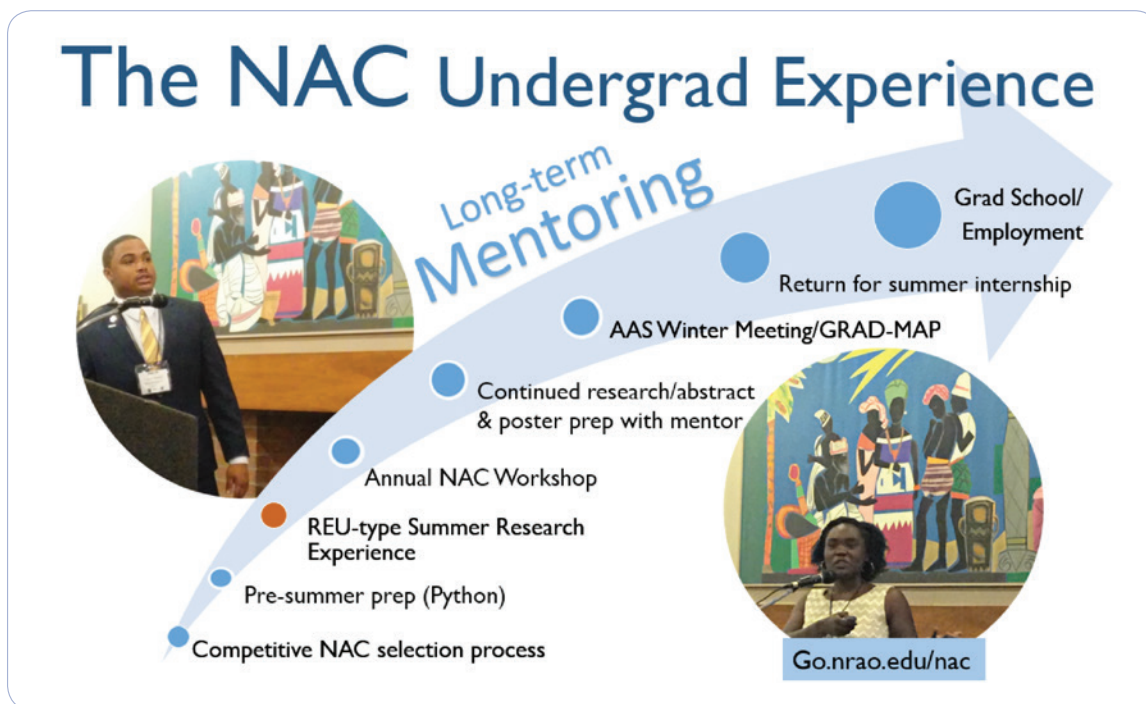
The NRAO national programs continued to grow and develop in 2016, resulting in important hands-on training for the next generation of scientists and engineers, from undergraduate to post-doctoral levels, with particular emphasis on reaching under-served and under-represented communities.

The *National Astronomy Consortium (NAC)* placed 13 undergraduate students, from community colleges and universities across the country, with trained mentors at NRAO – Central Development Laboratory, Headquarters, and Socorro – and two additional partner sites, the Space Telescope Science Institute and University of Wisconsin-Madison. Students were recruited from partner Minority Serving Institutions (MSIs) and Historically Black College/University (HBCUs), and via targeted outreach to Hispanic-serving Institutions (HSIs). The NAC students interacted with Research Experiences for Undergraduates (REU) students

for shared activities and worked on original research projects with their mentors. The NAC program included participation by the students in professional development workshops, attendance at weekly meetings with opportunities to present their research, and participation in diversity-related talks by invited speakers. NAC students and mentors were also offered the opportunity to complete online diversity training.

The NAC IV Annual Workshop was held 9-11 September 2016 at Howard University in Washington, DC, and featured presentations by 15 NAC students, representatives from several universities, and national funding and professional organizations. The workshop was designed to allow NAC students to meet, and present their research to each other and the professional community.

An important component of the NAC experience is the opportunity to develop confidence in presenting research. In addition to the presentation experience at the NAC Annual Workshop, 14 NAC students worked with their mentors to develop and submit an abstract and poster for the semi-annual AAS meeting.



Graphical description of major components of the NAC Undergraduate Experience.

In 2016, the *Physicists Inspiring the Next Generation (PING)* program, an EPO activity, supported a two-week summer camp experience for rising ninth-graders from the Washington, DC, area. The students were exposed to a variety of astronomy-related STEM careers, and experienced hands-on activities at Green Bank. Two PING undergraduate students, supported by ODI, participated in an eight-week research experience in Green Bank. As part of their PING experience, the student undergraduates served as mentors and instructors for the PING middle-school summer camp students.

The *Socorro Electronic Division Undergraduate Internship Program (SEDUIP)* supported two undergraduate students from The College of the Desert, a two-year community college and Hispanic-serving institution. Through this ten-week experience, the students were introduced to a professional laboratory environment and were provided with a mentor to guide and train them to make meaningful contributions to ongoing technical design work and other projects at the Observatory.

MANAGEMENT & ADMINISTRATION

Diversity and Cultural Awareness

NRAO continues to focus on education and training related to the importance of a diverse workforce and inclusive environment. In 2016, ODI and HR introduced a set of online training modules that included a Respect and Inclusion series, Diversity in Action, and Unlawful Harassment Prevention.

NRAO has identified at least one staff member at each site with a strong interest in Diversity and Inclusion efforts. These advocates promote the advancement of diversity and inclusion and serve as role models and facilitators. In 2016, these Advocates provided critical support to ODI by facilitating local training, and providing advice and assistance to the ODI Director.

In 2016, the NRAO Diversity and Inclusion Speaker Series included presentations about Imposter Syndrome, Implicit Bias, and Mentoring Students from Diverse Backgrounds. Partnering with HR, the series included presentations on strategies to enhance diversity and excellence in the hiring process, and two sessions on Post-Traumatic Stress Disorder.

The *NRAO International Exchange Program (NINE)* Program resumed under the leadership of a new Program Manager, Lory Wingate in 2016. A NINE website was developed, along with documents that described the mission, vision, and objectives of the NINE program. The NINE objectives were refined to emphasize the development of learning opportunities throughout all disciplines affecting the full spectrum of activities associated with designing, constructing, operating and maintaining radio astronomy observatories.

NINE hosted two nine-week Train-the-Trainer sessions (Spring and Summer 2016) for four international visitors – from Universities of Nigeria, Antananarivo, Madagascar; SKA South Africa – and two domestic visitors, including a post-doctoral representative from Hampton University. These visits resulted in the approval of an exchange hub at SKA South Africa, and commitment to long-term mentoring relationships between SKA South Africa and NRAO staff. The summer NINE program also resulted in the development of an Intro to Radio Astronomy distance-learning course to be offered at three HBCUs – Hampton, Howard, and Norfolk State Universities – in January 2017.



Graphical description of major components of the NINE Professional Experience.

NRAO provided a research project, and sponsor, for a student from the University of Virginia's *Louis Stokes Alliance for Minority Participation (LSAMP)* program, and incorporated the student into the many training and learning opportunities offered to the NAC students. Additionally, NRAO sponsored a day-long field trip to the Green Bank facility for a tour of the telescope, and an observing opportunity.

NRAO also supported *African-American Teaching Fellows (AATF)* mission to recruit, support, develop, and retain a cadre of African American teachers within our local community. ODI sponsored the annual AATF Summit at NRAO headquarters in Charlottesville on 28 June 2016. The summit featured NRAO staff presentations, hands-on activities, materials for teachers, and opportunities for regional schools to tap into NRAO EPO expertise. More than 25 educators attended the summit, including undergraduate student teachers, school principals, and experienced teachers and mentors.

Communications

The NRAO Communications Office (COM) organized the NRAO presence at the winter American Astronomical Society (AAS) meeting – 5-8 January 2016 in Kissimmee, Florida – including a day-long ngVLA Workshop, an NRAO Town Hall, and the NRAO participation in the meeting's multi-day exhibition. NRAO actively participated in the undergraduate orientation session, and the local public outreach events organized by the AAS and sponsored by AUI. COM also organized the NRAO presence at the summer AAS meeting – 12-16 June 2016 in San Diego, CA – including a Splinter Session describing the ALMA Development Program, and NRAO participation in the meeting's multi-day exhibition and local public outreach events organized by the AAS and sponsored by AUI.

NRAO organized and chaired a well-received science symposium at the 2016 Annual Meeting of the American Association for the Advancement of Science (AAAS), titled *Planet Formation with Radio Eyes*, that described how the much improved sensitivity, resolution, and imaging quality of ALMA and the Jansky VLA are enabling a revolution in our understanding of the physics and chemistry of star and planet formation. Presentations by Kevin Flaherty (Wesleyan), Andrea Isella (Rice), and David Wilner (Harvard – Smithsonian Center for Astrophysics) compellingly described the state-of-the-art observing campaigns crafted by astronomers to probe planet formation, and the wide range of new science that radio telescopes are yielding in this exciting field. With COM assistance, ODI and EPO each submitted a symposium proposal at the late April 2016 deadline for FY2017 AAAS meetings.

COM continued to edit and publish the monthly NRAO electronic newsletter, eNews, each issue of which was distributed to 9,500+ scientists around the world. COM also managed the high-level content at the NRAO science website and the NRAO Intranet. Occasional single-topic NRAO Announcements were written, edited, and distributed by COM to publicize key events and accomplishments. The 2016 NRAO Research Facilities brochure was updated and published immediately prior to the winter AAS meeting.

COM and CIS collaborated on the NRAO exhibit at the SC15 International Conference for High Performance Computing, Networking, Storage, and Analysis conference – 15-20 November 2015 in Austin, TX – an annual gathering of 10,000+ scientists, engineers, software developers, CIOs, and IT administrators from universities, industry, and government agencies.

Substantial progress was made on the 2015 NRAO Annual Report, though its completion was delayed to December 2016 owing to higher priority tasks that arose in mid-2016, including chairing a successful search for a new Assistant Director for Education and Public Outreach (AD – EPO), and serving as the interim AD – EPO for seven weeks in August – September 2016.

MANAGEMENT & ADMINISTRATION

COM collaborated with the Director's Office and staff across the Observatory to prepare NRAO reports, briefings, and support materials for NSF and for the 2016 Users Committee (UC), which met in Socorro, NM, on 18-19 May 2016. The ALMA North American Science Advisory Committee (ANASAC) met on 17 May as a standing sub-committee of the Users Committee. COM also collaborated with the Director's Office and the senior management team to prepare NRAO reports, briefings, and support materials for AUI and for the 2016 Visiting Committee (VC), which met in Charlottesville, VA, on 21-22 March 2016.

COM collaborated with Director's Office and the Observatory's management team on a wide variety of internal communications for the Observatory, and managed the high-level content of the NRAO internal website.

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 2016.

Domestic Spectrum Management

Iridium: After meetings with Iridium in December 2015 and March 2016, the NSF and National Telecommunications and Information Administration convinced the Federal Communications Commission (FCC) to attach strict conditions of non-interference to the license renewal of Iridium's new constellation of satellites, which was granted in July 2016. Although initial plans called for radio astronomy observations to be scheduled at Iridium's insistence, close dialogue and partnership with the NSF resulted in this important win for radio astronomy. NRAO provided all of the preparatory and background materials that were used during the domestic discussions with Iridium. Much of this will be useful at World Radiocommunication Conference (WRC)-19 where interference to radio astronomy is on the agenda in connection with Iridium's desire to be incorporated into the Global Maritime Disaster Safety System (GMDSS) that presently is monopolized by Inmarsat.

OneWeb and SpaceX: At a series of meetings hosted by NSF in spring 2016, NRAO supplied background material and explained the non-interference criteria to OneWeb and SpaceX, who are proposing constellations of approximately one thousand satellites using 10.7–12.75 GHz downlinks for global wireless broadband. This was also the subject of several pleadings by NRAO at the FCC International Bureau. Subsequently, OneWeb petitioned the FCC for immediate operation, which occasioned an opposition from NRAO and a conciliatory but uninformative communication from OneWeb.

Boeing WiGig at 60 GHz: At a series of meetings hosted by NSF and attended by NRAO and JPL/CORF, Boeing addressed the issue of allowing in-flight 57–64 GHz WiGig WiFi, which is now forbidden even though WiFi in that spectrum band is commonly available on new laptop computers. Boeing presentations were rudimentary on the basic issues, especially in regard to protection of 57 GHz satellite radar that is used to predict in-flight turbulence. In the end, FCC recognition of NRAO's plea not to approve this operation in the face of inconclusive discussions was a bright spot in the context of FCC's recent order approving spectrum allocations above 24 GHz, including 64–71 GHz, for mobile wireless broadband.

Raytheon: NRAO is coordinating with Raytheon which is building a test facility with 100 dB of shielding in South Tucson from which several tens of watts of power at 90 – 100 GHz may escape in the direction of Kitt Peak.

5G: The FCC approved a host of new frequency allocations for mobile wireless broadband at 24–86 GHz even while the same issues are just now starting to be studied at International Telecommunication Union-Radio (ITU-R) for WRC-19. The next issue

will concern protection of the RAS 42.5–43 GHz band that is heavily used for galactic tomography using SiO masers at the VLA. NRAO continued to file comments.

RFI2016 Conference: NRAO hosted the international meeting RFI2016 in Socorro in October 2016 and significant NRAO effort was put into the organization and support, financial and otherwise, for this gathering.

International Spectrum Management

WRC-19: The NRAO spectrum manager led the IUCAF delegation to the month-long WRC-15 during November 2015. IUCAF submitted a comprehensive information document detailing the radio astronomy positions on agenda items of relevance. The spread of 5G into new spectrum bands below 6 GHz identified at WRC-15 will impinge on radio astronomy but the radio astronomy bands will remain clear if the results of the compatibility studies conducted for WRC-19 are observed.

ITU-R: Preparations are underway for the new study cycle leading to WRC-19, and one meeting of WP 7D was held in April. Little of consequence transpired but the U.S. continues to stymie progress on the issue of defining acceptable levels of (inevitable) unwanted emissions into the passive service bands. In June, NRAO addressed the Satellite Interference Symposium on behalf of the science services.

Space Frequency Coordination Group: NRAO attended the 36th meeting of the Space Frequency Coordination Group in June in Mainz, Germany, where operators of remote sensing active (transmitting) satellites held their annual ten-day meeting. IUCAF is attempting to conclude an agreement whereby operators of high-power orbiting radars would avoid illuminating radio astronomy sites; currently they avoid illuminations only in the band 9-10 GHz. Our fellow scientists in Earth sensing are hardly more disposed to cooperation than any other satellite operators, but they did agree to calculate the surface level power fluxes of their missions, which will help to identify those which hold the most danger.



Observing Hours

Telescope performance for each of the VLA, VLBA, and GBT is characterized by the NRAO 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.

ALMA telescope time is reported by the Joint ALMA Observatory in two categories: Observing and Other.

Observing hours for each NRAO telescope are divided into the following 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.

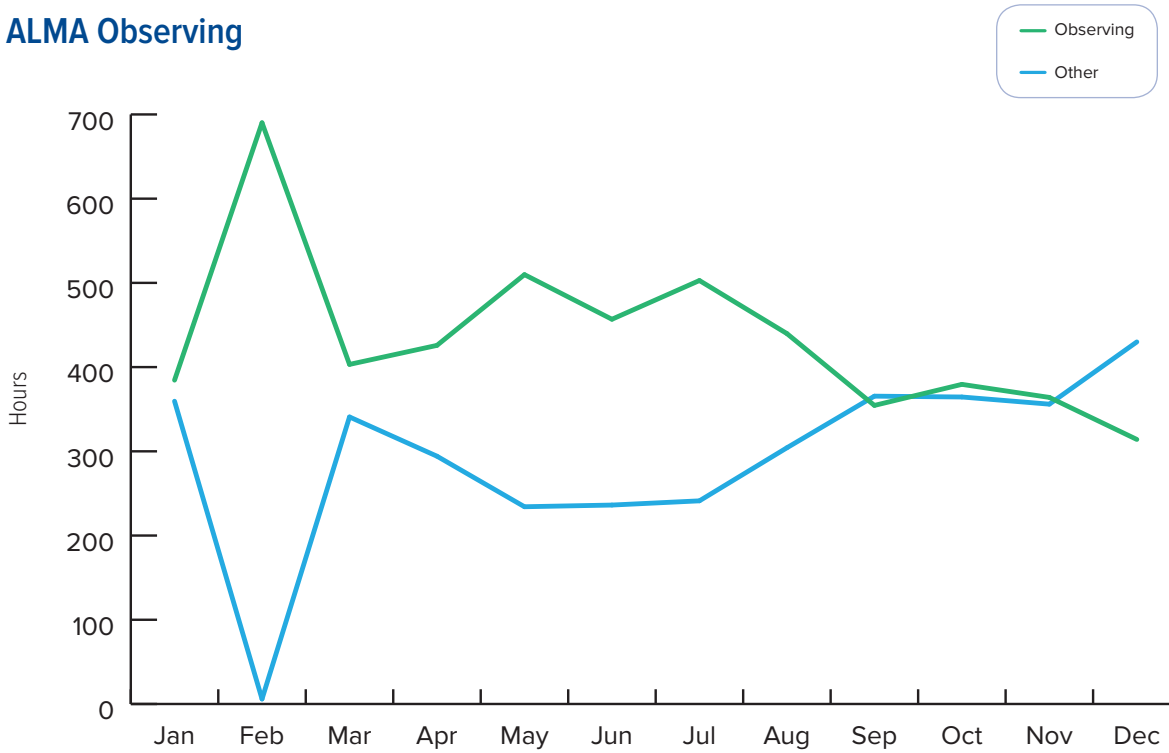
Shutdown: Actual shutdown hours, usually for a holiday. Other major shutdowns occur for major equipment work, such as GBT structural painting.



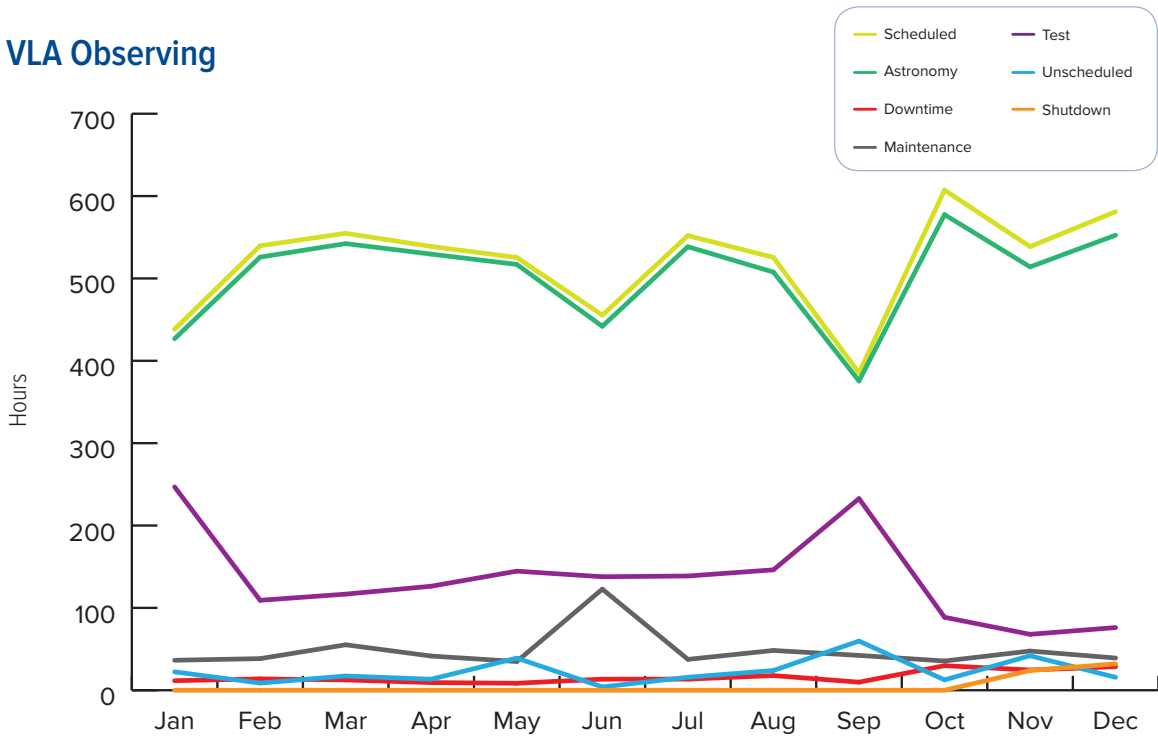
ALMA photograph by Pablo Carillo

2016 PERFORMANCE METRICS

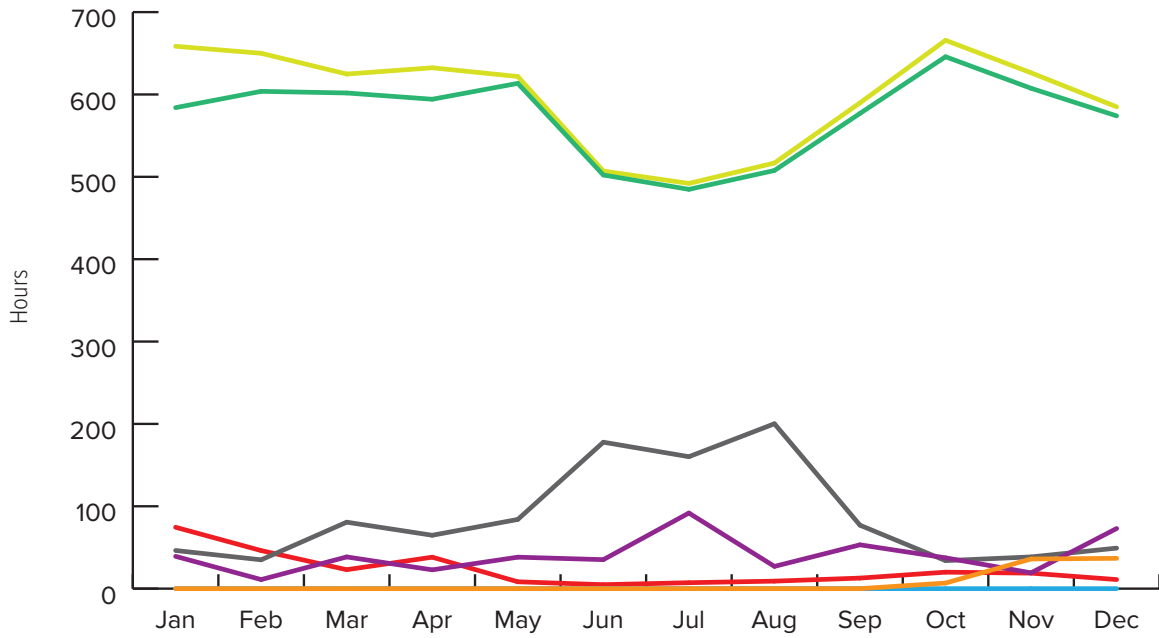
ALMA Observing



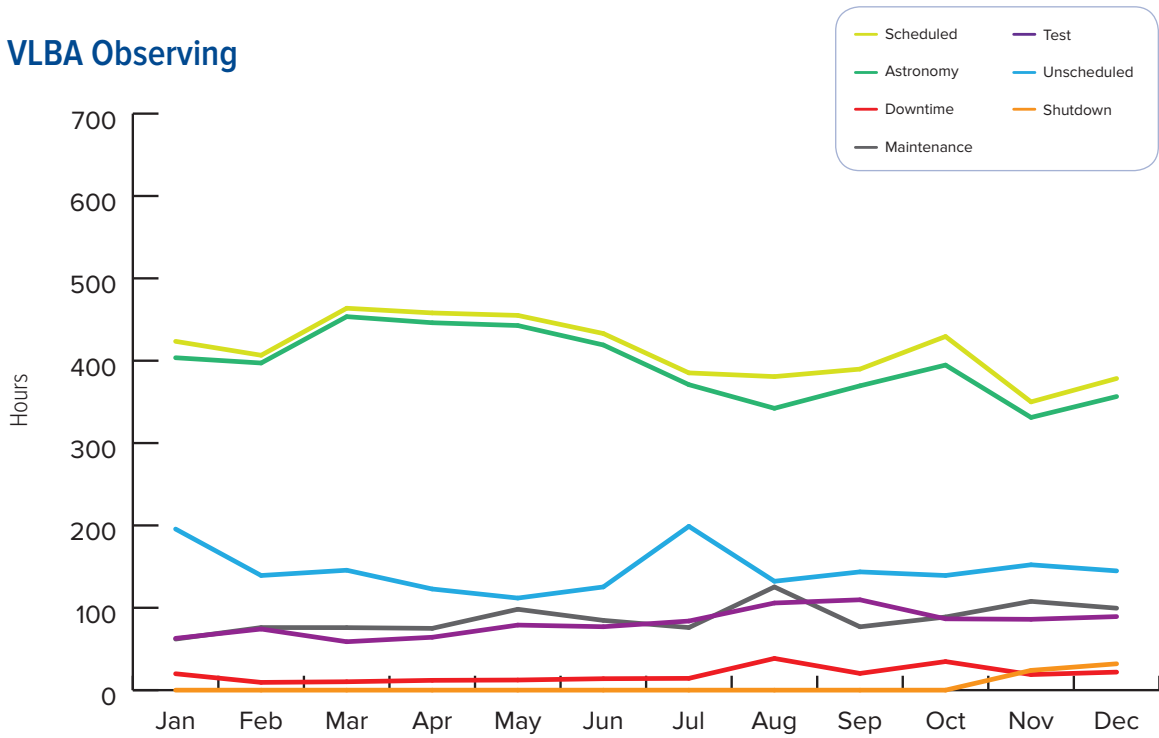
VLA Observing



GBT Observing

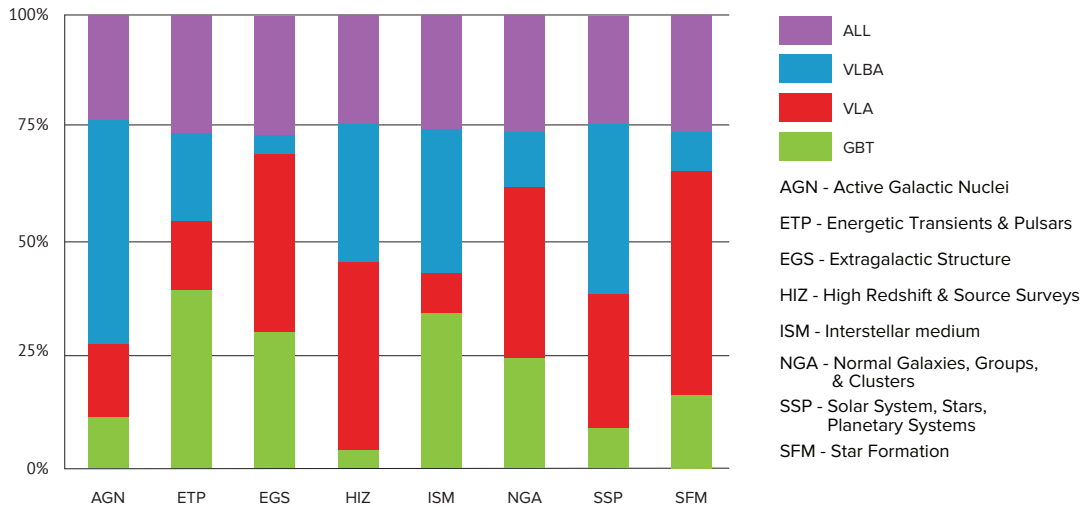


VLBA Observing



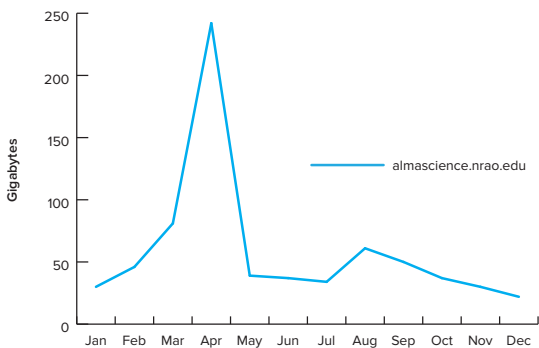
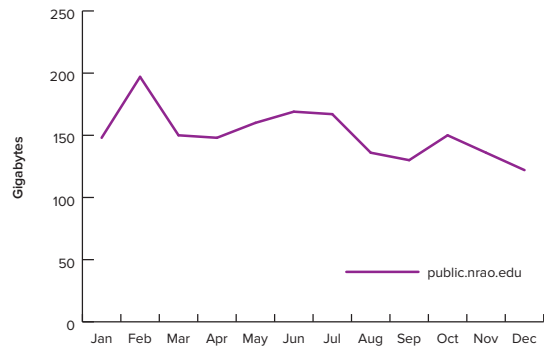
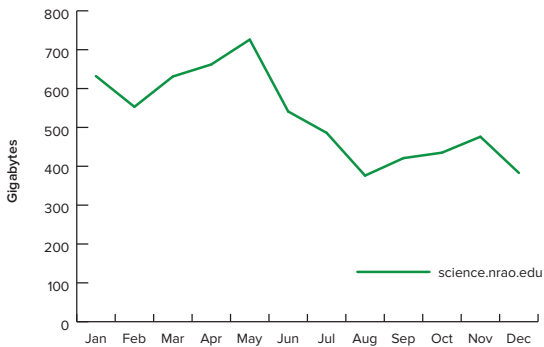
2016 PERFORMANCE METRICS

Observing Hours by Science Category



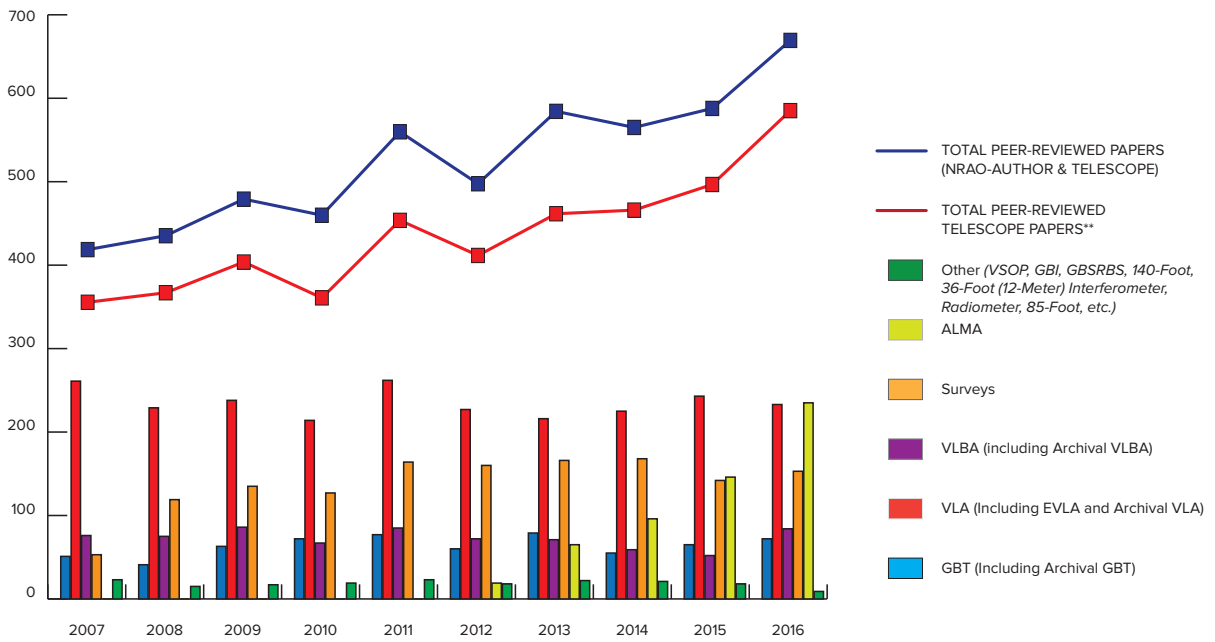
Observing hours for each of the GBT, VLA, and VLBA are tracked in the eight science categories defined in the NRAO proposal evaluation and time allocation process:

NRAO Website Volume



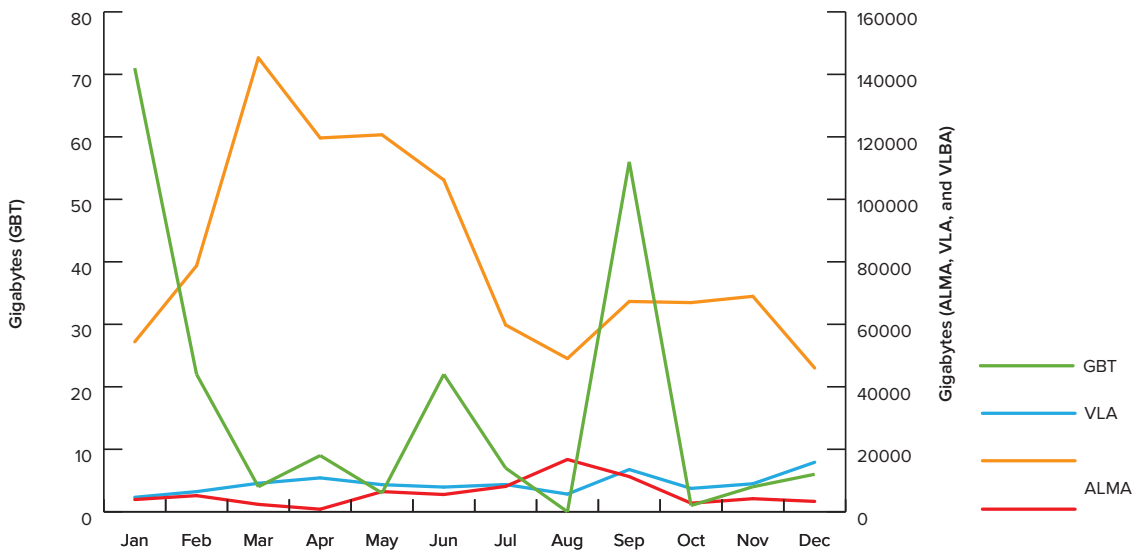
The almascience.nrao.edu website volume reflects activity by scientists interested in submitting observing proposals or seeking other professional astronomical information about ALMA. The science.nrao.edu website volume reflects activity by scientists interested in submitting observing proposals or seeking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

2016 NRAO REFEREED PUBLICATIONS

- Aalto, S.; Costagliola, F.; Muller, S.; Sakamoto, K.; Gallagher, J. S.; Dasys, K.; Wada, K.; Combes, F.; García-Burillo, S.; Kristensen, L. E.; Martín, S.; Van Der Werf, P.; Evans, A. S.; Kotilainen, J. "A precessing molecular jet signaling an obscured, growing supermassive black hole in NGC 1377?" *Astronomy and Astrophysics* 590: A73 (12 pp), 2016.
- Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M. R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; Adya, V. B.; Affeldt, C.; Agathos, M.; Agatsuma, K.; Aggarwal, N.; Aguiar, O. D.; Aiello, L.; Ain, A.; Ajith, P.; Allen, B.; Allocca, A.; Altin, P. A.; Anderson, S. B.; Anderson, W. G.; Arai, K.; Araya, M. C.; Arceneaux, C. C.; Areeda, J. S.; Arnaud, N.; Arun, K. G.; Ascenzi, S.; Ashton, G.; Ast, M.; Aston, S. M.; Astone, P.; Aufmuth, P.; Aulbert, C.; Babak, S.; Bacon, P.; Bader, M. K. M.; Baker, P. T.; Baldaccini, F.; Ballardin, G.; Ballmer, S. W.; Barayoga, J. C.; Barclay, S. E.; Barish, B. C.; Barker, D.; Barone, F.; Barr, B.; Barsotti, L.; Barsuglia, M.; Barta, D.; Barthelmy, S.; Bartlett, J.; Bartos, I.; Bassiri, R.; Basti, A.; Batch, J. C.; Baune, C.; Bavigadda, V.; Bazzan, M.; Behnke, B.; Bejger, M.; Bell, A. S.; Bell, C. J.; Berger, B. K.; Bergman, J.; Bergmann, G.; Berry, C. P. 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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

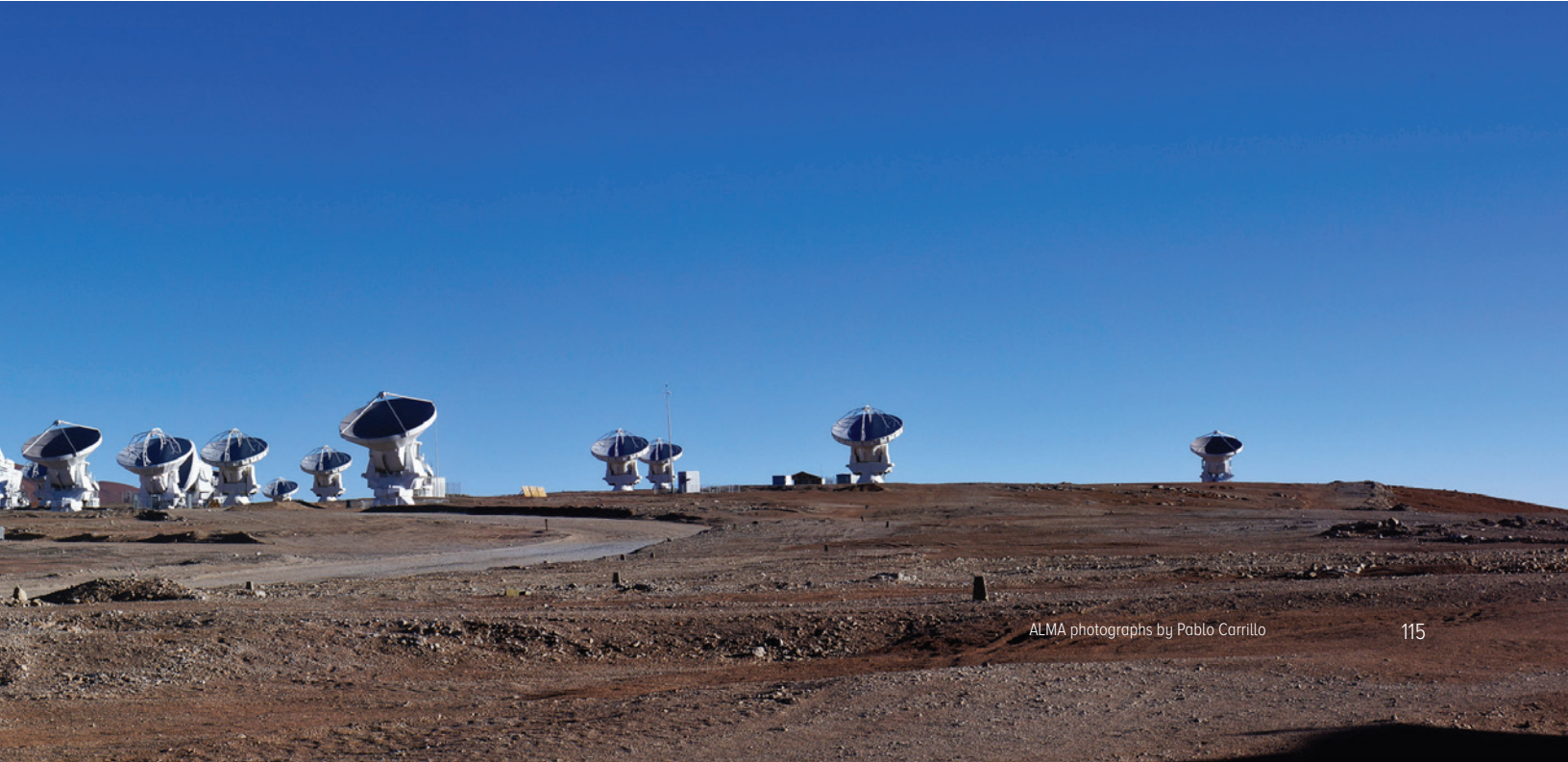
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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX B: EVENTS & MILESTONES

5 January 2016

NRAO Semester 2016B Call for Proposals opens

5-8 January

227th AAS meeting

Kissimmee, Florida
NRAO Town Hall
next generation VLA Workshop
NRAO Exhibit
Summer Student Presentations
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

6-9 January

**International Union of Radio Science
U.S. National Committee Annual Meeting**
Boulder, Colorado

25-26 January

AUI Board of Trustees meeting
Santiago, Chile

2 February

NRAO Semester 2016B Call for Proposals deadline

13 February

American Association for the Advance of Science Annual Meeting
Washington, D.C.
NRAO-sponsored science symposium: Planet Formation with Radio Eyes

18-19 February

NRAO Live!
McGill University
Montreal, Quebec, Canada

7-8 March

NRAO Live!
Boston University
Boston, Massachusetts

9 March

ARGUS installed on GBT

10 March

NRAO Live!
University of Texas
Austin, Texas

14-18 March

5th VLA Data Reduction Workshop
Socorro, New Mexico

15-16 March

NRAO Live!
University of Wisconsin
Madison, Wisconsin

22 March

**ALMA Cycle 4
Call for Proposals published**
Joint ALMA Observatory, Chile

28-29 March

12th NRAO Postdoctoral Symposium
Green Bank, West Virginia

31 March

NRAO Live!
Carnegie Observatories
Pasadena, California

4-7 April

NAASC Workshop: Molecular Gas in Galactic Environments
Charlottesville, Virginia

21 April

AUI Executive Committee meeting
Washington, D.C.

21 April

**ALMA Cycle 4
Call for Proposals deadline**
Joint ALMA Observatory, Chile

2-5 May

ALMA Baseline Correlator Workshop
Charlottesville, Virginia

17 May

ALMA North American Science Advisory Committee (ANASAC) meeting
A standing subcommittee of the NRAO Users Committee
Socorro, New Mexico

18-19 May

NRAO Users Committee Meeting
Socorro, New Mexico

23 May

MUSTANG-2 First Light on GBT

1-8 June

15th Synthesis Imaging Workshop
Socorro, New Mexico

9-10 June

AUI Board of Trustees meeting
Charlottesville, Virginia

12-16 June

228th AAS meeting
San Diego, California
NRAO Exhibit
Splinter Session: North American ALMA Development Program
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

1 July

**NRAO Semester 2017A
Call for Proposals open**

1 August

**NRAO Semester 2017A
Call for Proposals deadline**

3-5 August

**U.S. Radio–Millimeter–
Submillimeter Futures II**
Baltimore, Maryland

24-25 August

**ALMA Future Science
Development Program Workshop**
Charlottesville, Virginia

7 September

AUI Executive Committee meeting
Washington, D.C.

19-24 September

**Metrology and Control of
Large Telescopes**
Green Bank, West Virginia

20-23 September

**Half a Decade of ALMA: Cosmic
Dawns Transformed**
Indian Wells, California

30 September

**ALMA Cycle 3 science
observations ended**
Joint ALMA Observatory, Chile

1 October

**ALMA Cycle 4 science
observations began**
Joint ALMA Observatory, Chile

1 October

GBO and LBO Launch



AAS Meeting photo by Brian Kent (NRAO/AUI/NSF)

5-6 October

**Breakthrough Listen North
American Community Workshop**
Green Bank, West Virginia

20-21 October

AUI Board of Trustees meeting
Arlington, Virginia

24-28 October

**GBT Remote Observing Training
School**
Green Bank, West Virginia

27 October

**Jansky Lecture:
Dr. Jacqueline van Gorkom**
Gas & Galaxy Evolution
Charlottesville, Virginia

4 November

**32nd New Mexico Symposium
Jansky Lecture: Dr. Jacqueline
van Gorkom**
Gas & Galaxy Evolution
Socorro, New Mexico

14-17 November

SuperComputing16 (SC16) exhibition
Salt Lake City, Utah

7-8 December

NSF Program Review
Charlottesville, Virginia

8 December

AUI Executive Committee meeting
Washington, D.C.

16 December

ALMA Cycle 5 Pre-Announcement
Joint ALMA Observatory, Chile

APPENDIX C: ADVISORY COMMITTEES

ALMA North American Science Advisory Committee (ANASAC) Subcommittee of Users Committee

Alberto Bolatto (ANASAC/ASAC)

University of Maryland, 2016

Dan Marrone (ANASAC)

University of Arizona, 2018

Dominik Riechers (ANASAC)

Cornell University, 2016

Laura Chomiuk, UC Chair (ANASAC)

Michigan State University,
2016

Karin Öberg (ANASAC/ASAC)

Harvard University, 2018

Douglas Scott (ANASAC/ASAC)

University of British Columbia, 2017

Shih-Ping Lai (ANASAC)

National Tsing-Hua University,
2018

Rachel Osten (ANASAC/ASAC)

Space Telescope Science Institute,
2018

NRAO Users Committee

Loren D. Anderson

West Virginia University, 2018

Rachel Friesen

University of Toronto, 2018

Karin Öberg

Harvard University, 2018

Alberto Bolatto (ANASAC/ASAC)

University of Maryland, 2016

Trish Henning

University of New Mexico, 2019

Rachel Osten

Space Telescope Science Institute,
2018

Shami Chatterjee

Cornell University, 2016

Shih-Ping Lai

National Tsing-Hua University, 2018

Dominik Riechers

Cornell University, 2016

Laura Chomiuk, Co-Chair

Michigan State University, 2016

Joseph Lazio, Chair

JPL/CIT, 2016

Douglas Scott

University of British Columbia, 2017

Steven W. Ellingson

Virginia Tech, 2018

Dan Marrone

University of Arizona, 2018

Fabian Walter

Max Planck Inst. für Astronomie, 2019

AUI Visiting Committee

Edwin (Ted) Bergin

University of Michigan, Chair 2018

James Jackson

Boston University, 2020

Margaret Meixner

Space Telescope Science Institute,
2020

Rachel Akeson

IPAC/Caltech, 2020

Luis Felipe Rodriguez Jorge

Instituto de Radioastronomia y
Astrofisica, 2020

Greg Taylor

University of New Mexico, 2018

Katherine Blundell

Oxford University, 2018

Ryohei Kawabe

National Astronomical Observatory of
Japan, 2016

Dan Werthimer

University of California – Berkeley,
2018

Xiaoyu Hong

Shanghai Astronomical Observatory,
2016

Malcolm Longair

University of Cambridge, 2016

Time Allocation Committee

Semester 2016B

Jeremy Darling

Extragalactic Structure (EGS)
University of Colorado

Brenda Matthews

Solar System, Stars, and Planetary Systems (SSP)
National Research Council of Canada

Mark Whittle

Active Galactic Nuclei (AGN)
University of Virginia

Larry Rudnick

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APPENDIX D: FISCAL YEAR 2016 FINANCIAL SUMMARY

(all figures are \$k USD)

Functional Work Breakdown Structure Element	GBT	VLA	VLBA	ALMA	GB Ops	NM Ops	HQ & CV Ops	CDL	External Grants	Total
Administrative Services	\$150.36	\$2,067.37	\$747.86	\$13,461.51	\$3,111.22	\$2,117.70	\$5,768.74	\$0.00	\$0.00	\$27,424.8
Development Programs	\$277.32	\$0.00	\$0.00	\$2,429.74	\$703.19	\$0.00	\$747.04	\$3,171.54	\$0.00	\$7,328.8
Director's Office	\$0.00	\$0.00	\$0.00	\$5,394.71	\$44.69	\$1.92	\$4,890.70	\$0.00	\$0.00	\$10,332.0
Science Operations	\$628.12	\$33.71	\$38.13	\$7,848.49	\$21.99	\$0.00	\$6,742.81	\$0.00	\$0.00	\$15,313.2
Telescope Operations	\$5,022.47	\$8,075.37	\$4,126.06	\$6,511.25	\$272.18	\$116.54	\$1,566.65	\$0.00	\$0.00	\$25,690.5
External Grants	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$4,395.34	\$4,395.3
Grand Total	\$6,078.3	\$10,176.4	\$4,912.0	\$35,645.7	\$4,153.3	\$2,236.2	\$19,715.9	\$3,171.5	\$4,395.3	\$90,484.7

Fiscal Year 2016 = 1 October 2015 – 30 September 2016



VLA Antenna and Transporter
Credit: Jeff Helleman (NRAO/AUI/NSF)

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 Reionization 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



NRAO summer students visit the VLA. Credit: J. Mangum (NRAO/AUI/NSF)

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