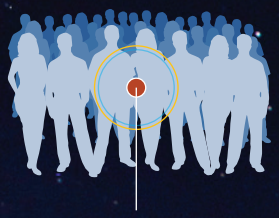
2017 ANNUAL REPORT

NRAO

NATIONAL RADIO
ASTRONOMY OBSERVATORY

NRAO FACTS & FIGURES



382 EMPLOYEES

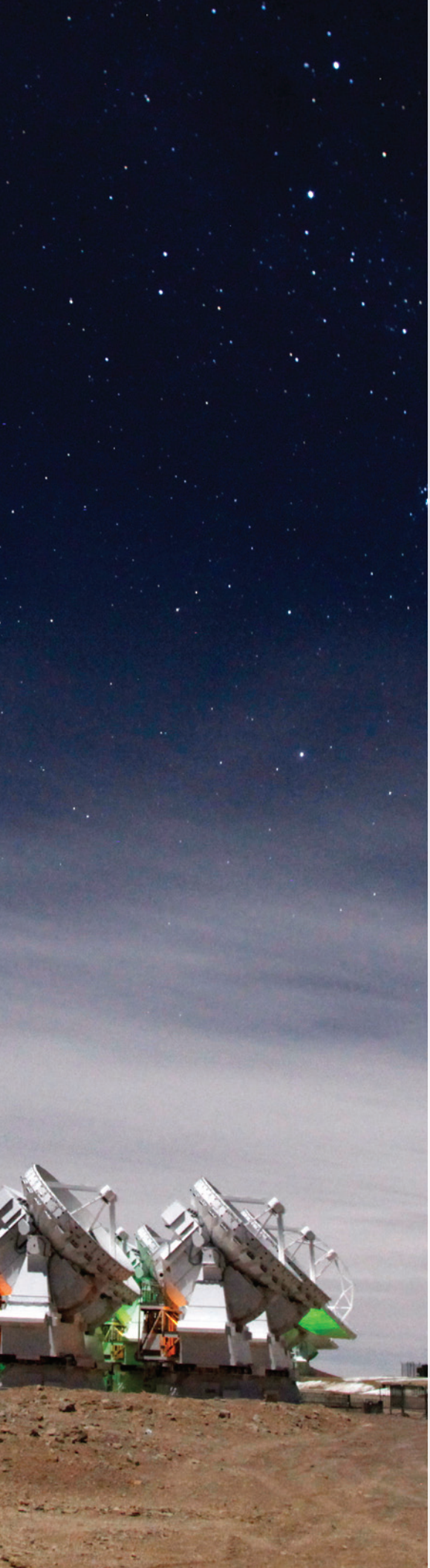
48 MEDIA RELEASES

844 REFEREED
SCIENCE PUBLICATIONS

500,000

CITATIONS FOR NRAO TELESCOPE PAPERS
REACHED: 15 MAY 2017, 0605 AM EDT

A Suite Of World-Class Astronomical Observatories



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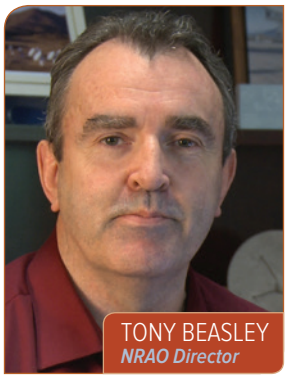
COVER: *An antenna of the Karl G. Jansky Very Large Array and the Milky Way.*
Credit: Knate Myers

LEFT: *The Atacama Large Millimeter/submillimeter Array in northern Chile.*
Credit: Carlos Padillo

DIRECTOR'S REPORT



The science that emerged in 2017 from the National Radio Astronomy Observatory (NRAO) telescopes spanned virtually every field of astrophysics.

The Jansky Very Large Array (VLA), for example, achieved two remarkable firsts: localizing the origin of a Fast Radio Burst, and detecting radio emission from the coalescence of a binary neutron star. These remarkable events, and the many others described in this 2017 Annual Report, showed NRAO at its best, providing the key instrumentation and expertise that enable our scientific community to obtain world-leading results. These outcomes depended on contributions from many people and groups across the Observatory, and the foresight of the National Science Foundation (NSF) in funding the Expanded Very Large Array (EVLA) upgrade that was completed in 2012 and is now routinely supporting a wealth of new science and discovery.

The Atacama Large Millimeter/submillimeter Array (ALMA) continued in 2017 as one of the most exciting instruments available to the international astronomy community, revealing new wonders on planetary and star-forming scales, in the high-redshift Universe and everywhere in between, attracting massive interest from all parts of the astronomy community.

Despite some uncertainty at the U.S. federal level regarding fundamental support for science, the National Science Foundation (NSF) and NRAO received adequate funding in 2017, the second year of the new ten-year Associated Universities, Inc. (AUI) cooperative agreement with NSF. New priorities and issues are emerging which may impact future federal discretionary budgets, where science lives, but U.S. Congressional support of science remains strong and bipartisan.

Our management organization, AUI, has a new President, Dr. Adam Cohen. In November 2017, we bid farewell to Dr. Ethan Schreier after many years of outstanding service to AUI and NRAO.

We have been working with NSF to identify new partners to support operations of the Long Baseline Observatory (LBO), i.e., the Very Long Baseline Array (VLBA). We have formed a partnership with the U.S. Naval Observatory to support VLBA operations long-term. As a result, the NSF has requested that NRAO provide a proposal to reintegrate the VLBA into NRAO, beginning in Fiscal Year 2019 (1 October 2018 – 30 September 2019). This outcome arose from the efforts of many people, and was enabled by the top-notch technical performance and efficiency of the LBO team. We continue to seek robust partnership options for the Green Bank Observatory, and I am confident a positive long-term arrangement for GBO will be established during 2018.

Several key NRAO initiatives were launched in 2017. The Very Large Array Sky Survey (VLASS) will be NRAO's contribution to the exciting field of transient astronomical science, working alongside other instruments like the Large Synoptic Survey Telescope, James Webb Space Telescope, and Laser Interferometer Gravitational-wave Observatory. An important renewal of the VLA site infrastructure commenced in 2017. The Science Ready Data Products (SRDP) project is underway, expanding the successful model being used for ALMA data delivery to all NRAO instruments. We have also initiated design and fund-raising for a new VLA Visitors Center.

Perhaps most importantly, our plans for a next-generation VLA (ngVLA) converged in 2017, and this initiative is now seeing strong interest and new resources. The NSF provided major new funding ($11M USD) available for the next two years to establish the ngVLA project office and begin design and development activities, including working with the science community and industrial partners to explore the scientific and technical options. The project team is driving this key NRAO initiative forward, though an ngVLA has many hurdles to clear in coming years. Thirty years elapsed as ALMA evolved from community ideas to the extraordinary instrument and science of today. The first glimpse of an ngVLA was in the EVLA

Phase II proposal written in 2000, and with some luck, ngVLA could begin full science operations in the early 2030s. These are the timescales of things worth doing, to achieve new science on the frontiers of knowledge. Building and operating these instruments for the U.S. and international science communities is what NRAO does.

The Central Development Laboratory (CDL) saw new leadership and enjoyed considerable technical success. The L-band cryogenic Phased Array Feed (PAF) Receiver was successfully evaluated, and produced the world's best noise-temperature-to-efficiency ratio. Commercialization efforts continued, with increasing sales of CDL-designed reflectionless filters. We are investing in new technologies, including those required for ngVLA and other applications, and a breakthrough superconducting technology – Traveling-Wave Kinetic Inductance Parametric (TKIP) amplifiers – holds the promise of quantum-limited receiver noise performance over wide frequency ranges that could revolutionize future receiver architectures. New positions are planned, including the first CDL Jansky Postdoc.

I would also note the outstanding 2017 performance of the NRAO Diversity team and our Safety team. NRAO Safety performance was better than ever, with standard metrics reaching record lows, and fewer incidents and injuries recorded than ever before. An external review of our Diversity Program confirmed that our efforts are making a substantial difference, inside the Observatory and in our community.

Engaged in the Observatory's mission, I am privileged to lead the extraordinary team of NRAO professionals who are dedicated to scientific adventure and discovery.

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.*

Created in 1956 by the NSF and AUI, the NRAO designs, builds, and operates the most capable astronomical telescopes and instruments at radio wavelengths. In 2017, NRAO operated a complementary suite of two world-class telescopes, each the world leader in its domain: the international Atacama Large Millimeter/submillimeter Array (ALMA), and the Karl G. Jansky Very Large Array (VLA). 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 Karl G. 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 upgraded 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.

The Central Development Laboratory (CDL) conducts the technological research and development that improves operational NRAO telescopes and helps realize next generation facilities. CDL oversees a science-driven 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; and the VLBA research facilities became a similarly independent Long Baseline Observatory (LBO), led by LBO Director Walter Brisken, with AUI management oversight.

NRAO telescopes operated individually and synergistically throughout 2017 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 broadly impacts science and society via its education and public outreach programs. A diverse program of compelling science, technology, engineering, art, and mathematics (STEAM) education programs are introducing young people every year to the excitement and opportunities of STEAM careers.

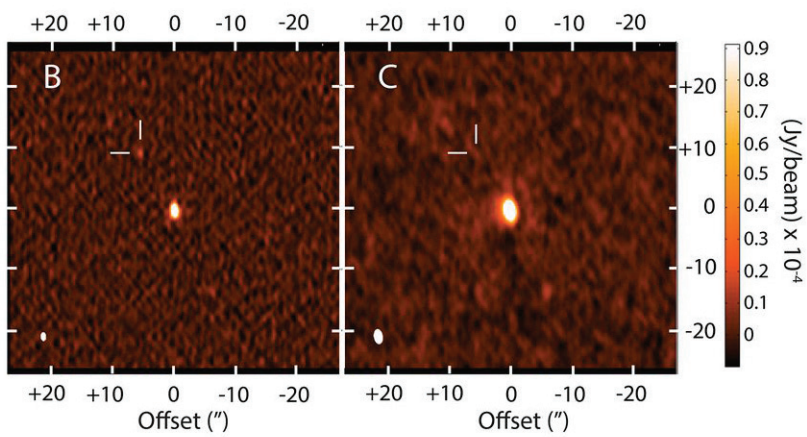
After more than six decades of continual improvement under AUI management, the NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for the astronomy community in the U.S. and around the world.

A Radio Counterpart to a Neutron Star Merger

On 17 August 2017, the Advanced Laser Interferometer Gravitational Wave Observatory (Advanced LIGO) detected a gravitational wave signal, GW170817, which was rapidly identified to be associated with the inspiral and coalescence of two neutron stars. This was the first ever detection of such an event. A burst of gamma-rays, GRB170817A, was detected ~2 seconds after the gravitational wave detection by the Gamma-ray Burst Monitor (GBM) of the Fermi Gamma-ray Space Telescope. With the addition of data from the Advanced Virgo interferometer, the gravitational wave source was localized to an area of 28 deg^2 (90% confidence region) and a distance of 40 ± 8 Mpc. There were 49 cataloged galaxies within this volume, allowing astronomers to rapidly search for electromagnetic counterparts. An optical counterpart, designated SSS17a, was detected within ~11 hours of the event by astronomers using the Swope telescope, localizing the merger to the S0-type galaxy NGC 4993 at a distance of 40 Mpc, and soon independently confirmed. Following the optical detections, targeted observing campaigns were initiated across the electromagnetic spectrum. Subsequent optical and infrared spectroscopic observations firmly established this optical counterpart to be associated with the neutron star merger GW170817.

In this work, Hallinan et al. report a coordinated effort to use the VLA, the VLA Low Band Ionosphere and Transient Experiment (VLITE), the Australia Telescope Compact Array (ATCA) and the Giant Metrewave Radio Telescope (GMRT) to constrain the early-time radio properties of the neutron star merger. Companion papers report the ultraviolet and X-ray properties and interpret the panchromatic behavior of the transient. The multi-wavelength counterpart to GW170817 is designated EM170817.

Hallinan et al. discovered the radio afterglow of the neutron star merger using the VLA 16 days after the gravitational wave burst. This radio detection was made possible by the ultra-sensitivity of the VLA. The radio afterglow is the key element in interpreting the event as a likely relativistic jet driven by the neutron star merger. Continuing observations with the VLBA and the Jansky VLA will solidify the interpretation of this event, heralding a new field of astronomy.

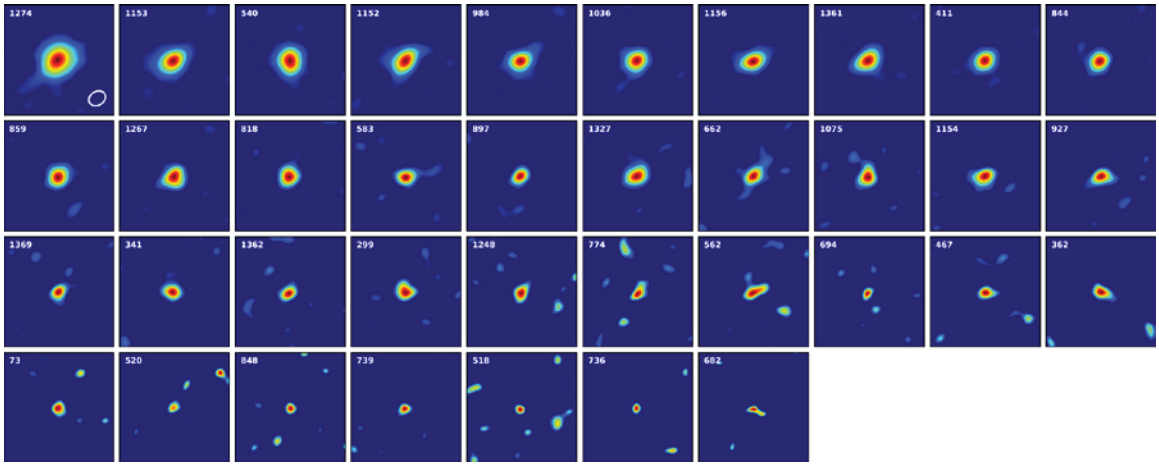


[Left] *Radio image created using VLA observations (6 GHz) on 9 September 2017, with the radio counterpart to EM170817 highlighted. Its flux density is 23 ± 3.4 μJy.* **[Right]** *A combined image from four VLA observations at 6 GHz spanning 22.6 August–1 September 2017. The flux density at the position of EM170817 is 7.8 ± 2.6 μJy, consistent with a marginal or non-detection.*

Publication: G. Hallinan (California Institute of Technology) et al., *A Radio Counterpart to a Neutron Star Merger,* 16 October 2017, Science, 358, 1579.

Protoplanetary Disks in the ALMA Era

The σ Orionis cluster is important for studying protoplanetary disk evolution, as its intermediate age (~3–5 Myr) is comparable to the median disk lifetime. Ansdell et al. used ALMA to conduct a high-sensitivity survey of dust and gas in 92 protoplanetary disks around σ Orionis members with $M_* \gtrsim 0.1\ M_\odot$. These ALMA observations cover the 1.33 mm continuum and several CO *J* = 2–1 lines: of 92 sources, 37 are detected in the millimeter continuum, 6 in ^{12}CO, 3 in ^{13}CO, and none in $C^{18}O$. Using the continuum emission to estimate dust mass, the authors find only 11 disks with $M_{dust} \gtrsim 10\ M_\oplus$, indicating that after only a few million years of evolution most disks lack sufficient dust to form giant planet cores. Stacking the individually undetected continuum sources limits their average dust mass to five times lower than that of the faintest detected disk, supporting theoretical models that indicate rapid dissipation once disk clearing begins. Comparing the protoplanetary disk population in σ Orionis to those of other star-forming regions supports the steady decline in average dust mass and the steepening of the $M_{dust} - M_*$ relation with age; studying these evolutionary trends can inform the relative importance of different disk processes during key planet formation eras. External photoevaporation from the central O9 star is influencing disk evolution throughout the region: dust masses clearly decline with decreasing separation from the photoionizing source. Collectively, the findings of Ansdell et al. indicate that giant planet formation is inherently rare and/or well underway by a few million years of age.



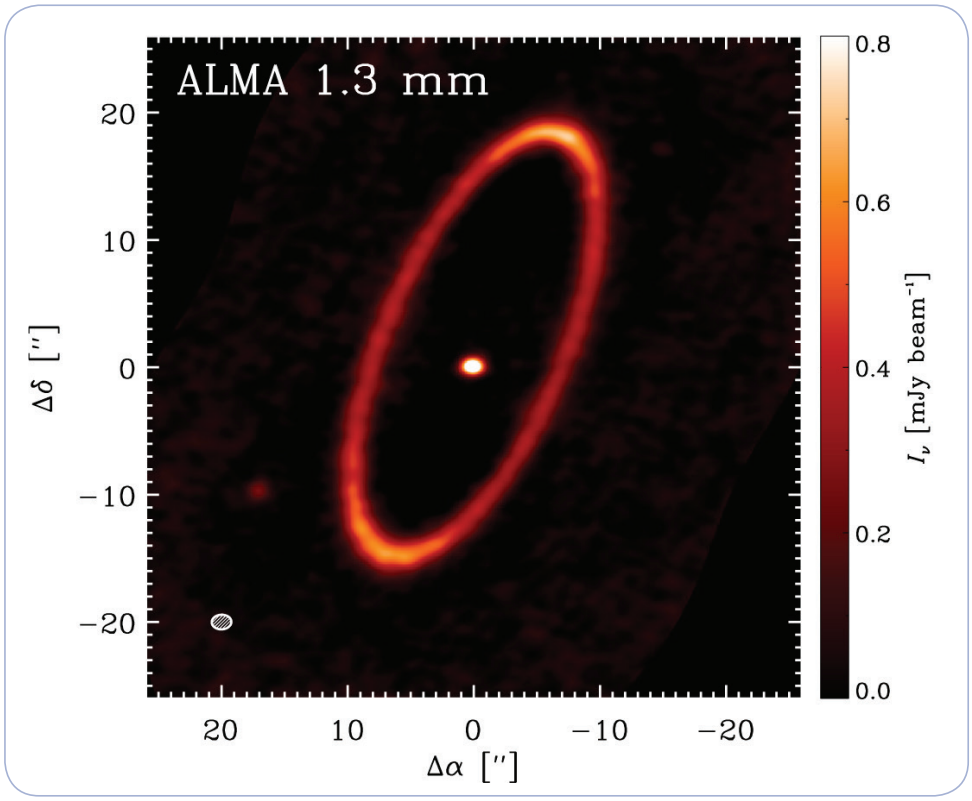
Continuum images at 1.33 mm of the 37 detected disks in the σ Orionis ALMA sample, ordered by decreasing flux density. Images are 2 x 2 arcsec; the typical beam size of 0.31 × 0.25 arcsec is shown in the first panel (top row, left end).

Publication: M. Ansdell (University of Hawai'i at Manoa) et al., *An ALMA Survey of Protoplanetary Disks in the σ Orionis Cluster,* 2017, Astronomical Journal, 153, 240.

Mapping a Complete Debris Disk

MacGregor et al. present ALMA mosaic observations at 1.3 mm (223 GHz) of the Fomalhaut system. These observations provide the first millimeter map of the continuum dust emission from the complete outer debris disk with uniform sensitivity, enabling the first conclusive detection of apocenter glow. The authors adopt a modeling approach that accounts for the eccentric orbital parameters of a collection of particles within the disk. The outer belt is radially confined with an inner edge of 136.3 ± 0.9 Astronomical Units (AU) and width of 13.5 ± 1.8 AU, with a best-fit eccentricity of 0.12 ± 0.01.

Assuming a size distribution power-law index of q = 3.46 ± 0.09, the dust absorptivity power-law index β is constrained to be $0.9 < \beta < 1.5$. The geometry of the disk is robustly constrained with inclination 65.6° ± 0.3°, position angle 337.9° ± 0.3°, and argument of periastron 22.5° ± 4.3°. These ALMA observations do not confirm any of the azimuthal features found in previous imaging studies of the disk with the Hubble Space Telescope (HST), the Submillimeter Common-User Bolometer Array, and ALMA. However, they cannot rule out structures ≤10 AU in size or that only affect smaller grains. The central star is clearly detected with a flux density of 0.75 ± 0.02 mJy, significantly lower than predicted by current photospheric models.



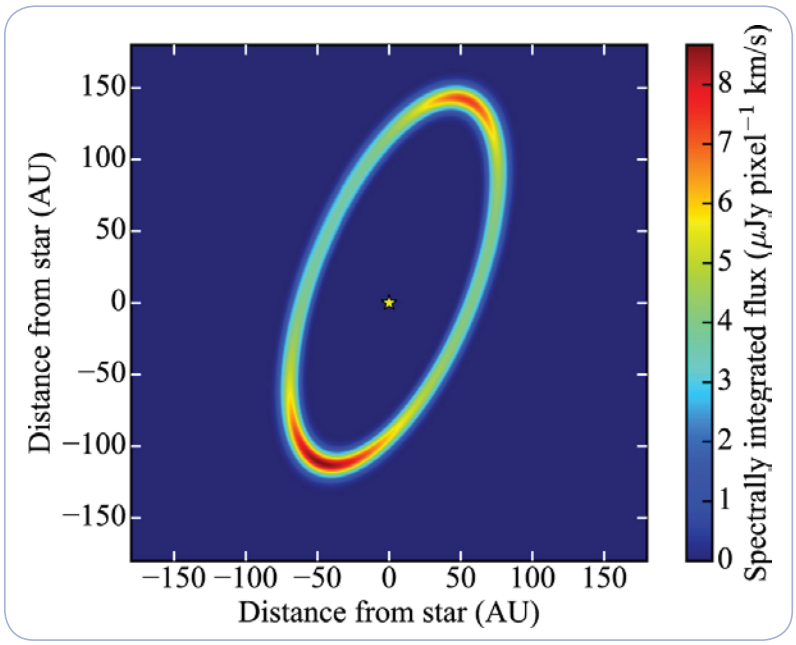
ALMA image of the 1.3 mm continuum emission from Fomalhaut. The dashed white ellipse in the lower left corner shows the natural weight beam size of 1.56 x 1.15 arcsec.

Publication: Meredith A. MacGregor (Harvard-Smithsonian Center for Astrophysics) et al., *A Complete Map of the Fomalhaut Debris Disk,* 2017, Astrophysical Journal, 842, 8.

Exocometary Gas

Recent ALMA observations present mounting evidence for the presence of exocometary gas released within Kuiper Belt analogs around nearby main-sequence stars. This represents a unique opportunity to study their ice reservoir at the younger ages when volatile delivery to planets is most likely to occur. Matrà et al. present the detection of CO *J* = 2-1 emission colocated with dust emission from the cometary belt in the 440-Myr-old Fomalhaut system. Through spectrospatial filtering, they achieve a 5.4σ detection and determine that the ring's sky-projected rotation axis matches that of the star.

The derived CO mass (0.65-42 x 10^{-7} $M_{\oplus}$,) is the lowest of any circumstellar disk detected to date and must be of exocometary origin. Using a steady-state model, the authors estimate the CO + CO_2 mass fraction of exocomets around Fomalhaut to be between 4.6% and 76%, consistent with Solar System comets and the two other belts known to host exocometary gas. This is the first indication of a similarity in cometary compositions across planetary systems that may be linked to their formation scenario and is consistent with direct interstellar medium inheritance. In addition, the authors find tentative evidence that 49 ± 27% of the detected flux originates from a region near the eccentric belt's pericenter. If confirmed, the latter may be explained through a recent impact event or CO pericenter glow due to exocometary release within a steady-state collisional cascade. In the latter scenario, Matrà et al. show how the azimuthal dependence of the CO release rate leads to asymmetries in gas observations of eccentric exocometary belts.



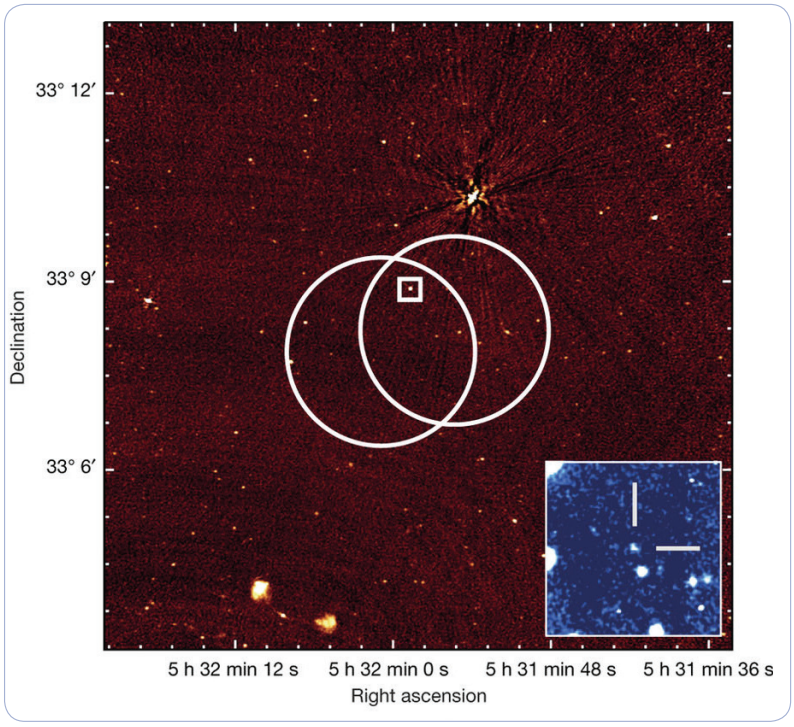
Model image for the maximum CO J = 2-1 flux enhancement expected at pericenter with respect to apocenter through steady-state CO production in the Fomalhaut ring. The model predicts a flux density enhancement of ~14.5% at the pericenter with respect to the apocenter location.

Publication: L. Matrà (University of Cambridge) et al., *Detection of Exocometary CO within the 440 Myr-old Fomalhaut Belt,* 2017, Astrophysical Journal, 842, 9.

A Fast Radio Burst and its Host

Fast Radio Bursts (FRBs) are astronomical radio flashes of an unknown physical origin with durations of milliseconds. Their dispersive arrival times suggest an extragalactic origin and imply radio luminosities orders of magnitude larger than those of all known short-duration radio transients. To date, all FRBs have been detected with large single-dish telescopes with arcminute localizations, and attempts to identify their source or host galaxy have relied on the contemporaneous variability of field sources or the presence of peculiar field stars or galaxies. These attempts have not resulted in an unambiguous association with a host or multi-wavelength counterpart.

In this contribution, Chatterjee et al. report the sub-arcsecond localization of FRB 121102, the only known repeating burst source, using high-time-resolution VLA radio observations that directly image the bursts. This precise localization revealed that FRB 121102 originates within 100 milli-arcseconds of a faint 180 micro-Jansky persistent radio source with a continuum spectrum consistent with non-thermal emission, and a faint optical counterpart. The flux density of the persistent radio source varies by ~10% on day timescales, and very long baseline radio interferometry yields an angular size of < 1.7 milli-arcseconds. These observations are inconsistent with the FRB having a Galactic origin or its source being located within a prominent star-forming galaxy. Instead, the source appears to be co-located with a low-luminosity active galactic nucleus or a previously unknown type of extragalactic source. Localization and identification of a host or counterpart has been essential to understanding the origins and physics of other kinds of transient events, including gamma-ray bursts and tidal disruption events. However, if other FRBs have similarly faint radio and optical counterparts, this research implies that direct sub-arcsecond localizations may be the only path to reliable associations.



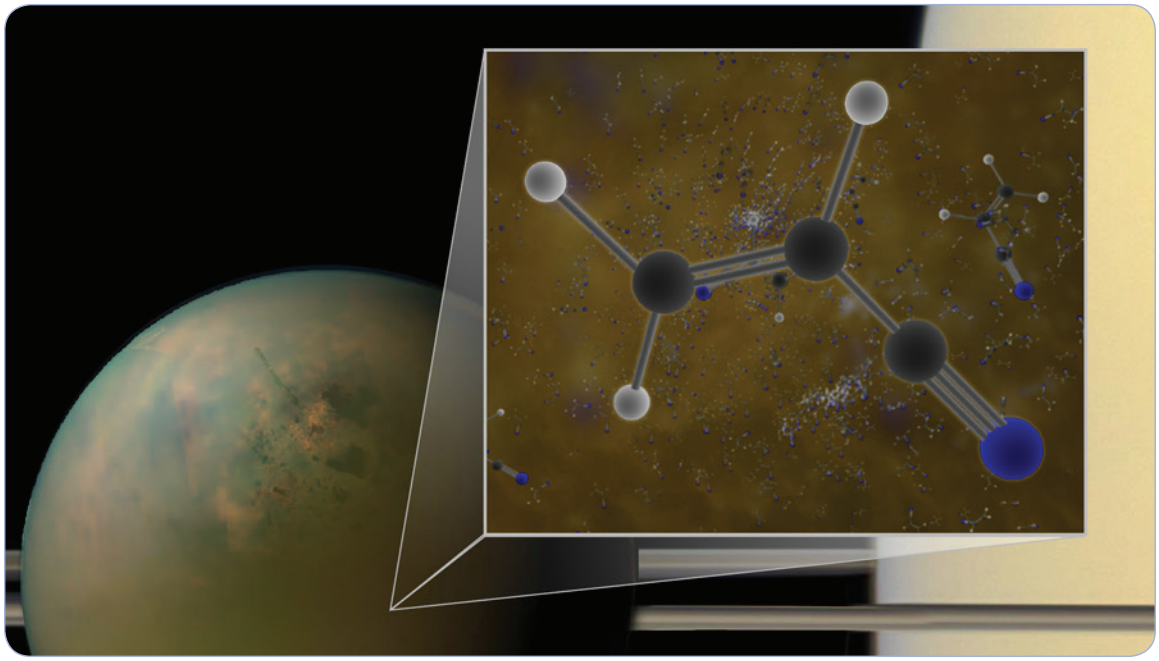
VLA image (3 GHz) of the FRB field at 2 arcsec resolution. The overlapping white circles are the Arecibo Observatory detection uncertainty regions (3′ beam FWHM). The radio counterpart of the bursts detected by the VLA is highlighted in a 20 arcsec white square within the overlap. **[Inset]** *Gemini Observatory image of the 20 arcsec square showing an optical counterpart (rAB = 25.1 ± 0.1 mag), as identified by the 5 arcsec bars.*

Publication: Shami Chatterjee (Cornell University) et al., *A Direct Localization of a Fast Radio Burst and its Host,* 2017, Nature, 541, 58.

Membrane Molecules on Titan

Recent simulations have indicated that vinyl cyanide is the best candidate molecule for the formation of cell membranes/vesicle structures in the hydrocarbon-rich lakes and seas of Titan, Saturn's moon. Titan is as large Mars, with a hazy atmosphere comprised primarily of nitrogen and a smattering of organic molecules that is possibly similar to Earth's primordial atmosphere. Although the existence of vinyl cyanide (C_2H_3CN) on Titan was previously inferred using mass spectrometry from the Cassini spacecraft, a definitive detection has been lacking.

Palmer et al. report the first spectroscopic detection of vinyl cyanide in Titan's atmosphere, obtained using archival ALMA data collected February – May 2014. The authors detected the three strongest rotational lines of C_2H_3CN in the 230 – 232 GHz frequency range, each with better than 4σ confidence. Radiative transfer modeling suggests that most of the C_2H_3CN emission originates at altitudes of $\approx$200 km, in agreement with recent photochemical models. The vertical column densities implied by the best-fit models are in the range of 3.7×10^{13} to 1.4×10^{14} cm^{-2}. The corresponding production rate of vinyl cyanide and its saturation mole fraction imply the availability of sufficient dissolved material to form $\sim 10^7$ cell membranes/cm^3 in Titan's sea, Ligeia Mare.



Archival ALMA data have confirmed that molecules of vinyl cyanide reside in the atmosphere of Titan, Saturn's largest moon. Titan is shown in an optical (atmosphere) infrared (surface) composite from NASA's Cassini spacecraft. In a liquid methane environment, vinyl cyanide may form membranes. Credit: B. Saxton (NRAO/AUI/NSF); NASA.

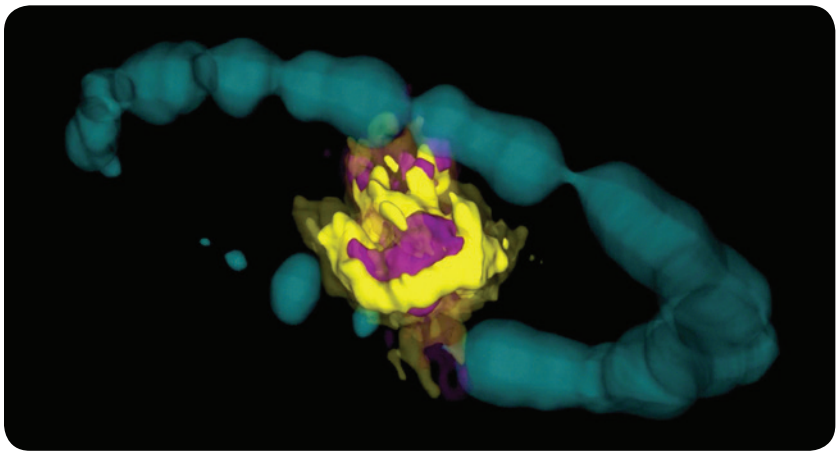
Publication: Maureen Y. Palmer (NASA-Goddard, St. Olaf College, Catholica University of America) et al., *ALMA Detection and Astrobiological Potential of Vinyl Cyanide on Titan,* 5 July 2017, Science Advances, Vol. 3, no. 7.

Probing Molecules in Supernova Remnants

Most massive stars end their lives in core-collapse supernova (SN) explosions and enrich the interstellar medium with explosively nucleosynthesized elements. Following core collapse, the explosion is subject to instabilities as the shock propagates outward through the progenitor star. Observations of the composition and structure of the innermost regions of a core-collapse supernova provide a direct probe of the instabilities and nucleosynthetic products. SN 1987A in the Large Magellanic Cloud is one of very few supernovae for which the inner ejecta can be spatially resolved but are not yet strongly affected by interaction with the surroundings.

F.J. Abellán (Universidad de Valencia) and colleagues analyze ALMA observations of SN 1987A with the highest resolution achieved to date, that reveal the detailed morphology of cold molecular gas in the innermost regions of the remnant. The 3D distributions of carbon and silicon monoxide (CO and SiO) emission differ, but both have a central deficit, or torus-like distribution, possibly a result of radioactive heating during the first weeks after the explosion. The size scales of the clumpy distribution are compared quantitatively to models, demonstrating how progenitor and explosion physics can be constrained.

M. Matsuura (Cardiff University, University College London) et al. report the first molecular line survey of SN 1987A at millimeter wavelengths. ALMA detected cold (20–170 K) CO, ^{28}SiO, HCO^+ and SO, with weaker lines of ^{29}SiO from ejecta, the first identification of HCO^+ and SO in a young supernova remnant. A dip in the J = 6–5 and 5–4 SiO line profiles suggests that the ejecta morphology is elongated. The CO and SiO line profile differences are consistent with hydrodynamic simulations, which show that Rayleigh–Taylor instabilities cause mixing of gas, with heavier elements much more disturbed, making more elongated structure. Low ^{29}Si and ^{30}Si abundances are consistent with nucleosynthesis models that show inefficient formation of neutron-rich isotopes in a low-metallicity environment, such as the Large Magellanic Cloud. The deduced large mass of HCO^+ ($\sim 5 \times 10^{-6}\,M_\odot$) and small SiS mass ($<6 \times 10^{-5}\,M_\odot$) might be explained by some mixing of elements immediately after the explosion. The mixing might have caused some hydrogen from the envelope to sink into carbon- and oxygen-rich zones after the explosion, enabling the formation of a substantial mass of HCO^+. Oxygen atoms may have penetrated into silicon and sulphur zones, suppressing formation of SiS.



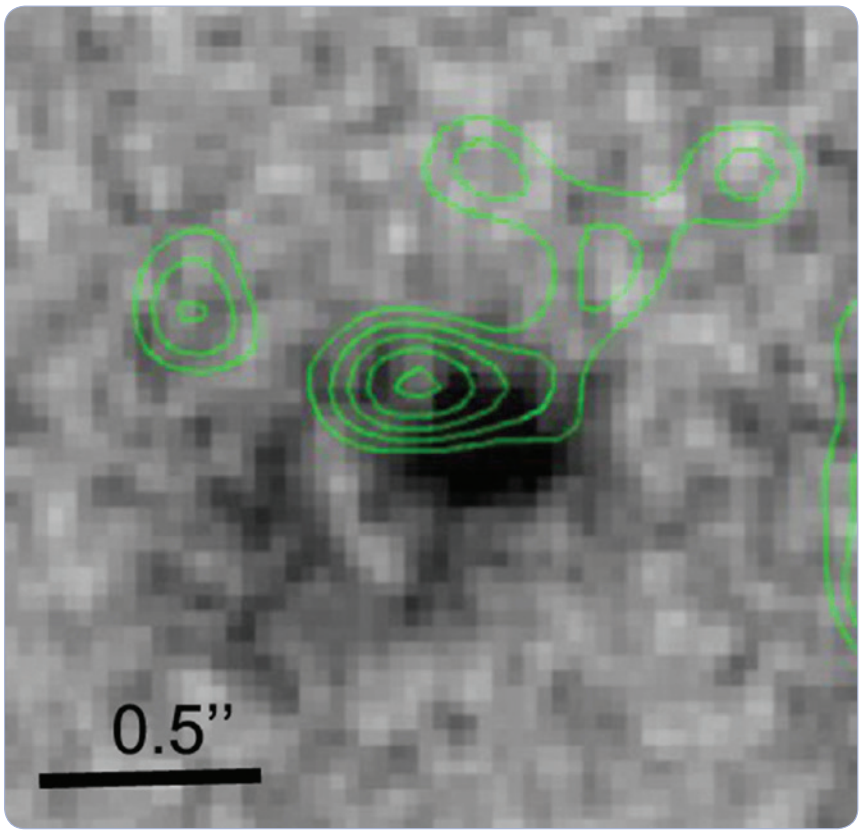
Remnant of SN 1987A as seen by ALMA. Purple area indicates emission from SiO molecules. Yellow area is emission from CO molecules. The blue ring is Hubble data that has been artificially expanded into 3-D. Credit: ALMA (ESO/NAOJ/NRAO); R. Indebetouw; NASA/ESA Hubble.

Publication: F.J. Abellán (Universidad de Valencia) et al., *Very Deep inside the SN 1987A Core Ejecta: Molecular Structures Seen in 3D,* 2017, Astrophysical Journal Letters, 842, L24.

Publication: M. Matsuura (Cardiff University, University College London) et al., *ALMA spectral survey of Supernova 1987A – molecular inventory, chemistry, dynamics and explosive nucleosynthesis,* 2017, Monthly Notices of the Royal Astronomical Society, 469, 3347.

The Most Distant Galaxy

Laporte et al. report on the detailed analysis of a gravitationally lensed Y-band dropout – designated A2744_YD4 – selected from deep HST imaging in the Frontier Field cluster Abell 2744. Band 7 observations with ALMA indicate the proximate detection of a significant 1 mm continuum flux suggesting the presence of dust for a star-forming galaxy with a photometric redshift of z = 8.38. Deep X-SHOOTER spectra confirm the high-redshift identity of A2744_YD4 via the detection of Lyα emission at a redshift z = 8.38. The association with the ALMA detection is confirmed by the presence of [O III] 88 μm emission at the same redshift. Although both emission features are only significant at the 4σ level, the authors argue their joint detection and the positional coincidence with a high-redshift dropout in the HST images confirms the physical association. Analysis of the available photometric data and the modest gravitational magnification ($\mu \sim 2$) indicates A2744_YD4 has a stellar mass of $\sim 2 \times 10^9$ $M_\odot$, a star formation rate of $\sim$20 $M_\odot$ per year, and a dust mass of $\sim 6 \times 10^6$ $M_\odot$. These observations imply that the interstellar medium in galaxies can be substantially enriched with metals and dust when the Universe was only ~600 million years old.



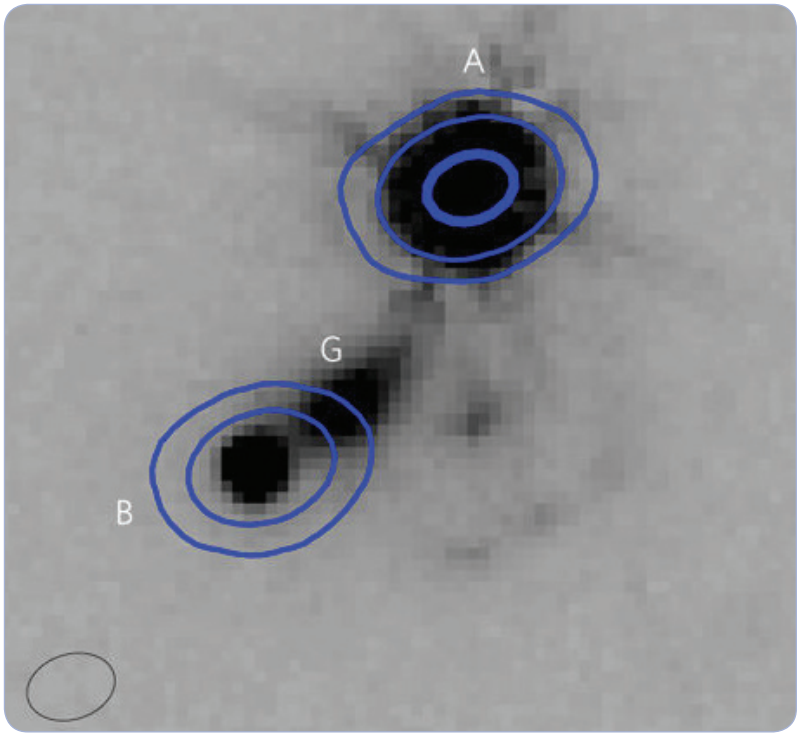
ALMA image contours superposed on a HST visible (F160W) image of A2744_YD4.

Publication: N. Laporte (University College London, Pontificia Universidad Católica de Chile, Millennium Institute of Astrophysics) et al., *Dust in the Reionization Era: ALMA Observations of a z = 8.38 Gravitationally Lensed Galaxy,* 2017, Astrophysical Journal Letters, 837, L21.

Large-scale Magnetic Fields in a Distant Galaxy

Magnetic fields play a pivotal role in the physics of interstellar medium in galaxies, but there are few observational constraints on how they evolve across cosmic time. Spatially resolved synchrotron polarization maps at radio wavelengths reveal well-ordered, large-scale magnetic fields in nearby galaxies that are believed to grow from a seed field via a dynamo effect. To directly test and characterize this theory requires magnetic field strength and geometry measurements in cosmologically distant galaxies, which are challenging to obtain due to the limited sensitivity and angular resolution of radio telescopes.

In this work, Mao and colleagues report the cleanest measurements yet of magnetic fields in a galaxy beyond the local volume, free of the systematics traditional techniques encounter. Using the Jansky VLA and exploiting the scenario where the polarized radio emission from a background source is gravitationally lensed by a foreground galaxy at $z = 0.439$, broadband radio polarization data reveal coherent micro-Gauss magnetic fields in the lensing disk galaxy as seen 4.6 Gyr ago, with similar strength and geometry to local volume galaxies. This is the highest redshift galaxy whose observed coherent magnetic field property is compatible with a mean-field dynamo origin.



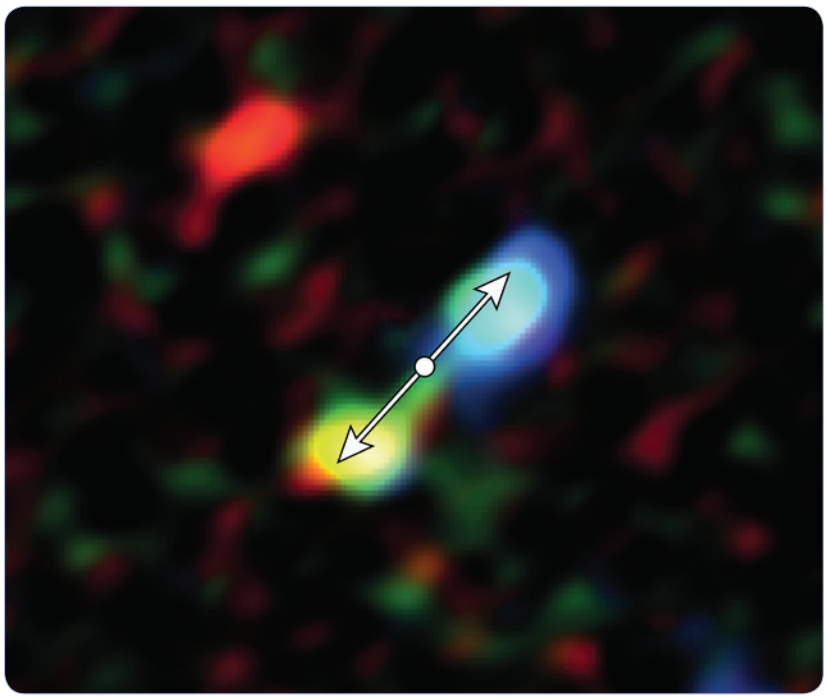
The 5 GHz total intensity radio contours from the Jansky VLA superposed on a Hubble Space Telescope visible (F814W) image of the gravitational lensing system CLASS B1152+199.

Publication: S. A. Mao (Max Planck Institute for Radio Astronomy) et al., *Detection of Microgauss Coherent Magnetic Fields in a Galaxy Five Billion Years Ago,* 2017, Nature Astronomy, 1, 621 (28 August 2017)

Young, Low Mass Stars Orbiting the Galactic Center

Low mass star formation was thought to be inhibited with a few parsecs of the Galactic Center by the turbulent, dense environment. Yusef-Zadeh et al., however, report the discovery of 11 bipolar outflows within a projected distance of 1 parsec of the Galactic Center, Sgr A*, based on deep ALMA observations of ^{13}CO, $H_30\alpha$, and SiO (5-4) lines with sub-arcsecond spatial resolution and ~1.3 km/sec velocity resolution.

These unambiguous signatures of young protostars manifest as approaching and receding lobes of dense gas swept up by the jets created during the formation and early evolution of stars. The lobe masses and momentum transfer rates are consistent with young protostellar outflows found throughout the disk of the Galaxy. The mean dynamical age of the outflow population is estimated to be 6.5 x 10^3 years. The rate of star formation is ~5×10^{-4} $M_\odot$ per year, assuming a mean stellar mass of ~0.3 $M_\odot$. This discovery provides evidence that star formation is taking place within clouds surprisingly close to Sgr A*, perhaps due to events that compress the host cloud, creating condensations with sufficient self-gravity to resist tidal disruption by Sgr A*. Low mass star formation over the past few billion years at this level would contribute significantly to the stellar mass budget in the central few parsecs of the Galaxy. The presence of many dense clumps of molecular material within a parsec of Sgr A* suggests that star formation could take place in the immediate vicinity of supermassive black holes in the nuclei of external galaxies.



Double-lobe feature produced by jets from one of the newly-forming stars. ALMA discovered 11 of these telltale signs of star formation remarkably close to the supermassive black hole at the center of our galaxy. Credit: ALMA (ESO/NAOJ/NRAO), Yusef-Zadeh et al.; B. Saxton (NRAO/AUI/NSF)

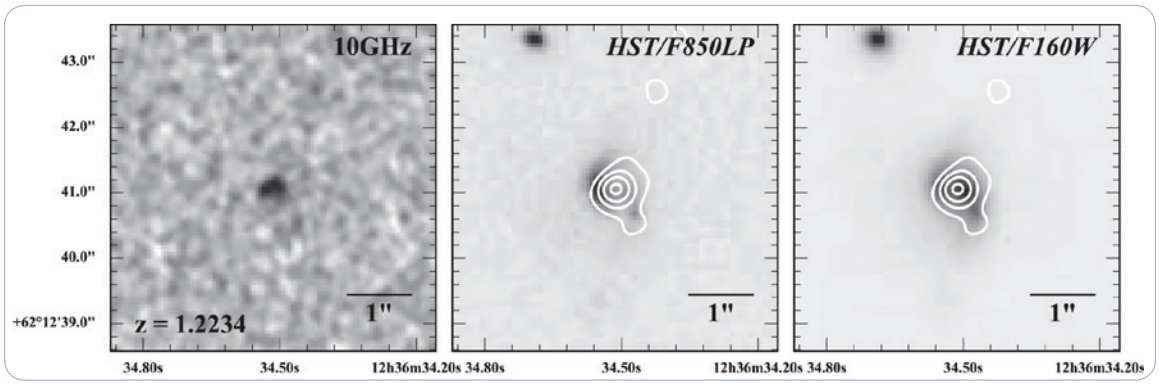
Publication: N. Laporte (University College London, Pontificia Universidad Católica de Chile, Millennium Institute of Astrophysics) et al., *Dust in the Reionization Era: ALMA Observations of a z = 8.38 Gravitationally Lensed Galaxy,* 2017, Astrophysical Journal Letters, 837, L21.

High Sensitivity Radio Surveys

Murphy et al. present initial results on a flux-limited sample of galaxies from pilot observations aimed at mapping the entire Great Observatories Origins Deep Survey-North (GOODS-N) field at 10 GHz. The GOODS-N field covers 160 arcmin^2 centered on the Hubble Deep Field–North and unrivaled in terms of its ancillary data, including extremely deep Chandra, HST, Spitzer and Herschel observations, deep ground-based imaging from U through K-band, ~3500 spectroscopic redshifts acquired with 8-10m class telescopes, and deep 1.4 GHz observations.

The new VLA X-band data (8–12 GHz) presented by Murphy and colleagues feature an r.m.s. sensitivity of 0.5 micro-Jansky and a resolution of 0.2 arcsec. This resolution is well-matched to the HST optical and infrared data from GOODS, and delivers a physical resolution of 1.9 kiloparsecs or less at any redshift. These new 10 GHz radio data provide an extinction-free view of the morphologies of dusty starburst galaxies that dominate the cosmic star formation activity between z = 1 and 3. In this redshift range, 10 GHz observations sample ~20–40 GHz in the source frame and provide accurate star formation rates for comparison with other diagnostics in the GOODS ancillary data, such as the far ultraviolet continuum, Hα, and [O III] 5007 Å.

These 10 GHz data provide accurate measurements of the radio sizes of high redshift star-forming galaxies. The observed median size is ~ 1.2 kiloparsecs, which corresponds to the dense, star-forming regions as also seen in dust continuum emission. The measured spectral indices of the detected galaxies are flatter than expected, implying a ~50% contribution to the rest from 20 GHz luminosity by free-free thermal emission. This important result opens a new, powerful means to obtain star formation rates for high redshift galaxies that are unbiased by dust.



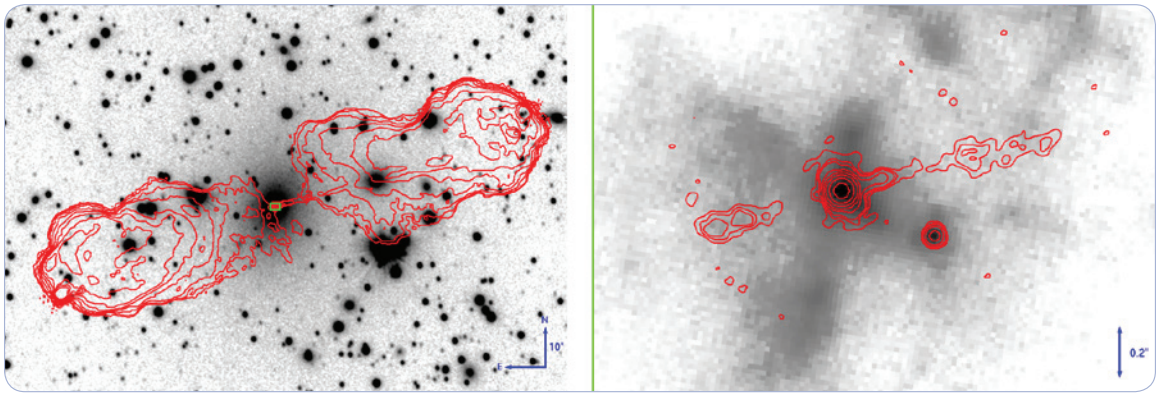
[Left] *A source detected in the 10 GHz Jansky VLA pilot observations.* **[Center, Right]** *HST Advanced Camera System z-band and Wide Field Camera 3 F160W images, respectively, with 10 GHz VLA contours overlaid. Each panel is 5 x 5 arcsec. These data illustrate the survey's ability to resolve the two cores in this merging galaxy pair at z = 1.2234.*

Publication: Eric J. Murphy (NRAO, IPAC) et al., *The GOODS-N Jansky VLA 10 GHz Pilot Survey: Sizes of Star-forming μJY Radio Sources,* 2017, Astrophysical Journal, 839, 35.

A Binary Supermassive Black Hole

D.A. Perley et al. report the serendipitous discovery of a new radio source at a projected offset of 460 parsecs from the nucleus of Cygnus A, one of the best-studied powerful radio galaxies. Cygnus A is the archetype of a class II radio galaxy, in which two powerful oppositely-directed jets of relativistic matter are observed to emanate from a central point source at the galaxy nucleus and terminate at bright hotspots in extensive edge-brightened radio lobes in the halo.

The flux density of the new source – designated Cygnus A-2 – rose from an upper limit of < 0.5 milli-Jansky in 1989 to 4 milli-Jansky in 2016 (ν = 8.5 GHz), but is currently not varying by more than a few percent per year. The radio luminosity of the source is comparable to the most luminous known supernovae, it is compact in Very Long Baseline Array observations down to a scale of 4 pc, and it is coincident with a near-infrared point source seen in pre-existing adaptive optics and HST observations. The most likely interpretation of this source is that it represents a secondary supermassive black hole in a close orbit around the Cygnus A primary, though an exotic supernova model cannot be ruled out. The gravitational influence of a secondary supermassive black hole at this location may have played an important role in triggering the rapid accretion that has powered the Cygnus A radio jet over the past 10^7 years.



[Left] *A wide-field image of the Cygnus A region. The background is Gemini Observatory optical imaging; the contours are VLA data at 2 GHz from 2015 November, showing the iconic jet and lobe structure.* **[Right]** *A zoom into the Cygnus A nuclear region. The background is Keck Observatory Adaptive Optics imaging from Canalizo et al. (2003). The radio contours are from a 35 GHz VLA image acquired in 2016 October. A distinct, luminous point source is detected 0.42 arcsec from the luminous nucleus in the radio and in the near infrared imaging.*

Publication: D. A. Perley (Liverpool John Moores University, University of Copenhagen) et al., *Discovery of a Luminous Radio Transient 460 pc from the Central Supermassive Black Hole in Cygnus A,* 2017, Astrophysical Journal, 841, 117.

U.S. RADIO-MILLIMETER-SUBMILLIMETER FUTURES

In 2015, the NRAO initiated the organization and execution of a series of three conferences for the astronomy community to enable broad discussion of potential U.S. futures for radio-millimeter-submillimeter (RMS) science in the 2020's and beyond. Funded by the Kavli Foundation and AUI, the third conference in this Kavli Conference Series – Futures 3 – was held 2–4 August 2017 at the David Brower Conference Center, Berkeley, California, U.S. with 85 scientists from universities, observatories, and laboratories from around the U.S. in attendance and representing virtually every field of modern astrophysics.

Futures I was held 15–17 December 2015 in Chicago and was structured around the key RMS science themes and community priorities identified in the Astro2010 Decadal Survey. This included fields where radio data was supporting other instruments, and those focused on possible standalone radio astronomy outcomes. 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 community and NRAO selected four areas for deeper discussion at the Futures 2 Conference, held 3–5 August 2016 in Baltimore: (1) a next generation VLA (ngVLA); (2) a Hydrogen Epoch of Reionization Array (HERA); (3) pulsar instrumental and scientific opportunities; and (4) the Cosmic Microwave Background (CMB). Parallel sessions broadly discussed potential RMS Flagship and small/midscale initiatives associated with these. Flagship options are major investments with widespread community benefit and support that would require funding by or on a scale comparable to the NSF Major Research Equipment and Facility Construction program; small/midscale initiatives are investments that might be funded via the NSF Mid-Scale Initiative Program.

Each of the Futures meetings featured excellent participation from across the astronomy community, including scientists whose research is concentrated in wavelength domains outside the radio. The focus of each of these conferences – "science" (Futures 1) to "options" (Futures 2) to "choices" (Futures 3) – has contributed towards the community's thinking for Astro2020.

The executive organizing committee formed and convened by NRAO, AUI, and the Kavli Foundation to define and guide the three-event Kavli Conference Series continued from Futures 1 and 2. The Local Organizing Committee (LOC) also continued from Futures 1 and 2.

Organizing Committee: Kavli Conference Series

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

Local Organizing Committee

- Karen Ransom (Chair)
- David Halstead
- Mark Adams

Sessions at Futures 2 broadly discussed potential RMS Flagship and Small/Midscale initiatives associated with the ngVLA, HERA, CMB, and pulsars. 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.

At the conclusion of Futures 3 and the conference series, four major themes emerged. each of which demonstrated great promise for the coming decade and beyond: (1) the CMB; (2) ngVLA; (3) pulsar science; and (4) Spectral-line cosmology / Epoch of Reionization. The community also expressed strong interest in an exciting range of midscale projects, reinforcing the importance of such efforts in a healthy community.

Moving forward to Astro2020, community and NRAO attention will now pivot to a more focused series of meetings, beginning in June 2018, that will be designed to realize the carefully considered RMS science and facilities choices made by the community via the Kavli Futures series. We thank the Kavli Foundation and AUI for their support of these important meetings.

Melissa Soriano (NASA JPL) speaking at the Futures 3 conference on 2 August 2017 at the David Bower Conference Center, Berkeley, California. Photo: David Halstead.

NORTH AMERICAN ALMA OPERATIONS

North 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 is responsible for multiple community programs for students and scientific professionals, including the Student Observing Support (SOS) program funded by North American ALMA and managed by the Science Support & Research (SSR) department.

Cycle 4 Supplemental 7-m Array Call for Proposals

On 6 April 2017, the ALMA Director announced that the JAO would accept observing proposals for the 7-m Array in the remainder of Cycle 4, which ended 30 September 2017. This enabled the community to propose projects for undersubscribed regions of the observing queue for the 7-m Array. Up to 800 hours on the 7-m Array was anticipated to be allocated through this opportunity.

Proposals could be submitted beginning 21 April 2017 and were reviewed as they were received. Instructions on how to submit a proposal through the ALMA Observing Tool were be made available on the ALMA Science Portal on 21 April 2017. Proposals could be submitted at any time through the end of Cycle 4 or until the available time was fully allocated.

The JAO received 198 proposals requesting a total of 4815 hours, an over-subscription rate of ~6. For comparison, for the Cycle 5 Call for Proposals, 62 proposals were received for the standalone Atacama Compact Array (ACA), also know as the Morita Array. Overall, the ACA was oversubscribed in Cycle 5 by a factor of ~4.

The supplemental proposals were reviewed by a committee that consisted of representatives from the Joint ALMA Observatory (JAO), the ALMA Regional Centers, and Chile. The primary criterion in assessing the proposals was the overall scientific merit of the proposed observations. The committee forwarded their scientific assessment to the ALMA Director, who made the decision on whether a proposal was scheduled. Review decisions were announced to the proposal teams in mid-June 2017.

A total of 32 proposals requesting 716 hours were accepted and added to the 7-m Array observing queue for the remainder of Cycle 4. The amount of time allocated was less than the 800 hours anticipated since snowstorms at the ALMA site in late May and early June 2017 adversely affected operations and reduced the amount of time available for science observations.

Cycle 5 Call for Proposals

In advance of the ALMA Cycle 5 Call for Proposals, the NAASC organized a series of ALMA proposal writing workshops at several North American institutions in March – April 2017. These events provided users with the knowledge required to carry out cutting-edge scientific research with ALMA. Reaching new users was a high priority.

These ALMA proposal preparation events were free, one- to two-day workshops designed in cooperation with institutions across North America, and hosted by experienced local postdocs as part of the ALMA Ambassadors program. The events included science talks, an introduction to submillimeter interferometry, and hands-on workshops designed to assist users in proposal preparation, observation planning, and data reduction for ALMA Cycle 5. Attendees needed to bring just a laptop to participate in the hands-on sessions. NRAO provided ready access to the free software, as well as a small dataset to be used in the demonstrations.

The ALMA Director, on behalf of the JAO and the partner organizations in East Asia, Europe, and North America, announced that the ALMA Cycle 5 Call for Proposals was open effective 21 March 2017, with a submission deadline of 20 April 2017. ALMA observing proposals were solicited for scientific observations to be scheduled from October 2017 to September 2018. The Call for Proposals announced the expectation that 12-m Array time and 3000 hours of ACA, in time would be allocated for successful proposals in Cycle 5.

New technical and observing capabilities in Cycle 5 included:

- Band 4 polarization observations;
- Band 5 spectral line and continuum observations, including all available polarization modes;
- 12-m Array configurations updated to reflect a minimum of 43 Array Elements; and
- compact configurations scheduled during the Chilean winter months to optimize high frequency proposal success.

The JAO received 1,661 proposals from the international community in response to the Cycle 5 Call for Proposals. The proposals were reviewed during an 18-23 June 2017 meeting in Antwerp. The review committee consisted of 146 Science Assessors grouped into 18 ALMA Review Panels (ARP) that 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).

The Review Panels in Categories 1-4 contained eight Science Assessors each; the Panels in Category 5 contained nine members each. Science Assessors were selected on the basis of scientific specialization while having regional affiliations that closely matched the nominal ALMA regional shares of observing time.

The 18 Panel Chairs served on the ALMA Proposal Review Committee (APRC) together with the APRC Chair, Anneila Sargent. The Review Panels conducted the initial scientific reviews and recommended which Large Proposals should be further discussed by the APRC. The APRC conducted the final review to recommend which Large Programs should be scheduled.

The JAO created an observing queue and assigned a priority grade to each proposal after considering the scientific rank determined from the review process, the share of observing time for each region, and scheduling feasibility. Priority Grade A was assigned to the highest ranked proposals. Grade B was assigned to high ranked proposals while maintaining balance of time across Grade A and B. Grade C was assigned to proposals that oversubscribed the time in a configuration by up to 50%.

Of the 1,661 submitted proposals, 132 received the highest priority of Grade A, 301 received Grade B, and 262 received Grade C. The Grade A and B proposals requested an estimated 3706 hours of execution time on the 12-m Array. Together with the estimated 300-400 hours of Cycle 4 Grade A proposals that were carried forward to Cycle 5, this constituted the 4000 hours of 12-m Array time expected to be available for successful executions in Cycle 5.

A detailed report on the ALMA Cycle 5 selection statistics can be downloaded from the ALMA Science Portal, http://almascience.nrao.edu

Cycle 6 Call for Proposals

A pre-announcement for the ALMA Cycle 6 Call for Proposals was published to the ALMA Science Portal on 18 December 2017. Information on the Cycle 6 configuration schedule will appear at the ALMA Science Portal on 1 February 2018.

Capabilities to be offered for ALMA Cycle 6 include:

- Circular polarization proposals for Bands 3, 4, 5, 6, and 7 in all (including circular) polarization modes for continuum and spectral-line observations.
- Band 8 as a standard mode.
- Band 6 IF bandwidth increased by 0.5 GHz, enabling ^{12}CO, ^{13}CO, and $C^{18}O$ J=2-1 to be observed simultaneously within broader spectral windows for Galactic sources and nearby galaxies.

New ALMA Director

After a competitive selection process that began in January 2017, the international governing board of ALMA selected Dr. Sean Dougherty as the new ALMA Director for a five-year term beginning in April 2018.

Dougherty has been the director of the Dominion Radio Astrophysical Observatory, Canada's national radio astronomy facility, run by the National Research Council – Herzberg Astronomy and Astrophysics. He has served as a member of the ALMA Board representing North America for four years and was the chair of the ALMA Budget Committee for the last two years.

Dougherty received his bachelor's degree in mathematics and physics from the University of Nottingham, England and his Ph.D. in astrophysics from the University of Calgary, Canada.

Dougherty has more than 20 years of science and engineering management experience in radio astrophysics. This includes Canada's contributions to international radio astronomy facilities and Research & Development projects as well as leadership of major science and engineering activities at the Dominion Radio Astrophysical Observatory. He also led the construction and delivery of the Wideband Interferometric Digital Architecture Correlator (WIDAR) for the Karl G. Jansky Very Large Array and the international consortium designing the correlator and beamformer for the Square Kilometre Array (SKA).

Upon making this selection, the ALMA Board extended its appreciation to Dr. Stuartt Corder for his service as the ALMA Acting Director during the transition process.

ALMA Development Program

ALMA Development Program upgrades typically progress through three development phases corresponding to increasing technological readiness:

- Conceptual study (including scientific justification, specification, and outline costing)
- Prototype/pre-production
- Production and implementation.

The ALMA Development Cycle 5 Call for Proposals solicited proposals for Projects and Studies in three categories:

- **Project:** a large-scale (typically $1M+), multi-year initiative involving relatively mature technology which may lead to full implementation in the ALMA Observatory.
- **Strategic Study:** a mid-scale (≤ $0.4M) two-year investigation of an emerging technology of specific, strategic interest which may lead to a Development Project.
- **General Study:** a small-scale (≤ $0.2M), one-year investigation of an emerging technology of general interest which may lead to a Development Project.

Unlike Development Calls for Proposals in preceding years, the call release dates for Cycle 5 projects and studies differed, and were staggered due to the difference in the approval process for studies and projects. A Call for Project Proposals was released 10 October 2016 for proposals due 30 January 2017. A Call for Study Proposals (Strategic and General) was released 1 March 2017. Notifications of project down-selection and study awards commenced 31 July 2017.

New ALMA Development Projects

Following an evaluation process that included rankings by independent referees and discussion with the NSF, two Cycle 5 Development Projects were provisionally selected for funding, pending ALMA Board approval.

- *A Significant Upgrade to the ALMA 64-Antenna Correlator,* Principal Investigator (PI) R. Lacasse (NRAO), $10.9M
- *Enabling New Science with the ALMA Phasing System,* "Phase 2", PI L.. Matthews (MIT), $0.954M

Down-selected project proposals were forwarded to the ALMA Management Team (AMT), which includes representatives of the three ALMA Partners and the JAO. The AMT collaborates with the PI, the ALMA Development Program Manager, the JAO Observatory Scientist, the JAO Observatory System Engineer, and the appropriate ALMA Integrated Product Team(s) to:

- Assess the science case and its relevance for the vision and aims of the ALMA Development Program;
- Prepare a refined Implementation Plan (schedule and budget);
- Prepare a Technology Readiness Assessment that determines if the proposed project is technically feasible;
- Prepare an Operational Impact Assessment that defines requisite facilities and estimates the total life-cycle cost of the project including operation, maintenance, decommissioning and telescope time; and
- Consider the development capabilities in the Partnership regions so that ALMA enhancements and renewal can be sustained in the long-term.

The project titled *A Significant Upgrade to the ALMA 64-Antenna Correlator* was revised based on discussions with the AMT and was re-scoped to achieve a successful Preliminary Design Review (PDR) in 2018. Following the PDR, the Correlator Upgrade resolution increase implementation proposal is expected to proceed to ALMA Board approval. The project titled *Enabling New Science with the ALMA Phasing System, Phase 2* (PI L. Matthews) progressed towards ALMA Board approval in November 2017.

New ALMA Development Studies

Two Cycle 5 General Studies were funded and commenced 1 October 2017.

- *Full-Mueller Mosaic Imaging with ALMA,* PI S. Bhatnagar (NRAO), $0.197M
- *Neuroscope: Neural Machine Intelligence Tools for Discovery and Interpretation in Complex ALMA Data,* PI E. Merenyi (Rice), $0.182M

Two Cycle 5 Strategic Studies were funded and commenced in 2017.

- *Wideband Low-Noise Balanced IF Amplifiers for ALMA Band 6, with Future Application to ALMA Bands 3-10,* PI Kerr (NRAO), $0.300M
- *Quantum-Limited Very-Wideband 4-Kelvin RF and IF Amplifiers for ALMA,* PI O. Noroozian (NRAO), $0.399M.

Ongoing ALMA Development Projects

Fiber Optic Project – JAO

The ALMA Observatory to Santiago fiber optic link is fully functional and operating pursuant to a temporary permit. The project remains open for administrative purposes while the final operating permit is being processed by the Chilean Ministry of National Assets.

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

This project procured and tested all the required modules and equipment to complete Photonic Local Oscillator subarray five. The complete chain was installed, tested, and commissioned at the Array Operations Site (AOS) Technical Building. The completed system was integrated into the software control system and a final report was submitted October 2017.

Design and Testing of a Prototype Band 2 Cartridge – NRAO

A Band-2 (67–90 GHz) Prototype Cartridge Preliminary Design Review held 30-31 May 2017, granted approval to proceed to detailed design. A Cycle 5 project proposal for a Band 2+ project was well rated but was not selected to proceed.

Band 3 CCA Magnet and Heater Installation for Deflux Operations – NRC

This project is evaluating the use of a heater installed in the Band 3 Cold Cartridge Assembly (CCA) to reduce observed azimuth-dependent total power variations. The heater solution was successfully tested at NRC-Herzberg and has been undergoing verification testing by the JAO. However, the efficacy of the solution has yet to be proven since there has been no recurrence of the total power variations. NRC-HIA is preparing an implementation plan to complete the heater kits in accordance with ALMA Operations Hardware Upgrade processes.

Completed ALMA Development Studies

The following seven ALMA Development Studies were completed in 2017.

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

This study defined pulsar phasing and data modes using the ALMA Phasing Project and developed software for resampling and reformatting for use in pulsar and transient search and timing pipelines. Test data was 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 were used.

Feature Extractions and Visualization of ALMA Data Cubes – University of Utah

This study used 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, the overall data load can be reduced in a mathematically robust manner. Visualizations were designed to be intuitive, informative, and interactive and the visual analysis preserves and presents structures within the data to support scientifically meaningful analytic tasks.

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

This study investigated 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 required to realize a future Band 11 receiver.

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

The ALMA Phasing Project provided hardware and software to coherently sum the signals of up to 61 ALMA antennas in Bands 3 or 6 and record the resulting data stream in VLBA Data Interchange Format. This phasing capability permits ALMA to function as the equivalent of a single large-aperture dish with collecting area sufficient to boost global VLBI experiment sensitivity operating at millimeter and submillimeter wavelengths by an order of magnitude.

Improving the Calibration of Atmospheric Spectral Features – NRAO (Cycle 3)

The atmospheric calibration of ALMA science data is performed with the correlators operating in a coarse spectral resolution mode, the effect being 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 investigated a method to reduce or eliminate these features using an online software module.

Spectral Resolution and Bandwidth Upgrade of the ALMA Correlator – NRAO

This study developed the integration consequences, cost, and labor requirements for increasing the spectral resolution of the 64-antenna ALMA correlator by a factor of eight. Present modes achieve frequency resolution adequate for resolving the narrowest thermal lines known at 100 GHz. Higher resolution is needed at the lowest frequencies that will soon come online, since narrow line widths in these bands require narrower frequency bins and at present are insufficiently resolved. A preliminary design, construction timelines, and cost estimates, along with key design simulations led to the successful submission of a Cycle 5 project proposal already described.

Development of 2nd Generation SIS Receivers – NRAO

This study continued 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 IF. This study continued work supported under earlier ALMA development studies. Several of the proposed developments are expected to be applicable to second generation receivers in the higher-frequency ALMA bands which use SIS mixer receivers.

Ongoing ALMA Development Studies

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

The ALMA correlator technologies are a decade old. This study will investigate improvements of bandwidth, spectral resolution, and integrate native features such as phased array recording for VLBI and pulsar work. This same upgrade may substantially reduce the required power and ALMA correlator size. A conceptual design – including recommendations on the specifications and technologies and estimates of schedule and cost – is being developed that will serve as the basis for follow-on work building the next generation combined correlator and ALMA phased array system.

Cleaning Up Interactive Cleaning – University of Alberta

This study is developing a new interactive cleaning tool based upon the tools created by the Cube Analysis and Rendering Tool for Astronomy (CARTA) project. The new tool will interface with the CASA clean tasks and will provide a simple messaging interface between computational processes.

Total Power Map to Visibilities – Stony Brook University

This study is developing a software tool (TP2VIS) that implements the joint-deconvolution of ALMA 12m, 7m, and Total Power array data on the Common Astronomy Softwarer Applications (CASA) platform. Combining data from the ALMA arrays is a critical driver for scientific topics that simultaneously probe size scales of extended and compact structures. This study gives ALMA users immediate access to joint deconvolution. TP2VIS is being built using the existing CASA toolkit.

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

This study is enhancing and expanding the capabilities of the ALMA Phasing System (APS) without requiring 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. These changes add capability while leaving existing software intact. This study will enhance the APS flexibility and significantly diversify the science applications of this new capability.

Prototype Dual-Linear 2SB Block and Single-Polarization Balanced 2SB Block – NRC-Herzberg

This study is designing, fabricating, and evaluating prototypes for dual-linear and single polarization double-sideband (2SB) block assemblies. Prototype-1 explores possible improvements in image rejection, narrowband noise temperature, and integration. Prototype-2 evaluates the added advantages of a balanced receiver. Measurements will be completed using a spare ALMA Band 3 receiver cartridge and test set available at NRC-Herzberg.

Digital Back End Article – NRAO

This study is evaluating the design and feasibility of a Digital Back End Antenna Article to replace the existing article with a simplified, robust, and flexible set of digital hardware. The study will develop an implementation plan for an array-ready product that can double the processed bandwidth to 16 GHz dual-polarization IFs or 32 GHz of a single IF. This path will integrate with other Front End and Correlator developments, keeping ALMA at the forefront of astronomy.

Photo by Pablo Carrillo

NEW MEXICO OPERATIONS

Photo by Jeff Hellerman

NRAO – New Mexico Operations is responsible for the operation, maintenance, and further development of the Karl G. Jansky Very Large Array (VLA). The Jansky VLA consists of twenty-seven 25-meter diameter antennas laid out in a Y-shaped configuration on the Plains of San Agustin in west-central New Mexico. The original VLA was dedicated in 1980 and has been one of the most scientifically productive telescopes in the world throughout its existence.

The VLA underwent a major upgrade in 2002-2012 via the Expanded Very Large Array Project which: (a) increased the bandwidth of the VLA receiving systems; (b) enabled continuous frequency coverage from 1 to 50 GHz in eight contiguous frequency bands; (c) replaced the waveguide data transmission system with a fiber optic-based system; (d) provided a new, wide bandwidth correlator; and (e) developed the software tools and processes for complete dynamic scheduling, maximizing the array's observing efficiency. The NRAO delivered this major upgrade on time, on budget, and to specification, and full science operations capability with this essentially new instrument were initiated in January 2013.

Throughout 2017, the NRAO continued to provide a suite of robust and scientifically powerful observational capabilities on the VLA that are tailored to address the highest priority science of the astronomy community. The availability of these capabilities is made possible through a wide variety of operational, maintenance, and development activities performed by a dedicated VLA staff.

Two major science initiatives were high priorities in NRAO New Mexico Operations in 2017:

- a new VLA Sky Survey (VLASS) of the entire northern sky at S-band; and
- development of a next generation VLA (ngVLA) design concept.

VLA Sky Survey

In the 20 years since the observations were acquired for the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST), these pioneering programs have defined the state-of-the-art in centimeter radio sky surveys and produced a steady stream of excellent science. Given the enhanced capabilities of the Jansky VLA, it seemed an appropriate time to exploit the dramatic scientific potential of a new centimeter-wavelength sky survey.

The astronomy community recognized that several of the high priority science goals of the 2010 decadal survey in Astronomy and Astrophysics could be addressed by a new VLA sky survey. Many community members expressed keen interest in using the VLA to conduct new, wide-area centimeter wavelength sky surveys in support of multi-wavelength synoptic surveys at existing and future facilities, such as the Large Synoptic Survey Telescope (LSST). A community-led Science Survey Group (SSG) was organized by the NRAO to define the science program and key components of a new VLA Sky Survey (VLASS).

After detailed consultation and input from the broad astronomy community, comprehensive planning, and multiple reviews, a VLASS pilot survey was conducted May – September 2016 to test key aspects of the data acquisition and processing. The pilot survey properties included:

- S-band (2-4GHz)
- 1024 channels of 2 MHz width
- B-array configuration (2.5" resolution)
- Observing mode: On-the-Fly (OTF) mosaics scanning in right ascension at constant declination
- Mapping speed ~20 degress / hour
- 196 hours duration

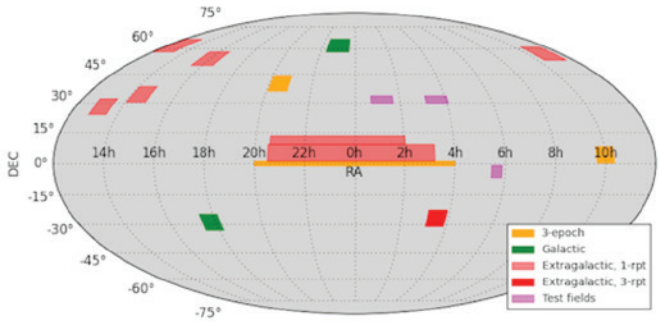
The success of the pilot survey and additional consultation and iteration with the community led to the initiation of observations for the full VLA Sky Survey (VLASS) on 7 September 2017. The following table summarizes the survey goals and characteristics.

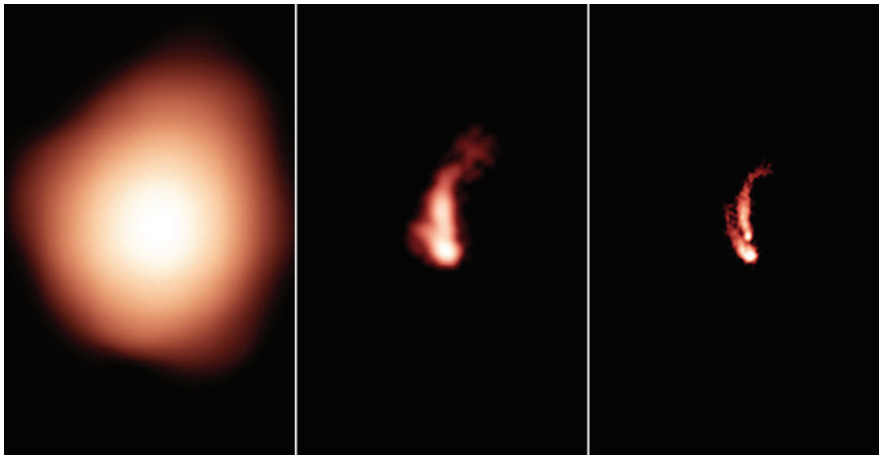
VLASS Goals & Characteristics	
Frequency	**2 - 4 GHz**
Resolution	**2.5 arcsec**
Sky coverage	**All Sky North of Dec. -40° (33,885 deg^2)**
Sensitivity per epoch	**120 µJy r.m.s.**
Combined (3 epoch) sensitivity	**69 µJy r.m.s.**
Polarization	**I, Q, U**
Cadence	**3 epoch each separated by 32 months**
Start Date	**7 September 2017**
Expected number of sources	**~5,000,000**

Using an improved and enhanced Common Astronomy Software Applications (CASA) package Calibration Pipeline, and a new Imaging Pipeline, NRAO will create and make available a range of Basic Data Products (BDPs) for the survey through the NRAO archive, including:

- Raw visibility data (available immediately)
- Calibration tables (within 1-2 weeks of observation)
- Quicklook 2D Stokes I images (within 2 weeks of observation)
- 2D images in Stokes I (per epoch and cumulative; available ~6-12 months after observations)
- RMS images
- Coarse resolution cubes (128 MHz channels, IQU polarization) around ~10^6 bright sources
- Fine resolution (16 MHz channel, IQU polarization) cubes around the ~50000 brightest sources
- Catalogs of source components from both the 2D images and the cubes.

Quick Look images – 1 arcsec per pixel scale, Stokes I continuum – are posted to the VLA Sky Survey Resources web page as soon as they have passed quality assurance. Better sampled images in Stokes I, Q, and U, spectral index maps, and spectral cubes around bright sources (also in Stokes IQU) will be made available on a timescale of 6–12 months.





[Left] *A radio galaxy observed with the NRAO VLA Sky Survey (NVSS; left), the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey (middle), and the new VLA Sky Survey (right), illustrating the improvement in resolution being achieved with the new survey.* **[Above]** *VLASS Pilot Sky Coverage.*

Next Generation Very Large Array (ngVLA)

Inspired by dramatic discoveries from the Jansky VLA and ALMA, the astronomy community has initiated discussion of a future large area radio array optimized for imaging of thermal emission to milli-arcsecond (mas) scales that will open new discovery space from proto-planetary disks to distant galaxies.

This Next Generation Very Large Array (ngVLA) is envisioned to include:

- 10x the collecting area of the Jansky VLA and ALMA;
- science operations from 1.2 - 116 GHz;
- 10x longer baselines (300 kilometers) that yield milli-arcsecond resolution; and
- a dense antenna core on kilometer-scales for low surface brightness imaging.

The ngVLA is envisioned to be an interferometric array with ten times the sensitivity and ten times higher spatial resolution than the Jansky VLA and ALMA. It will be optimized for observations at wavelengths between the exquisite performance of ALMA in the submillimeter, and the future SKA-1 at decimeter to meter wavelengths, and will thus be complementary with these facilities. In doing so, the ngVLA will open new windows on the Universe via ultra-sensitive imaging of thermal line and continuum emission to milli-arcsecond resolution, as well as unprecedented broad band continuum polarimetric imaging of non-thermal processes.

A workshop on *Developing the ngVLA Science Program* was held in Workman Center on the New Mexico Tech campus in Socorro, New Mexico, 26 – 29 June 2017. Registration exceeded the capacity of the venue, and 150 people participated in the workshop. The program consisted of contributed and invited talks highlighting recent results from existing instruments – such as the Jansky VLA and ALMA – and discussed how these results inspire and influence planning for the ngVLA. The synergies between the ngVLA and future major astronomical facilities were also discussed, including the James Webb Space Telescope, Large UV/Optical/Infrared Surveyor, Habitable Exoplanet Imaging Mission, Origins Space Telescope, Lynx, Large Synoptic Survey Telescope, Extremely Large Telescopes, and the Square Kilometre Array.

Status reports on the ngVLA Community Studies were presented, with the first day of the workshop dedicated to reports on technical design studies and the following days to reports on science design studies.

On the final day of the workshop, the ngVLA Science Working Groups (SWGs) evaluated the relative importance of various design alternatives to their Key Science Goals. The SWG co-chairs reported on their findings, which were in turn used to refine the ngVLA concept recently summarized in ngVLA Memorandum 17.

The NRAO Education and Public Outreach department hosted a workshop reception that featured professional artists specializing in artwork based on astronomy and space science themes. The artists attended the entire workshop with the goal that discussions during the meeting would inspire work that will convey the excitement of the ngVLA to a broader audience.

Participants in the Developing the ngVLA Science Program *workshop.*

Community Studies

Given the success of the first round of ngVLA Community Studies, a second round was initiated to tackle some of the most pressing questions unveiled by the initial studies. The primary objective for this second round of community studies was to further develop the Key Science Goals.

Twelve scientific studies were approved in October 2017 via this second round (see Table below). All accepted Community Studies publish their findings as part of a peer-refereed journal article or ngVLA memo, and present their progress or final results at the *Astronomy Frontiers in the next Decade and Beyond* conference, 26-29 June 2018 in Portland, Oregon.

Approved ngVLA 2nd Round Community Studies

PI (affiliation)	Proposal Title
Sarah Burke Spolaor (WVU)	Exploring Nanohertz Multi-messenger Capabilities of the ngVLA
Laura Chomiuk (Michigan State)* and Tom Maccarone (Texas Tech)*	The Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy
Richard Dodson (ICRAR, UWA)	Enhancing ngVLA capabilities using multiple frequencies
Justin Linford (George Washington)*	Classical Novae: A Test Case for ngVLA Stellar Outflow Imaging Capabilities
Liton Majumdar(JPL)	HOCO+ Emission as a Diagnostic of Planet-forming Regions of Disks: Bridging ngVLA and JWST
Carl Melis (UCSC)*	Astrometry with the ngVLA
Kristina Nyland (NRAO)	Imaging Fidelity and Detectability of Cold Gas with the ngVLA
Luca Ricci (CSUN/JPL)*	Witnessing the Origin of Solar System Analogues with the ngVLA
Mark Sargent and Anna Cibinel (University of Sussex)	Tracing the Build-up of Mass Inside Galaxies: Using ngVLA to Map the SFR Distributions of Distant Galaxies
Sascha Schediwy (ICRAR, UWA)	Phase Synchronization of the ngVLA
Gregory Taylor (UNM)*	Taking a Census of Supermassive Binary Black Holes with the ngVLA
Peter Teuben (U. Maryland)* and Daniel Dale (U. Wyoming)*	Short Spacing Issues for the Mapping of Milky Way Extended Emission and Nearby Galaxies

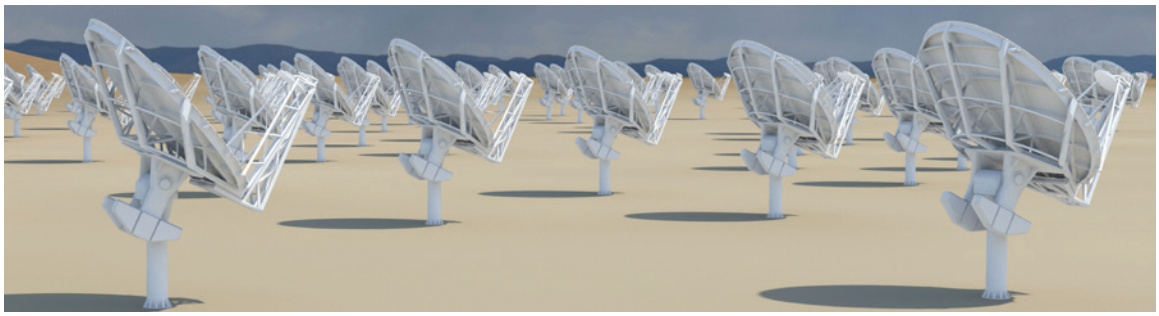
**Requested and approved for additional funding.*

Science Book

The ngVLA Science Book is in preparation and is a major deliverable to the Astronomy 2020 Decadal Survey. This science volume is being crafted by the ngVLA Science Advisory Council, in consultation with the astronomical community at large, and the ngVLA Project Scientist. The volume will provide an extremely useful summary of the ngVLA Key Science Mission for Astro2020 panel members, as well as demonstrate the Project's firm handle on the associated technology requirements and cost, and will be published in the Astronomical Society of the Pacific monograph series. This will ensure that the book and individual chapters will be listed in the SAO/NASA Astrophysics Data System for maximum visibility to the Astro 2020 panel members.

First Draft chapters are due to either SWG chairs or the ngVLA project scientist by 31 March 2018. Additional contributions for the final book will likely be solicited at this time.

Design & Development Support



Beginning in October 2017, the NSF approved $11M of funding to support design and development activities focused on the ngVLA. These funds will further develop the instrument scientific and technical definition, define major costs and technical needs associated with the project, and enable the participation of other major groups within the Observatory, such as the Central Development Laboratory. A key use of the funding will be exploration of the high-performance antennas required to enable the array science.

Funding for the new initiative was enabled by the NSF – Division of Astronomical Sciences allowing NRAO to re-profile $11M in funding planned for instrument development over a longer time period into a focused two-year effort. This NSF decision allows NRAO to accelerate the early design studies. This will enable the ngVLA concept to be more fully developed for the next U.S. astronomy Decadal Survey, commencing in 2019-2020, where all major new instrument and capabilities proposals will be considered by the research community. The NRAO is discussing ngVLA partnership opportunities with scientific colleagues in the U.S. and around the world.

6th VLA Data Reduction Workshop

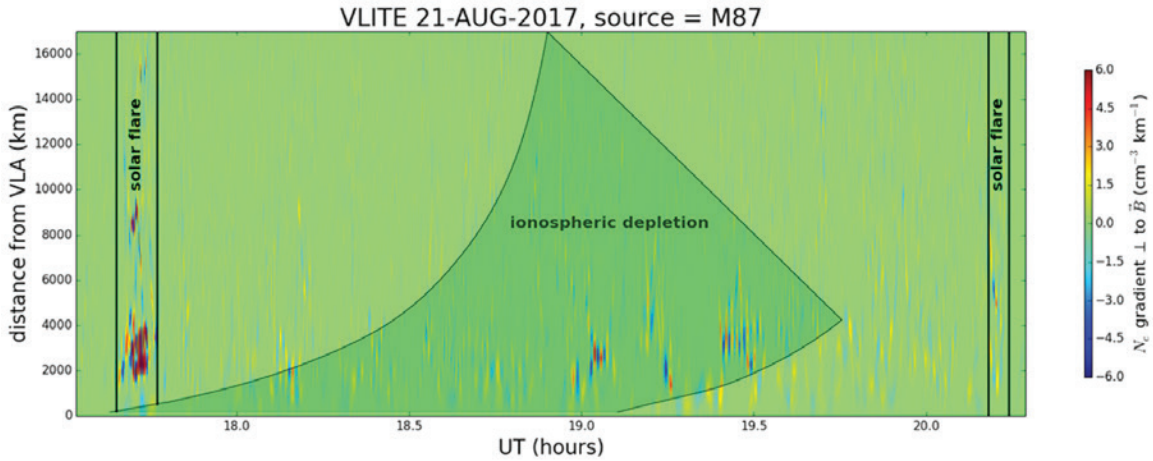
The 6th VLA Data Reduction Workshop was held 23-27 October 2017 in Socorro, New Mexico. The main goal of this Workshop was to assist observers with the challenges of VLA data reduction posed by the increased flexibility and complexity of the instrument. NRAO scientific staff provide lectures on key topics and allow participants to reduce some of their own data while local expert staff is available for consultation. This was an advanced Workshop and, it complements the bi-annual summer

NRAO Synthesis Imaging Workshop, which is targeted at persons unfamiliar with radio interferometry. Prior experience with the Astronomical Image Processing System (AIPS), the Common Astronomy Software Applications (CASA) package, or the Multichannel Image Reconstruction, Image Analysis and Display (MIRIAD) was required.

VLITE Finds Disturbed Ionosphere in Solar Eclipse Wake

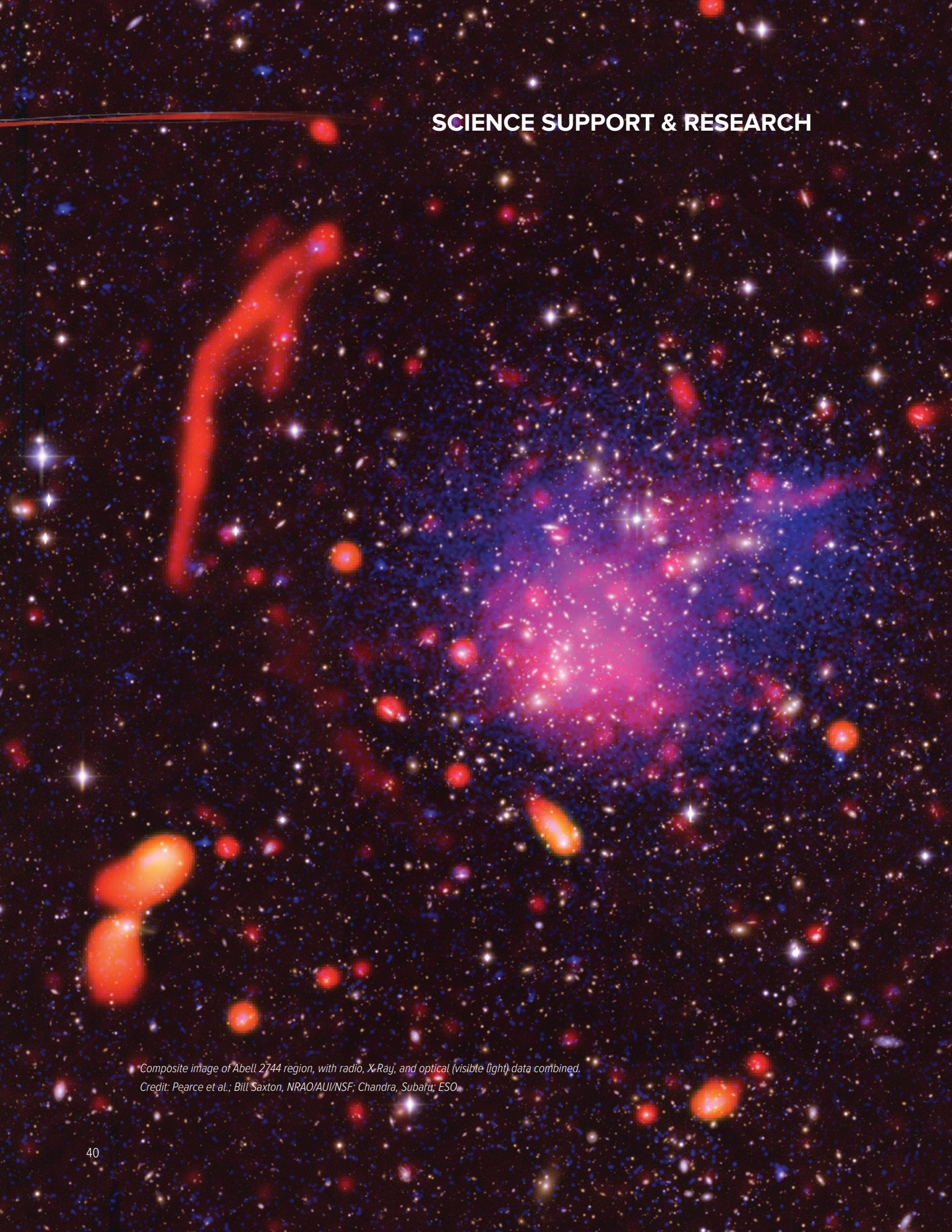
On 21 August 2017, Americans across the continental U.S. were treated to an event not seen for several decades: a total solar eclipse. While many citizens enjoyed the spectacle from backyards and road-trip destinations throughout the country, observatories focused their "eyes" on the Sun as well. The Jansky VLA was no exception, observing the Sun at multiple frequencies before, during, and after the eclipse. However, the VLA also simultaneously conducted a unique set of observations aimed at characterizing the effects of the eclipse on Earth's ionosphere / plasmasphere. This work was conducted by Joe Helmboldt (Naval Research Laboratory, NRL), Frank Schinzel (NRAO), and other members of the NRL VLA Low-band Ionosphere and Transient Experiment (VLITE) team.

While most of the VLA antennas were pointed at the Sun, 12 antennas observed the bright radio galaxy M87. These 12 antennas are part of VLITE, a dedicated backend that continuously captures, correlates, and analyzes data at 320-384 MHz. In addition to traditional synthesis imaging, VLITE characterizes fluctuations in ionospheric / plasmaspheric density via measured variations in visibility phases. When observing a bright cosmic source, this can be done with unmatched precision, the equivalent of ~1-10 ppm.



To look for ionospheric / plasmaspheric disturbances tied to the eclipse, a specialized spectral decomposition was applied to the M87 VLITE data. This method exploits the fact that disturbed flux tubes within the plasmasphere appear to the VLA as magnetic eastward-directed waves because the plasmasphere is dynamically dominated by co-rotation. The phase speeds of these waves are proportional to distance, allowing for a reconstruction of the electron density gradient as a function of (slant) range and time. The range / time image for the M87 VLITE data is shown in the figure above. The time ranges spanned by the large-scale ionospheric depletion seen within concurrent Global Positioning System (GPS) data as a function of longitude were mapped to the imaged flux tubes and are shaded in dark green. With the exception of some solar flare-induced fluctuations, the observed disturbances appear confined to this part of the image. This strongly implies the disturbances resulted from the rapid depletion and slower recovery of the ionosphere / plasmasphere system brought on by the eclipse. These disturbances are not apparent within the GPS data, highlighting VLITE as a uniquely capable ionospheric / plasmaspheric disturbance hunter.

SCIENCE SUPPORT & RESEARCH



Composite image of Abell 2744 region, with radio, X-Ray, and optical (visible light) data combined.
Credit: Pearce et al.; Bill Saxton, NRAO/AUI/NSF; Chandra, Subaru; ESO.

The NRAO Science Support and Research (SSR) department coordinates, aligns, and manages the collective efforts across NRAO sites to support science users of NRAO facilities, to broaden the Observatory's impact through education and visitor programs, and to oversee the research and performance of the scientific staff. It does so through two groups:

- Telescope Time Allocation (TTA) manages the process and tools by which users prepare and submit proposals for use of the VLA and, through Service Level Agreements (SLAs) with the GBO and LBO, the GBT, and VLBA, respectively. TTA also manages the proposal evaluation and time allocation process.

- Scientific User Support (SUS) is responsible for providing the scientific community with the support necessary to execute successful scientific programs with NRAO facilities.

In addition, SSR provides two observatory-wide services: (1) NRAO Reference comprises the NRAO Library and the Historical Archives; and (2) Statistics and Metrics aggregates data for internal use and to report various metrics to the NSF, to AUI, and to external review committees. Key Observatory Performance Metrics are given in Section 12 of this Annual Report.

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

Jansky Fellowships

The NRAO Jansky Fellowship program supports outstanding postdoctoral scientists whose research is broadly related to the mission and scientific goals of the NRAO. Jansky Fellows formulate and carry out investigations either independently or in collaboration with others within the wide scientific framework of interests of the Observatory. The program is open each fall to candidates with interest in radio astronomy, instrumentation, computation, and theory, and prior radio experience is not required. Multi-wavelength projects leading to a synergy with NRAO instruments are encouraged. Three new Jansky Fellows joined NRAO in 2017.

Kazunori Akiyama is a Jansky Fellow at the MIT Haystack Observatory. He completed his Ph.D. at the University of Tokyo under the supervision of Mareki Honma and was previously a Japan Society for the Promotion of Science fellow at Haystack. Kazunori studies the immediate environment of the supermassive black holes in our Galactic Center, Sagittarius A*, and Messier 87 with the Event Horizon Telescope (EHT). Kazunori is also developing new EHT imaging algorithms to create the first images of black holes.

Kunal Mooley is a Jansky Fellow with a joint appointment at NRAO in Socorro and Caltech. During his Ph.D., Kunal worked on transient surveys with the VLA, and after receiving his degree in May 2015, went to Oxford as a Hintze Research Fellow to expand his transient program using other telescopes such as the Arcminute Microkelvin Imager and Giant Metrewave Radio Telescope. Kunal has expertise in the study of Galactic and extragalactic transients, the execution of radio surveys, and with rapid multi-wavelength follow-up observations. With his Jansky Fellowship, Kunal will leverage the VLA Sky Survey to study hidden explosions, and will use the Jansky VLA mapping of Gravitational Wave bursts as Afterglows in Radio program on the VLA to search for the radio afterglows of neutron star mergers.

Nithyanandan Thyagarajan is a Jansky Fellow at NRAO in Socorro. He received his Ph.D. from Columbia University working with David Helfand on identifying and characterizing one of the largest compilations of radio transients to date from the VLA

Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey. His current research focuses on characterizing the factors that determine the sensitivity of low frequency cosmology experiments, such as the detection of redshifted neutral hydrogen from the Epoch of Reionization (EoR). At NRAO, he is contributing to designing instruments and experiments for a first successful EoR detection, implementing a novel radio interferometry architecture that has the efficiency and versatility to image and process data from hundreds to thousands of receiving elements while simultaneously addressing the challenges of computational cost and data throughput faced by large arrays of next-generation radio telescopes.

Telescope Time Allocation: Semester 2017B

A total of 187 new VLA proposals were received by the 1 February 2017 submission deadline for Semester 2017B. The oversubscription rate (by proposal number) was 2.9 and the proposal pressure (hours requested over hours available) was 2.0. A number of large, time-critical (triggered) and multi-observatory proposals were received.

The Semester 2017B 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 2017 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 18–19 April 2017 at NRAO in Socorro, New Mexico. The TAC – comprising the eight SRP chairs – was charged with recommending a science program for Semester 2017B to the Observatory Director. The recommended program was reviewed and approved on 3 May 2017.

A disposition letter was sent to the principal investigator and co-investigators of each proposal on 12 May 2017 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.

Telescope Time Allocation: Semester 2018A

A total of 259 new VLA proposals were received for the 1 August 2017 submission deadline for Semester 2018A. The oversubscription rate (by proposal number) was 2.2 and the proposal pressure (hours requested over hours available) was

1.8. One large and 30 time-critical (triggered) proposals were received. There was significant demand for the time made available on space observatories through inter-observatory agreements, and 26 proposals requesting time on the Hubble Space Telescope, Swift, or Chandra X-ray Observatory (together with AUI/NRAO telescope time) were submitted.

The proposals were reviewed for scientific merit by eight SRPs and for technical feasibility by NRAO staff. These reviews were completed in September–October 2017 and then considered by the TAC at a face-to-face meeting on 24–25 October 2017 at the Green Bank Observatory in West Virginia. The TAC – comprising the eight SRP chairs – was charged with recommending a science program for Semester 2018A to the Observatory Director. The recommended program was reviewed and approved on 7 November 2017. (Proposals submitted to the GBO and LBO were assessed through the same process.)

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 13 November 2017, 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.

Student Observing Support Awards

The NRAO Student Observing Support (SOS) Program supports research at U.S. colleges and universities by students working on approved ALMA or Jansky VLA programs. The program currently supports about 12 students for each ALMA Cycle and about three students for each VLA semester, providing up to $35,000 per award. The overall success rate of SOS proposals has been almost 50% in recent calls.

The SOS committee, an external panel, made the following awards for ALMA Cycle 5.

- Bandon Decker (Univ. Missouri-Kansas City; supervisor Mark Brodwin), *ALMA Observations of the Most Massive Galaxy Clusters at z > 1*
- Molly Gallagher (Ohio State Univ.; supervisor Adam Leroy), *A Wide, Deep Dense Gas Map of M100 to Connect Extragalactic and Galactic Dense Gas Results*
- Rachel Harrison (Univ. Illinois; supervisor Leslie Looney), *Morphology of Polarization in T Tauri Stars: What the Flux?*
- Sreevani Jarugula (Univ. Illinois; supervisor Joaquin Vieira), *Resolving water emission in the early universe*
- Andy Lam (Univ. Virginia; supervisor Zhi-Yun Li), BOPS: *B-field Orion Protostellar Survey*
- Jed McKinney (Univ. Massachusetts Amherst; supervisor Alexandra Pope), *Science with ALMA and JWST: Tracing the Heating and Cooling in Star Forming Regions in Galaxies at Cosmic Noon*
- Ismael Mireles (Wesleyan Univ.; supervisor Meredith Hughes), *Measuring the Chemical Composition of Molecular Gas in the Debris Disk around 49 Ceti*
- Nickalas Reynolds (Univ. Oklahoma; supervisor John Tobin), *Are Close Binaries Formed Through Disk Fragmentation?*
- Yohan Yea Seang (Univ. Delaware; supervisor Sarah Dodson-Robinson), *eta Crucis campaign*
- May Wang (Harvard-Smithsonian Center for Astrophysics; supervisor Qizhou Zhang), *Are Magnetic Fields Dynamically Important in Massive Star Formation?*
- David Setton (Univ. Pittsburgh; supervisor Rachel Bezanson), *How universal are surprisingly significant molecular gas reservoirs in massive post-starburst galaxies at z~0.6?*

NRAO–GBO Summer Student Workshop

NRAO and the Green Bank Observatory (GBO) summer students visited Green Bank, West Virginia 5–9 June for the 2017 Summer Student Workshop, affectionately nicknamed the Radio Astronomy Bootcamp. The students attended lectures on radio astronomy fundamentals from NRAO and GBO staff, learned about instrumentation and observatory operations, and enjoyed several science talks, including a keynote presentation by Duncan Lorimer (West Virginia University) on Fast Radio Bursts. The students also participated in team-based observing projects, received an introduction to pulsar data analysis, and toured the Green Bank Telescope and the Green Bank site. Discussions on career building and applying to graduate school were high points for many of the attendees. After hearing tips on public speaking, each student team gave a presentation on their observing project to their classmates.

From the Archives: NRAO Summer Student Programs

Students participating in NRAO summer student programs arrive at their respective NRAO sites in late May and early June. Since its inception in 1959, the summer student program has engaged well over 1,000 young people in scientific research, and many NRAO summer students have gone on to distinguished careers in astronomy and other physical sciences. The list of former NRAO summer students now includes women and men who represent a wide range of career stages, research interests, geographic locations, and ethnic backgrounds. Applications for the NRAO summer student programs are generally due each year on or about 1 February.

This photo is of the 1970 summer students in Green Bank. **[Front row, left to right]** Shawn Donley, Dale Deniston, Bengt Pettersson, Diane Williams, Alan Levine. **[Back row, left to right]** Arnold Rots, Kevin Bromberg, Uday Sengupta, Charles Cox, Michael Allen, Steven Chu, Fred Cooper.

Jansky Lectureship Awarded to Dr. Bernard Fanaroff

AUI and the NRAO awarded the 2017 Karl G. Jansky Lectureship to Dr. Bernie Fanaroff, recently retired from the Square Kilometre Array South Africa. The Jansky Lectureship is an honor established by the trustees of AUI to recognize outstanding contributions to the advancement of radio astronomy.

Dr. Fanaroff, as the 2017 Jansky Lecturer, was recognized for his exceptional contributions to radio astronomy and his unparalleled leadership through public service. He presented his lecture – Observing the Universe from Africa: Linking Radio Astronomy and Development – at each of the AUI-managed research facilities.

NRAO – Charlottesville, VA	Wednesday, 25 October 2017
Green Bank Observatory, WV	Friday, 27 October 2017
NRAO – Socorro, NM	Friday, 3 November 2017

This was the 52nd 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.

Robert L. Brown Outstanding Doctoral Dissertation Award

The 2016 Robert L. Brown Outstanding Doctoral Dissertation Award was awarded to Dr. Jennifer Weston for her thesis on *Radio Observations as a Tool to Investigate Shocks and Asymmetries in Accreting White Dwarf Binaries*. Her research was based on long-term multi-frequency VLA observations of novae and symbiotic stars, i.e., mass-transfer binary systems containing a white dwarf. Dr. Weston demonstrated that some classical novae emit synchrotron emission shortly after outburst, and she explored the degree to which symbiotics are powered by shell burning or mass accretion on the white dwarf.

Dr. Jennifer Weston

Jennifer is an NRAO Postdoctoral Fellow at the Green Bank Observatory. She received her Ph.D. in 2016 from Columbia University, and her B.S., Summa Cum Laude, from Brandeis University in 2008.

The award was presented 13 April 2017 at NRAO Headquarters in Charlottesville, Virginia after which Jennifer delivered a colloquium based on her thesis research.

The Robert L. Brown Outstanding Doctoral Dissertation Award is administered by AUI and the NRAO on behalf of Bob Brown's friends and family to honor Bob's life and career. The Award is given each year to a recent recipient of a doctoral degree from any recognized degree granting institution in the United States, that is substantially based on new observational data obtained at any AUI facility and is considered to be of an exceptionally high scientific standard.

Kwok-Yung (Fred) Lo

Five-hundred-meter Aperture Spherical radio Telescope (FAST)

Fred Lo Science Symposium & Fifth U.S. – China Workshop on Radio Astronomy Science & Technology

The Fifth U.S. – China Workshop on Radio Astronomy Science & Technology was held in Charlottesville, VA on 27–29 July 2017 and was preceded on 24–26 July by a Symposium celebrating the life and career of former NRAO Director Kwok-Yung (Fred) Lo. The Symposium featured science sessions highlighting Fred's many contributions to radio astronomy throughout his career.

The Science and Technology Workshop continued the discussions and planning held in previous years to support collaborations in joint scientific programs as well as cooperation in planning, building, and commissioning new facilities and instrumentation. Potential joint observing programs included the VLBA, the new Shanghai Astronomical Observatory 65m radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST), and other existing and planned U.S. and Chinese facilities. Technical discussions included the proposed 110m QiTai radio Telescope (QTT), handling big data, space VLBI, and back ends.

Project Director Appointed for Science Ready Data Products

Jeff Kern has been appointed as Project Director for Science Ready Data Products (SRDP) at the NRAO. Jeff formally assumed his new SRDP role on 21 March 2017 in Charlottesville and thereafter ramped down his role as CASA package lead.

Jeff Kern

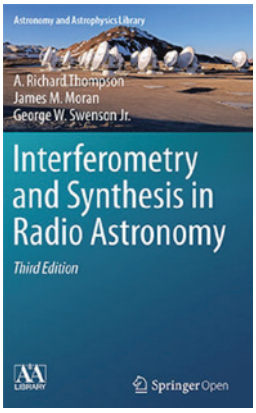
Jeff will play a key role in defining the requirements and deliverables of the project and will be responsible for tracking progress and overseeing delivery and acceptance testing of the necessary software product. In his new role, Jeff will work as part of the SSR department but with a close interface to the Data Management & Software (DMS) department led by Brian Glendenning.

The SRDP initiative is a key NRAO strategic goal and is a central commitment of the new AUI – NRAO Cooperative Agreement with the NSF. It is also an exciting initiative that builds on ALMA investments over the last three decades, uses the VLASS

calibration pipeline as a stepping stone along the path to extend the automation of calibration and ultimately imaging to the VLA, and will significantly expand the user base for NRAO telescopes.

Jeff has been on the NRAO staff since 2005 having joined as a software developer on the ALMA Control Software Team following completion of his Ph.D. studying giant pulses from the Crab Pulsar under Tim Hankins at New Mexico Tech. He played a significant role in the software development effort for ALMA in a variety of roles prior to assuming the CASA Lead position.

Interferometry and Synthesis in Radio Astronomy



The third edition of the classic textbook *Interferometry and Synthesis in Radio Astronomy* by Dick Thompson, Jim Moran, and George Swenson was published by Springer International in 2017.

This book has been a popular reference on radio interferometry since the first edition appeared in 1986. The new edition is 25% longer than the second edition of 2001, has been extensively revised, and contains much new material. Advanced data restoration techniques such as compressive sensing are described, and the section on visibility model fitting has been expanded. The discussion of atmospheric propagation and site characterization has been thoroughly updated. Modern spectral analysis techniques, such as polyphase filter banks, are explained and a generalized treatment of correlation of quantized signal is included. Tutorial appendices have been added on the radiometer equation, basic Fourier transform theory, the discrete Fourier transform, and the derivation of the structure function for two- and three-dimensional turbulence.

This book is available as an Open Access publication. It is published under the Creative Commons Attribution License and can be downloaded by anyone free of charge at www.link.springer.com. Hardbound copies are available for $60 from Springer, Amazon.com, and other bookstores. Softbound "my copy" versions are available for $25 at institutions that have Springer subscriptions. Open Access availability was made possible by publication grants from Harvard University and the NRAO.

A Half Million Citations

On 15 May 2017 at 6:05 a.m. Eastern Daylight Time, the number of citations for NRAO telescope papers broke the half-million mark. As of 2017, the NRAO publications bibliography contains 16,257 refereed papers. The NRAO Library has tracked papers since the first written by David Heeschen in 1957 (Astrophysical Journal, 126, 471); however, prior to 1975, papers were not coded to telescopes or authors. So, the half-million citation mark is impressive in just over 41 years. Note that the citation count does not include any papers using GBT data or VLBA data completed since the creation of the Green Bank Observatory and Long Baseline Observatory in Fiscal Year 2017.

DATA MANAGEMENT AND SOFTWARE

The substantial responsibilities of the Data Management & Software (DMS) department include: managing data archiving across NRAO, including access, distribution, provisioning, and operation; reduction pipeline infrastructure implementation and technical operation; high-performance computing platform definition, acquisition, and operation; network provisioning to the external community and between NRAO sites; pipeline hardware definition, procurement, and operation; all user-facing software; and shared responsibility for telescope software, primarily monitor & control.

The DMS user-facing software responsibilities include the Common Astronomy Software Applications (CASA) package that comprises the data analysis tools required for analyzing ALMA and Jansky VLA data, as well as the Astronomical Image Processing Software (AIPS), Pipeline, Archive, Phase 1 and Phase 2 program tools, and more. DMS also provides management and standards for telescope software, and the telescope staff provide priorities, testing, and oversight.

Scientific Information Services

The Scientific Information Services (SIS) division is matrixed into the information technology-centric Computing and Information Services (CIS) division. This enables sharing of skilled staff for telescope supporting science responsibilities within DMS, as well as general IT support via CIS.

In 2017, SIS successfully supported the data processing, storage, and network infrastructure needs of ALMA Cycle 4, and the preparations for ALMA Cycle 5 and VLASS. A key component of this was the additional memory for both clusters to better support imaging tasks as well as allowing for execution concurrency of multiple batch jobs on a single node. External computing providers – Amazon Web Services (AWS) and the Extreme Science and Engineering Discovery Environment (XSEDE) – have been productively engaged to address data reprocessing and performance benchmarking needs. The combined archive and cluster storage capacity managed by SIS increased by 22% in 2017 to 7+ PetaBytes. Improved reporting of Lustre storage usage has resulted in a close interaction between stakeholders to ensure equitable access to finite resources between pipeline operations, commissioning, and project commitments, as well as interactive usage by staff and visitors.

Sustained NRAO–JAO cooperation has resulted in the testing and deployment of updated CASA pipeline workflows being executed at the NAASC, the products of which are then released through the ALMA Archive by JAO for Principal Investigator access. This has been helped by the increase of bandwidth to the Edgemont Road building, by the University of Virginia, to 10 Gbps. However, there remains a need to plan for increased bandwidth from Chile in coordination with JAO, the National Optical Astronomy Observatory (NOAO), Red Universitaria Nacional (REUNA), America's Path (AMPATH), and Internet2.

ALMA System Software

NRAO is responsible for delivering software to the JAO as part of the Integrated Computing Team that is staffed by personnel in the three ALMA Executives and the JAO. The bulk of the work done at NRAO by the ALMA System Software group consists of Offsite Maintenance and Repair. This group is also responsible for the NRAO software contribution to the ALMA Phasing Project. The NRAO ALMA System Software group contributed to these ALMA ICT work areas in 2017.

Control/Correlator Software: This software controls and monitors all ALMA equipment other than the ALMA Atacama Compact Array correlator, interprets the scheduling blocks, and forms the bulk data and auxiliary data for the post-observing and archive systems. It includes many online Graphical User Interfaces (GUIs), including the quick-look display screens. It also includes the NRAO contributions to the ALMA Phasing Project.

Scheduling: The NRAO is responsible for the dynamic scheduling ranking software, manual and queued observing modes, scheduling GUIs, and an offline planning mode.

The planning priorities for this group are the responsibility of the JAO. The emphasis during 2017 has been on improving efficiency, reliability, and data quality, and the highest priority items items for the ALMA System group included the following.

Q2 2017 release: The ALMA System group provided bug-fixes and support targeted for Cycle 5, support for the stationary beacon, extended the current weather station software to provide observing condition information to other sub-systems (first release), conducted a lab evaluation of real-time operating systems, and improvements in the GUIs used by observers.

Q4 2017 release: Included further bug fixes for the Cycle 5 release, ported significant sections of the control system to the new real-time operating system, supplied the final release of software for providing the observing conditions, improved observer GUIs, and addressed the highest priority item from the Cycle 6 ObsMode meeting.

ALMA Baseline Correlator: Work focused on continuing maintenance and improvement of simulation capability. Simulation improvements will expand the capability to test offline as more array time is dedicated to science observations.

A May 2016 workshop defined areas in which to improve the correlator sub-array efficiency, including parallelization, reducing duplication, moving processing to components with a lighter workload, and re-using previously computed results. In 2017, work that optimizes the execution of multiple sub-arrays at the same time, resulting in greater efficiency was completed. Work on the real-time infrastructure upgrade reached test release status in 2017.

Correlator software personnel participated in the preparation of an ALMA Development Project proposal for upgrading the correlator hardware.

Scheduling: Changes in the scheduling software focused on: (1) developing and improving the Scheduling Planning Tool for long-term scheduling planning and assigning grades after the ALMA Proposal Review Committee meeting; and (2) providing the ability to run periodic simulations throughout the cycle with realistic weather patterns and updated configuration schedules to calculate the likelihood that a project will be executed, and therefore increase the global observing efficiency. These were released for testing.

VLA System Software

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

VLA Commissioning and Observing in Semesters 2016B, 2017A, and 2017B: This work included supporting pulsar phase bins, currently-used solar capabilities, and tipping scans, as well as commissioning of new solar capabilities. Support was provided as required for major VLA projects, including fast transient detection, VLASS, and ngVLA.

Pulsar Phase Bins: Use of the Wideband Interferometric Digital Architecture (WIDAR) Correlator for phase-binned observations of pulsars was commissioned. It is now possible to set up these observations in the current software due to the development of pulsar phase bins in the VLA low-level software.

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

Solar Capabilities: Currently used modes were implemented in the VLA model software and in the Observation Preparation Tool (OPT).

TIP Scans: TIP scans were implemented fully in the OPT in 2017 in support of the development of heuristics for atmospheric opacity determination.

Software Development

Substantial progress was made in 2017 on user-facing software development at the NRAO.

New NRAO Archive and Reprocessing: The prototype software for the new NRAO archive was migrated into production, in parallel with the current archive. Developments included making it operational, simplifying to improve its long-term supportability, and providing integration between NRAO and ALMA data. Some planned work, such as image ingestion and retrieval, was moved to a 2018 release.

The Reprocessing Pipeline Interface (RPI) was also migrated into production. This initial delivery of reprocessing capability has demonstrated the ability to convert formats and apply calibration flags via CASA from the NRAO and ALMA archives, delivered through the new archive interface.

CASA: Development of CASA, the NRAO post-processing software, continued to emphasize support for the VLA and ALMA.

CASA version 4.7 was released in late 2016, providing support for ALMA Cycle 4, and including improvements and support for the imaging pipeline. The capabilities of the visibility exploration tool were expanded. The DMS team continued to address stability and robustness issues, completing initiatives to address technical debt in the calibration and imaging subsystems.

CASA version 5.0 included improvements to the ALMA pipeline for Cycle 5 and a new VLASS pipeline. Improved primary beam models for ALMA and the VLA were included, as well as development of an automated masking algorithm to support the ALMA pipeline and refinement of On The Fly Interferometry (OTFI) techniques for VLASS. DMS continued to address technical debt, looking at the behavior of the disk IO subsystem and the management of memory footprint to improve robustness and performance. Technical debt reduction included implementing a new, unified way to access, store, and process visibilities for tasks and tools. A refurbishment of the UV-FITS import-export infrastructure increased compatibility with other data reduction packages.

CASA version 5.1 was released in 2017 to support VLASS, providing support for ALMA Cycle 5, the ALMA pipeline, and the first production release of the automated masking algorithm for ALMA.

Efforts on the parallelization and performance of the CASA package continued. Multi-threaded implementations of many expensive image analysis tasks were delivered, improving performance for the pipeline and user exploration of their data.

A framework for improved curation of documentation was developed. Significant progress was made on populating this framework with existing documentation, with the initial delivery occurring in the CASA 5.0 release.

The international CASA development team, led by NRAO, continued to increase support for single dish data reduction and high-performance computing (HPC) capabilities working on the integration of HPC capabilities with the standard reduction pipelines. The team continued to support and develop new imaging and calibration algorithms via a close connection to the NRAO Algorithm Research and Development Group (ARDG). A collaboration with Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) resulted in the startup of a new development group in 2017, the ASIAA CASA Development Center. This collaboration has augmented CASA development staff, with an initial focus on CARTA development for production.

CASA Pipeline: The CASA Pipeline continued to evolve, building on experience with ALMA and VLA operations. A major release was delivered to coincide with ALMA Cycle 4. This release included imaging capabilities to improve overall process efficiency and support faster delivery of data to PIs. An internal checkpoint release of the pipeline was provided in preparation for Epoch 1 of VLASS, and for ALMA and VLA Ops. Later in 2017, an early release of the Pipeline was delivered to support ALMA and the VLASS start of observations.

Proposal Submission Tool (PST): The PST was updated to support required functionality for the 2017B and 2018A calls for proposals. A prototype PST eliminating the sessions concept in the user interface, a high priority NRAO User Committee request, was created for internal evaluation.

Proposal Handling Tool (PHT): The PHT was updated to support required functionality for the Time Allocation Committee meetings for the 2017B and 2018A observing semesters.

Observation Preparation Tool (OPT): The OPT for the VLA was updated to support new instrumental capabilities during each observing semester. This included support for commissioning observations, and once commissioned, for general observing.

Tool Development and Design Elaboration: An initial design roadmap for the user facing tool suite – PST, PHT, OPT – was completed in 2016. The design specified short-term changes for the current tools and a more comprehensive overhaul to follow. A PST version with sessions removed was prototyped and tested, ready for integration into the production software. Further design towards the initial roadmap has been deferred until the detailed requirements are developed

Testing: In support of CASA's move to continuous integration (CI) scheme in 2017, the testing group reorganized the tests and transitioned to the new system. Test categories were made more granular and applied at specific appropriate times in the CI process, with a priority on newly committed code.

New NRAO CASA Lead

Ryan Raba joined NRAO as the CASA Lead on 25 September 2017. Ryan has degrees in Astrophysics and Computer Engineering from Pennsylvania State University, and a Master's of Science degree in Systems Engineering from Cornell University. Prior to joining the NRAO, Ryan worked on digital signal processing techniques with interferometers at Lockheed Martin for 13 years, then moved to the U.S. Federal Bureau of Investigation, where for the past six years he has worked as an investigative Computer Scientist and program manager of a large distributed team.

Ryan Raba

CENTRAL DEVELOPMENT LABORATORY

The mission of the Central Development Laboratory (CDL) is to maintain and 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 2017, work 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.

In 2017, with the beginning of the new ten-year Cooperative Agreement between AUI and the NSF for the management of the NRAO, the Observatory was divested of two of its major instruments: the VLBA became the Long Baseline Observatory (LBO) and the NRAO Green Bank, WV site became the Green Bank Observatory (GBO). Both facilities continued to be managed by AUI, but their relationship with the CDL was altered, although some functional relationships remain by the way of service level agreements.

Five notable technical successes marked 2017 at CDL. (1) The University of Virginia Microfabrication Lab (UVML) made the first all-NbTiN SIS junctions with mixer quality low-leakage I(V) characteristics and high energy gap voltage. (2) The 4–12 GHz superconducting 90° hybrid design was validated with the successful evaluation of a device from the first batch manufactured at UVML, although certain fabrication issues remain to be addressed to improve yield. (3) The L-band cryogenic Phased Array Feed (PAF) Receiver was successfully evaluated on the GBT, and produced experimental results confirming the excellent predicted performance. (4) Design of the integrated-receiver type Front End for W-band, now being fabricated, was completed. (5) The ALMA Band 2+ prototype project concluded with a successful PDR.

Various CDL groups completed and delivered Work for Others projects in 2017, and continued to make significant technical strides. Design and prototyping of the ALMA Band 1 Local Oscillator system was completed and a successful Critical Design and Manufacturing Readiness Review was held. The on-budget and on-schedule construction and delivery of cryogenic low noise amplifiers for the ALMA Band 1 receiver project continued through 2017. CDL also provided mission support for the continued upkeep and operation of NRAO telescopes.

New Central Development Laboratory Director

Dr. Bert Hawkins was appointed as CDL Director on 10 July 2017. Bert arrived at NRAO after spending five years as the director of the Science and Technology Directorate at the U.S. Army National Ground Intelligence Center (NGIC), just north of Charlottesville, VA. At NGIC, he led a team of 300+ scientists, engineers, analysts, and support personnel located in Virginia, Maryland, and various centers around the world. He is experienced across several disciplines, including millimeter, submillimeter, infrared, and acoustic technology development and analysis; foreign Research & Development and weapons systems performance, and radar characterization of physical objects. Bert's Ph.D. thesis in electrical engineering from the University of Virginia studied the modeling of moving targets in compact centimeter / millimeter-wavelength radar ranges. He brings highly relevant experience to the CDL in microwave, radar, and related technologies, combined with significant leadership and lab management experience.

Bert Hawkins

As NRAO continues to develop innovative instrumental options for projects like the ngVLA, an upgraded ALMA, and other domestic/international instruments and opportunities, Bert's experience, creativity, contacts, and organizational skills will position CDL and NRAO to take a major role in the future of our field and find opportunities in adjacent markets of interest.

Repair, Maintenance, Production, Support

The core CDL production and support activities for 2017 are described below.

Millimeter and Submillimeter Receivers

Maintenance and production of ALMA Band 6 (211–275 GHz) mixer-preamplifiers was delayed over the past two years by the inability to reproduce mixer-preamps with the stringent gain flatness of those used in the original receiver production run. The problem was likely related to the use of commercial components in the preamps which differed from those that were available when the receivers were first produced. Commercial resistors and capacitors are generally not specified for operation at 4 K, and even slight changes in manufacturing – use of a different high relative permittivity dielectric in a capacitor or a change in the resistive film used in a resistor – will typically not be indicated by a change of part number as long as their specifications were unchanged within the normal operating temperature range.

CDL initiated work in 2016 to produce a direct replacement preamp that included an Superconductor-Insulator-Superconductor (SIS) mixer bias chip. When used with NRAO's sideband-separating Band 6 SIS mixers, excellent noise and image rejection were obtained; however, the mixer-preamp gain had a positive slope across the 4–12 GHz IF band which resulted in the power-density slope still being out of spec. To remedy this problem, a passive gain slope equalizer was designed, built, and tested in 2017. This equalizer significantly improved the overall gain slope performance of the Band 6 cartridges, and has been incorporated into the revised mixer-preamplifier design that has been submitted for acceptance.

Low Noise Amplifiers (LNA)

The CDL Amplifier Group continued to produce replacement amplifiers and/or repair amplifiers for the NRAO VLA, LBO, GBO, and ALMA telescopes.

Twenty-four amplifiers were repaired. Amplifier production work, under the contract to manufacture 160 amplifiers for ALMA Band 1 cartridges, continued during FY2017; 54 Band 1 amplifiers were accepted by and shipped to NAOJ/ASIAA; 9 of 12 amplifiers for the final quarter of FY2017 have been shipped.

ALMA Offsite Hardware Support

Extensive offsite hardware support was provided by the CDL offsite support team, including diagnosis consultancy, visits to the Operations Support Facility in northern Chile, software and firmware support, and repair and return of malfunctioning line replaceable unit hardware. A few notable modules repaired during 2017 included four Band 6 cold cartridge assemblies, three Front End (FE) bias modules, three FE Monitor & Control modules, and 35 warm cartridge/local oscillator assemblies (various bands).

Work For Others (WFO)

Various CDL groups completed the following WFO projects and delivered the requested hardware and/or services to the larger radio astronomy community:

- Band 7 power amplifier Monolithic Millimeter-wave Integrated Circuits (MMICs) for Institut de Radioastronomie Millimétrique, France.
- Design and development of ALMA Band 1 LO assemblies, and subsequent production of several pre-production articles for ASIAA, Taiwan.
- Comprehensive evaluation of the prototype ALMA Band 1 receiver cartridge in the ALMA test cryostat for ASIAA, Taiwan.
- Production of ALMA-style Band 7 Warm Cartridge Assemblies (WCAs) for the Atacama Pathfinder Experiment for Onsala/Chalmers, Sweden.

- Production of ALMA-style Band 7 WCAs and multipliers for the Atacama Submillimeter Telescope Experiment (ASTE) for NAOJ, Japan.
- Production of ALMA-style Band 6 mixers for Steward Observatory, Arizona Radio Observatory.
- Production of ALMA-style Band 7 and 8 WCAs and multipliers for ASTE for the Korean Astronomy and Space Science Institute, South Korea.
- Design of a multitude of reflectionless filter variants for MiniCircuits, Inc.

Research and Development

The CDL Research and Development (R&D) efforts in 2017 supported NRAO Strategic Goals:

- Developing technologies necessary for the long-range objectives of the Observatory.
- Advancing the state-of-the-art in mission-related technology.

Millimeter and Submillimeter Receivers (MSMRx)

Assisted by UVML, the CDL continued to develop the next generation of SIS mixers in 2017. This technology is considered critical for upgrading ALMA receivers and included:

- The development of SIS junctions with AlN tunnel barriers that have high critical current density and sufficient reproducibility to permit receiver production on ALMA scales. This will allow all receivers from Band 6 to Band 10 to be produced with flatter noise temperature and gain versus frequency performance than is currently the case.

- The development of SIS junctions with one or both electrodes of NbTiN, greatly improving receiver performance above ~600 GHz.

- The development of a balanced 4–12 GHz IF amplifier with low power dissipation for ALMA SIS receivers. This will allow current and future SIS receivers to operate with essentially flat noise and gain across the full 4–12 GHz IF band, and is a technology applicable to ALMA Bands 3–10, all of which are SIS mixer based.

UVML made the first all-NbTiN SIS junctions with mixer quality low-leakage I(V) characteristics and high energy gap voltage. This represented an important first step towards realizing mixers using this material system to produce flatter noise temperature and gain devices (higher critical current density due to AlN barrier), and improved performance at higher frequency (due to higher band gap energy).

A 4–12 GHz superconducting quadrature hybrid (3 x 1 mm chip) was designed and fabricated at UVML and successfully tested. This hybrid forms an essential element of the balanced IF amplifiers proposed as a possible upgrade for ALMA Bands 3–10, which will use commercially procured low noise amplifiers.

Work on superconducting parametric amplifiers for radio astronomy, initiated in a recent ALMA study proposal, will be continued in the CDL under another ALMA study proposal. The Traveling-wave Kinetic Inductance Parametric (TKIP) amplifier uses the nonlinearity of the kinetic inductance of a superconducting transmission line to produce gain over a wide band in the presence of a strong pump wave. The goal is to develop a prototype ALMA Band 3 compatible FE TKIP amplifier operating at 4 K with near quantum-limited noise. This type of device was invented at Caltech/JPL, and recent laboratory demonstrations have resulted in near quantum-limited noise performance over more than an octave of microwave bandwidth and operating

temperatures as high as 4 K, suitable for ALMA cryostats. These have the potential to be used as front-end replacements for ALMA's millimeter/submillimeter SIS mixer based receivers and also as one-size-fits-all replacements for microwave (IF) amplifiers for all bands.

Two 2-year ALMA Cycle-5 Strategic Studies were proposed in 2017 and funded:

- Quantum-Limited Very-Wideband 4-kelvin RF and IF Amplifiers for ALMA ($400K).
- Wideband Low-Noise Balanced IF Amplifiers for ALMA Band 6, with Future Application to ALMA Bands 3–10 ($300K).

Additionally, CDL is the PI institution for the NASA Research Opportunities in Space and Earth Science-2016 Astrophysics Research and Analysis proposal on Photon-Counting Kinetic Inductance Detectors for the Origins Space Telescope (OST). This three-year project was selected for funding and this work will be done in concert with NASA Goddard Space Flight Center to develop ultra-sensitive submillimeter/THz detectors for the OST.

Integrated Receiver Development (IRD)

The IRD program seeks to develop compact, mass-producible FE hardware for the next generation of radio telescope facilities by leveraging modern advances in MMIC/integrated technology and DSP. This work is applicable to the future centimeter- and millimeter-wave radio telescopes, such as SKA, ngVLA, and even ALMA.

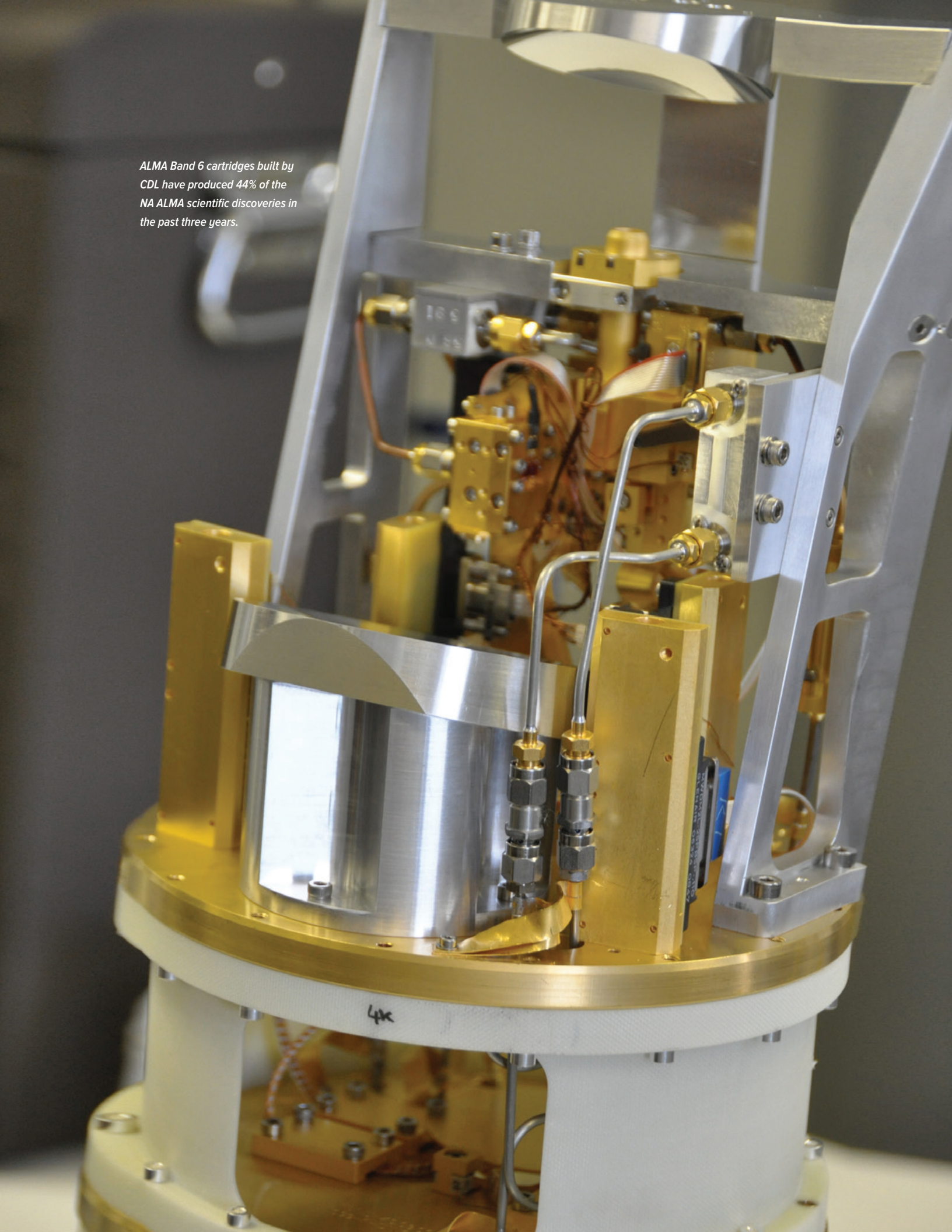
Through 2016, CDL IRD focused on laboratory demonstrations of integrated FEs and custom signal processing algorithms operating at L-, S-, and X-bands, where the prototype hardware and DSP capacity were most cost-effective. Many of these innovative techniques were matured to the level where it was considered beneficial to demonstrate FE systems at higher frequency and with larger instantaneous bandwidth.

In 2017, effort was focused on assembly of the necessary components to demonstrate warm, integrated FEs operating at W-band. These could also serve as the prototype IRD type receivers for the ngVLA Band 6 (70–116 GHz). Key to this development was a broadband I/Q mixer chip, which was designed in 2016, but received and evaluated in 2017. Two W-band signal source modules, which were completed in 2016 in anticipation of this effort, were used in the first part of 2017 to probe-test the mixer chip. A complete sideband-separating mixer module was also constructed utilizing this chip along with a broadband IF quadrature hybrid to verify amplitude and phase balance. In addition to development, prototyping and evaluation of W-band components, the design of a full W-band IRD style FE was completed ahead of schedule. Parts and components for these were ordered, and assembly, integration, and verification of this system is planned for 2018. Furthermore, algorithms to synthesize polarizations in the IRD digital backend were designed, implemented, and demonstrated.

In parallel, efforts to increase the throughput of the unformatted serial link were also successful. While the past implementations utilized 2.5 Gbps fiber optic components, this year the unformatted serial links were successfully prototyped using 10 Gbps components. This resulted in realization and demonstration of multi-GHz IF bandwidth of the prototypes.

Work also continued on further development of the reflectionless filters—a relatively well known spinoff of the IRD effort. Twenty new baseline reflectionless filter models/designs were synthesized for Mini-Circuits to expand their catalog, and fabricated by the vendor.

Patents were issued in the U.S. (#9,705,467) and in Taiwan for Sub-Network Enhanced Reflectionless Filter Topology, and in China for Statistical Word Boundary Detection in Serialized Data Streams (previously issued in the U.S.).



ALMA Band 6 cartridges built by CDL have produced 44% of the NA ALMA scientific discoveries in the past three years.

Digital Signal Processing (DSP) and Correlators

The focus of the DSP group is to develop technology and techniques for signal processing in radio astronomy. Digital technology continues to evolve at a rapid pace in terms of both device density and operating frequency, and the computational power of devices has increased exponentially. Some aspects of astronomical signal processing that could only be performed using analog components a decade ago can now be carried out more accurately and economically using digital hardware. The DSP group continued to track the advances in this field while assessing the limits of state-of-the-art computational hardware for radio astronomical purposes.

One of the recent notable products of this effort was the ALMA Baseline Correlator. Since its formal delivery in 2012, this instrument has become one of the most reliable ALMA sub-systems. However, many parts of this design are over a decade old. Digital technology has improved and significant increases in observing efficiency could be obtained by upgrading or replacing the correlator. In this spirit, the DSP group participated in two correlator upgrade studies. The first, led by the DSP group, focused on an upgrade of the existing infrastructure to achieve a two times improvement in bandwidth and a eight times improvement in resolution. The other study, led by the Smithsonian Astrophysical Observatory with DSP participation, focused on the eventual replacement of the existing correlator to achieve a four times improvement in bandwidth and a large improvement in resolution.

The ALMA Cycle 5 Correlator Upgrade project proposal was submitted in January 2017 and NSF approved $10.9M funding. The CDL correlator team continues to prototype circuit boards in preparation for the upgrade. As part of the design study, laboratory experiments confirmed that the line driver designed to double the correlator bandwidth operates with excellent signal to noise.

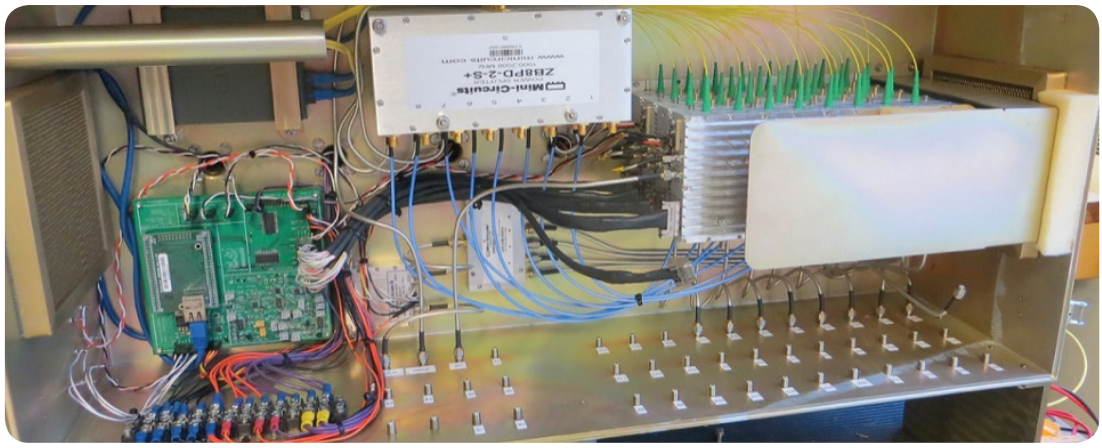
The CDL is also participating in a European ALMA study project, investigating replacing the current analog IF Back End with a completely digital unit to improve overall performance. This has hallmarks of CDL's own IRD-style receiver configuration.

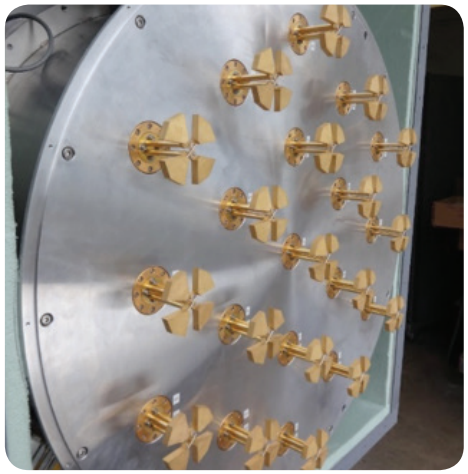
Although there are no immediate implementation plans, joint time-frequency analysis and higher order statistics were selected for further study as the most promising single-dish detection technique. A tensor-based Radio Frequency interference (RFI) mitigation technique with application to interferometric arrays was successfully applied to VLA data, and a potential architecture for RFI detection and excision at the 'F' stage of an FX correlator were defined. Work continues on the study of the performance of pre-correlation RFI detectors for the ngVLA. Looking forward, an RFI data collection/database campaign, and a study of post-correlation RFI detection techniques have been planned.

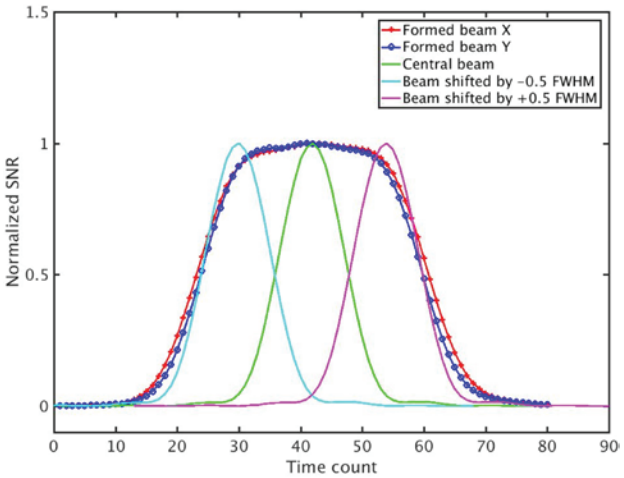
Additional effort was aimed at developing calibration techniques for Digital Sideband Separating (DSS) receivers, such as CDL's integrated receiver. DSS receivers can improve image rejection ratios by a factor of a thousand compared to their analog counterparts. However, additional hardware is required to calibrate the coefficients of the digital rejection filter, such as a means for injecting a calibration tone into the receiver. To simplify the receiver, a novel method for calibrating DSS receivers directly from noise correlation measurements has been developed. The method has been designed and its effectiveness assessed through computer simulation.

Phased Array Feed (PAF)

An L-Band cryogenic PAF receiver was designed, assembled, debugged, installed on the GBT, and evaluated in 2017. On-telescope evaluation on GBT confirmed the predicted excellent PAF performance. These tests have also validated the in-system performance of the unformatted digital link technology developed by the CDL IRD group.







Photographs of PAF dipoles **[bottom left]**, *and PAF Digital Downconverter housing* **[top]**. *Plots* **[bottom]** *show the central synthesized beam along with two off-axis beams. Also shown is the composite beam formed in each of two polarizations, demonstrating the mosaicking capability of PAF for extended field of view observing.*

Following this evaluation, the PAF front end, RF converter, digitizer, fiber link, and Roach2 DSP processor hardware were integrated with the Beamformer backend – a GPU based 38-channel 150 MHz processor – and commissioning work has taken place on the GBT at GBO. With all its goals achieved, the PAF project was declared a success.

Low Noise Amplifiers

Research continued on the fundamental noise properties of microwave transistors, with special emphasis on the limits of the noise performance of Indium Phosphide (InP) Heterojunction Field-Effect Transistors (HFETs). This work focused especially on scaling of the gate length and the so-called "noise cancellation techniques" used in CMOS transistors. Although this last research topic has no significant impact on the state-of-the-art low noise receivers for radio astronomy, it may have a significant impact on the direction of SKA and ngVLA development work.

Optics and Electromagnetic Components

Optical components such as feed horns and passive electromagnetic (EM) components such as polarizers form essential parts of state-of-the-art low-noise receivers. In some cases, such as the ALMA receivers, focusing elements like dielectric lenses or tertiary reflectors are required to match the beam waist of the feed horn to that of the antenna. CDL has been developing and optimizing these components to yield excellent performance, broader bandwidths, and simpler mechanical designs easing fabrication procedures. In 2017, these efforts were directed towards supporting the VLA and ALMA.

Significant effort was expended on refining, fabricating and evaluating the optics and orthomode transducer (OMT) design for the ALMA Band 2 cartridge, first for the 67–90 GHz frequency range, and then subsequently for the 67–95 GHz extended frequency range.

General development work on EM components for millimeter and submillimeter wavelengths, as well as for broadband feeds for the ngVLA project also continued in 2017. An improved version of a Dunning OMT for the 75–110 GHz band was analyzed. This OMT could be scaled and fabricated for use for the ALMA Band 6 cartridge upgrades that are currently envisaged.

Optics design and analysis of 18m, 20m, and 25m class dual-offset reflector antennas continued during this period. Both Gregorian and Cassegrain subreflectors with opening angles from 30° to 44° were analyzed with the subreflector size of 3.2m, large enough for 1.2 GHz operation.

ALMA Band 2 Receiver Development

A successful May 2017 PDR marked the conclusion of work on this ALMA Development Cycle 2 project. The two-year development project timeline was tight to design, fabricate, and construct MMIC based LNAs and then construct the receiver. Consequently, the receiver prototype was built around CDL chip and wire E-band LNAs in parallel with the CRAL MMIC development effort. The receiver was subsequently upgraded with MMIC LNAs when they were delivered.

Since the ALMA Cycle 5 Band 2 construction proposal failed to secure funding, the in-flight design tasks underway following the successful PDR were continued to their next logical stop points and then systematically wound down.

Low Frequency Radiometry Laboratory

The Cosmic Twilight Polarimeter, a Dark Ages Radio Explorer (DARE) deliverable, was constructed, laboratory tested, and delivered for deployment.

The group acquired ~$300K funding as a sub-award from the Moore Foundation, via the Massachusetts Institute of Technology (MIT) to help fund participation in instrument R&D activities at CDL. The goals of the three-year work package (June 2017-May 2020) include: (1) assist MIT researchers to develop designs for a 60–120 MHz narrowband feed and a 60–200 MHz wideband feed for the existing Hydrogen Epoch of Reionization Array (HERA) dishes to extend the frequency range into that required for Epoch of X-ray studies; and (2) make improvements to the antenna beam mapping system that uses downlink signals from the satellite constellation.

The group received a $400K grant over five years (July 2017-June 2022) from the NASA Network for Exploration and Space Science to support a graduate student for DARE-related technical development.


OLYMPUS
Alphametals
SHENANDO

EDUCATION & PUBLIC OUTREACH

The Education & Public Outreach (EPO) department transitioned in 2017 owing to: (1) the divestiture of Green Bank Observatory, requiring a start-up phase to establish a new infrastructure of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education programs, and (2) the arrival of a new Assistant Director for EPO. An Education Specialist was hired in New Mexico in May 2017, and a STEAM Education Program Development Officer was hired in Charlottesville in June 2017. The Development Officer has taken the lead for STEAM initiatives, coordinating efforts in Charlottesville and New Mexico. Charles Blue has moved into the positon of News and Public Information Manager, coordinating efforts in New Mexico and Chile. Visitor Center operations are covered part time by the Education Officer in New Mexico, and the multimedia group is being managed by the Assistant Director with a distributed management strategy that has different team members serving as project coordinators.

STEAM Education

STEAM Education is the practice of formal and informal instruction in STEM topics. Educators added the "A" to be inclusive of the Arts to broaden the reach of programming. The EPO department designs teaching and learning experiences for K-to-Grey learners, with the exception of authentic research experiences for undergraduates that are managed by SSR.

A new STEAM Education division is headed by the STEAM Education Program Development Officer hired in June 2017. The new STEAM Education Specialist hired in New Mexico in May 2017 will kick start design and development of new and innovative programs for the visitor center.

VLA Sky Survey (VLASS): A national group of EPO-experienced scientists from the user community is working with NRAO EPO to determine a program of learning and sharing with a common theme of results of the VLASS. This was launched in 2017 with an informational website that will be expanded in 2018 to include lesson plans and opportunities for scientists to connect with the NRAO EPO team to develop broader impacts for the research proposals. Opportunities could include citizen science projects, and simplified data sets for classroom use.

Sister Cities: This program partners the high school in Magdalena, NM with the high school in San Pedro, near the ALMA site in northern Chile, in a joint cultural and learning exchange using a scientific experiment as a thread of inquiry. EPO continued the cultural exchange in 2017, providing stakeholders with crucial information about soft skills needed to navigate program planning across borders, languages, and continents. NRAO's Office of Chilean Affairs conducted a needs assessment with their participating school and NRAO will do the same in 2018, expanding the programming to help meet those needs.

Physics Inspiring the Next Generation (PING): This Green Bank program evolved into Radio Astronomy and Physics in New Mexico (RAP-NM). A pilot residential camp was run in July 2017 with 11 rising ninth graders from Magdalena and Socorro. The residential camp was held on the New Mexico Tech campus, taking advantage of their classrooms, dormitories, cafeteria, and recreational facilities. Faith Vowler, NRAO's new Education Specialist, completed the training for Skynet Junior Scholars. This online program gives participants access to robotic telescopes to make observations and conduct some simple investigations with filters.

Teacher Training: The Chautauqua Short Course program was held in Socorro. This one-week immersive training brings radio astronomy concepts and discoveries to college educators capable of integrating them into their classrooms. To broaden participation, NRAO dedicated travel funds in 2017 to assist four educators whose home institutions could not afford to reimburse attendance. Twelve college instructors from across the country attended.

In addition, 472 New Mexico students and teachers in Santa Fe and Roswell were served with the Box of Stars outreach materials. Nine teachers and 350 students at Mark Twain Elementary School in Albuquerque were served with Eclipse outreach materials; 148 students – 68 at San Antonio Elementary School and 80 at Zimmerly Elementary School – were given basic astronomy programming with the NRAO Starlab.

Informal STEAM Education Programs: Informal STEAM Education is the sharing of STEAM topics and concepts in a face-to-face setting that is not a classroom, and does not require a certified teacher be present. Informal education outreach was mostly conducted in NM, but will be ramping up in Charlottesville in in 2018 with the hire of the STEAM Education Program Development Officer.

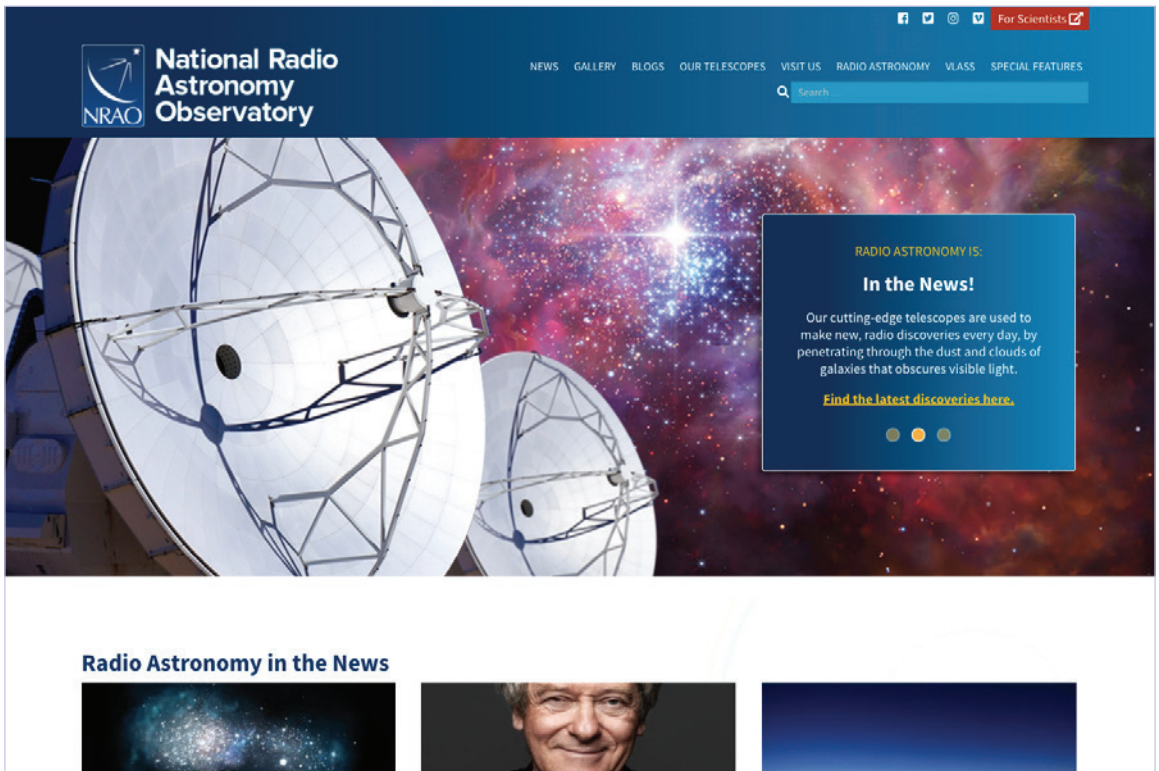
In Charlottesville, NRAO participated in several large-scale events to introduce students to NRAO careers, including Piedmont Virginia Community College's 7th Grade Career Day (March 2017), E-STEAM Charlottesville (September 2017), and the Astronomy on the National Mall event in Washington, D.C. (June 2017). The Assistant Director partnered with the Office of Diversity & Inclusion to offer a full packet of bilingual STEAM activities (June 2017) to the African American Teaching Fellows, including demonstrations of safe observation techniques for the solar eclipse on 21 August 2017.

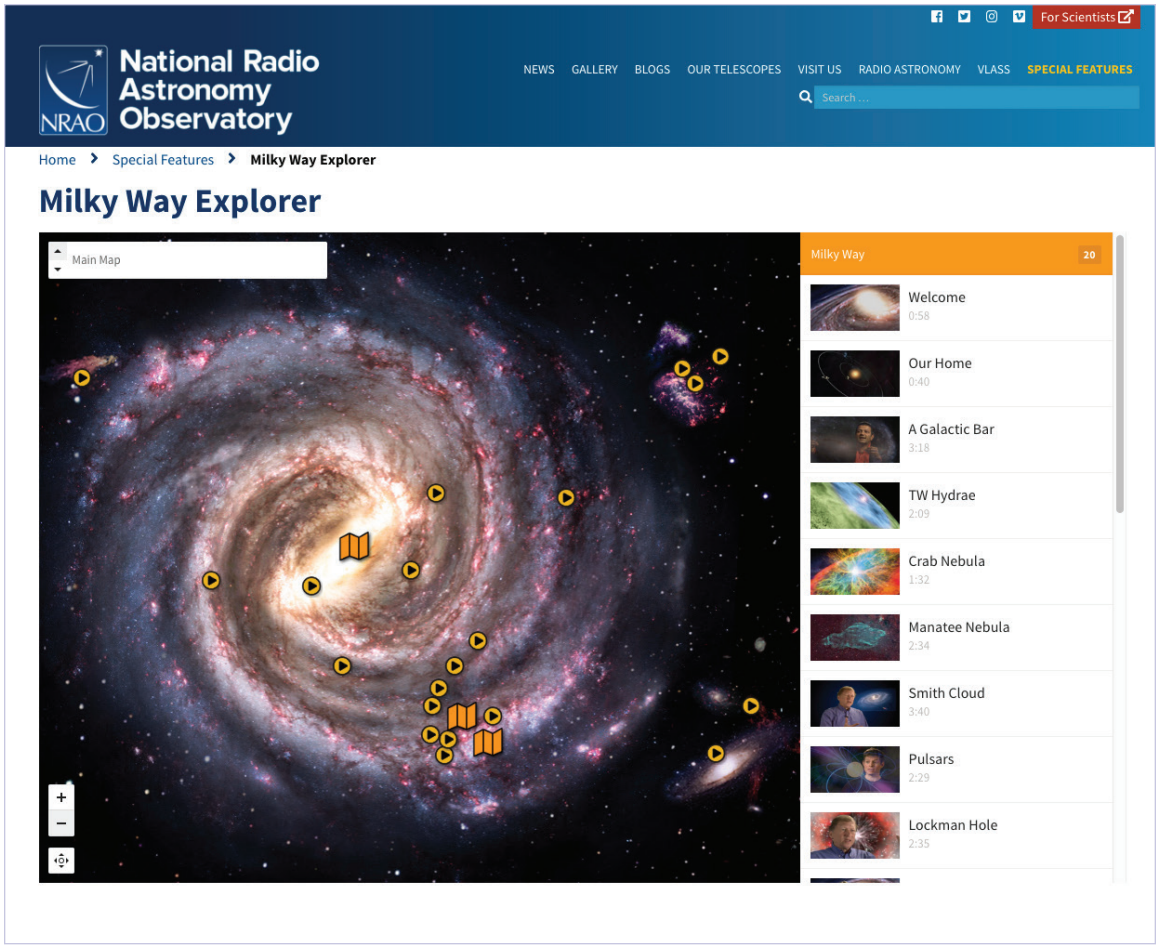
News and Public Information

The two NRAO Publication Information Officers (PIOs) authored 51 unique press products in FY2017, and managed dozens of site access requests from broadcasters and journalists interested in producing feature stories on NRAO. This small division publishes regular news content for the public website in cooperation with internal and external stakeholders, including artists and scientific staff. At the January 2017 American Astronomical Society meeting, Dave Finely organized a press conference for Fast Radio Burst discovery that was coordinated with a *Science* magazine cover story.

In 2017, the PIOs lead regular Media Communications Training sessions for management groups, Green Bank Science Public Outreach Team (SPOT) groups, and NM Tech communications classes. Charles Blue hosted a reporters roundtable through Newswise service to feature the future of radio astronomy with ngVLA and ALMA science. An intern was recruited via the American Association for the Advancement of Science (AAAS) and served over the summer, assisting with revision of the glossary for the website and the development of a Terzan 5 tip sheet that evolved into a full press release, one of seven produced under a service level agreement with GBO and LBO.

Communications training was also offered in partnership with ODI following the NSF-funded 'Portal to the Public' model. Training was conducted for Research Experiences for Undergraduate students in Charlottesville and for students at the NAC workshop in DC.





Multimedia Engagement

New Public Website: NRAO launched a new design of its public website to deliver content inside new WordPress templates and via a WordPress content management system, that has improved the user interface for both internal and external stakeholders. This new website integrates a Mission Control Live tracker that displays where NRAO telescopes are pointed, plus a live webcam of the ALMA high site. Additionally, the team developed a new multi-wavelength image viewer called the Cosmic Coloring Compositor.

ALMA Explorer: The ALMA Explorer videos were updated with exclusive, new footage and interviews, and a Chilean Spanish version of the new content was delivered.

Milky Way Explorer Expansion: EPO produced new online video features for the Milky Way Explorer that focus on extragalactic topics, such as radio galaxies, megamasers, ALMA deep fields, and the Cosmic Microwave Background. These videos star NRAO scientific staff and users who describe their work. The EPO team provides animations and data visualizations to accompany each story.

Social Media: With a new science writer hired in 2017, NRAO social media platforms have had regular care and feeding and the audience has steadily grown on Twitter and Facebook. EPO added an Instagram account that has also grown.

Visitor Center Operations

NRAO operates a Visitor Center on the site of the Jansky VLA, west of Magdalena, NM. The site currently has indoor and outdoor public exhibits, an award-winning film narrated by Jodie Foster, popular gift shop, and monthly tour programs. Management is overseen on a part-time basis by the NM STEM Education Officer. Services remained at a high level as the site served 22,275 visitors in FY2017 and conducted guided tours for 24 adult groups with 852 participants; 26 school groups with 964 participants; and 2963 First Saturday tour participants. Visitors spent $357,624.

EPO did not hire and train paid tour guides in 2017, but combined the salary allocation for those positions with the part-time Education Specialist funding to create a fulltime position. The Education Specialist enhanced the tours with interactive demonstrations and took on many of the tour duties of the Education Officer, creating time for additional STEAM development.

EPO and NM Operations jointly proposed a VLA Visitor Center renovation and experiences upgrade program plan that will improve and expand didactic and face-to-face learning experiences for VLA visitors. This process began late in 2017 with building inspections of the cafeteria and existing Visitor Center. An interpretive planning workshop will be soon conducted to determine the goals and themes for a new VLA Visitor Center experience.

The year 2017 was the 20th anniversary of the release of *Contact,* the blockbuster movie filmed at the VLA and involving staff and local residents. An October Open House celebrated the anniversary.

*Visitors attending the October VLA Open House were given the opportunity to be photographed as Dr. Ellie Arroway from the 1997 movie **Contact** starring Jodie Foster.*

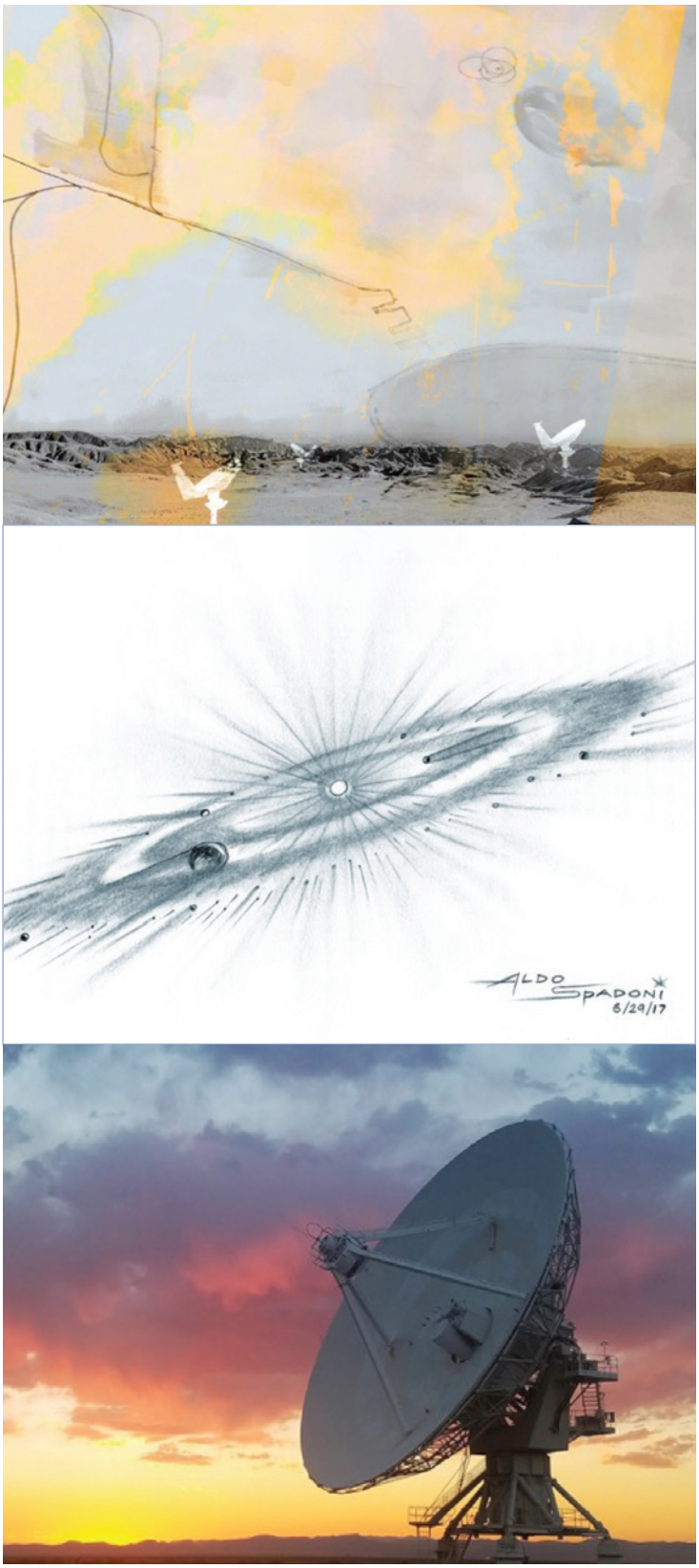
Science Communication for the ngVLA

Imagine the challenge of crafting a comprehensive and compelling science case for a next-generation observatory, one that promises transformational discoveries but will require a decade or more of planning and development. To succeed, this observatory will need strong support from the science community and the general public. Communicating the profound impacts of this project to the science community is challenging enough; communicating the project's profound value to the public requires capturing its imagination.

EPO has taken a unique approach to this daunting task. EPO commissioned artists with different styles and creative backgrounds for the June 2017 ngVLA Science Program Workshop and asked them to listen to the many scientific presentations and illustrate the ideas generated by the discussions. This unique collaboration between scientists and artists illustrates the vital role art can play in relaying complex ideas to the public.

Each artist works in different media, from a Hollywood film consultant for the movie Apollo 13 to an illustrator who uses collage to interpret complex concepts. The results are spectacular and compelling. Each artist will develop additional ideas and concepts to help us visually explain to the public the importance of such a large-scale project.

Illustrations by **[Top]** *Eddie Edwards,* **[Middle]** *Aldo Spadoni,* **[Bottom]** *Jon Ramer*



MANAGEMENT & ADMINISTRATION

AUI President
Cohen

Director's Office
Director - Beasley
Deputy Dir - Jewell

NRAO - CHILE
Bocaz

Administration
Geiger

Human Resources
Giles

Program Management
Wingate

Director's Office
Chief Scientist - Carilli
Communications - Adams
Diversity & Inclusion - von Schill

NA ALMA
Jewell

NM Operations
McKinnon

Central Development Laboratory
Hawkins

Science Support & Research
Ball

Data Management & Software
Glendenning

Education & Public Outreach
Gurton

New AUI President

Dr. Adam Cohen became the new President of AUI, effective 1 November 2017. Dr. Cohen's appointment was the culmination of an extensive search conducted by the AUI Board of Trustees. He succeeds Ethan Schreier, who served as AUI President since 2004.

Dr. Cohen was most recently a Senior Associate with the Center for Strategic and International Studies, Energy and National Security Program. Until May 2017, he served as the Deputy Under Secretary for Science and Energy at the U.S. Department of Energy (DOE), overseeing basic science, applied energy research, technology development, and deployment efforts, including the stewardship of 13 of the 17 DOE National Laboratories. His experience includes nearly seven years as Deputy Director for Operations at the Princeton Plasma Physics Lab, and 18 years at Argonne National Laboratory, where he held positions including Deputy Associate Director for Energy Sciences and Engineering, and Deputy Director/Chief Operations Officer. He has served as head of the U.S. Delegation on the ITER Council, on the New Jersey Department of Environmental Protections' Oyster Creek Oversight Panel, and on the DOE Laboratory Operations Board. Dr. Cohen earned his bachelor's degree in engineering from Columbia University, his M.B.A. from the University of Chicago, and his Ph.D. in materials science from Northwestern University.

Dr. Cohen leads AUI as it enters its next decade of oversight of the state-of-the-art U.S. research facilities for radio astronomy funded by the NSF. He is focused on identifying and pursuing substantial new opportunities to apply AUI experience in large-scale facility management that will further benefit the international research community.

Senior Management Organization

The NRAO organization in 2017 consisted of departments, which were made up of divisions, which consisted of groups. This organization emphasizes 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 Assistant Director **Mark McKinnon**. 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 .

MANAGEMENT & ADMINISTRATION

Assistant Director **Lewis Ball** led the Science Support & Research (SSR) department. SSR is responsible for the Observatory's scientific interface to the NRAO user community. This Observatory-wide department also 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.

Assistant Director **Suzanne Gurton** led the Education & Public Outreach department. 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.

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.

The Central Development Laboratory (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. CDL accomplishes this through development of the enabling technologies: low-noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components, including feeds and phased arrays. **Bert Hawkins** joined NRAO and took up the role of Assistant Director: CDL effective 10 July 2017.

Based in Charlottesville and led by Associate Director **Steven Geiger**, the Administration department provides the administrative 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, Assistant Director for Human Resources, directs Observatory-wide human resources policies and programs; including compensation, benefits, recruiting, employment, employee relations, diversity, organizational development, performance management and training.

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) led by Program Manager **Lyndele von Schill**, 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.

Diversity and Inclusion

The Office of Diversity and Inclusion (ODI) was established in 2015 to support NRAO efforts to increase 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 2017, the ODI Director worked closely with HR, EPO, and SSR to develop and maintain programs that affect the NRAO work force, broader impact efforts, pipeline initiatives, and the internal NRAO culture and climate.

National Programs

NRAO national programs continued to grow and develop, 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.

National Astronomy Consortium (NAC): The NAC placed ten undergraduate students from community colleges and universities with trained mentors at NRAO and three partners: Space Telescope Science Institute, University of Wisconsin-Madison, and Princeton University. Students were recruited from Minority Serving Institutions (MSIs) and Historically Black Colleges and Universities (HBCUs), and from Hispanic-serving Institutions (HSIs). The NAC students interacted with REU students for activities such as colloquia, and worked on original research with their mentors. The NAC program included student participation in professional development workshops, 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 Annual Workshop held in Washington, D.C. 15-17 September 2017 featured presentations by ten NAC students, two NAC alums in graduate school, three high school students from the RAMP-UP program, and representatives from universities, national funding, and professional organizations. A key NAC experience is the opportunity to develop confidence in presenting research. The NAC workshop enabled students to meet and present their research, and engage with the professional community. In addition, 14 NAC students worked with their mentors to develop and submit an abstract and poster for the 227th AAS meeting.

Radio Astronomy & Physics – New Mexico (RAP-NM): This summer camp experience for rising ninth graders from the Socorro, NM area was managed by NRAO EPO, and was partially supported by ODI which funded the participation of undergraduate student mentors from New Mexico Tech. RAP-NM replaces PING as NRAO's summer camp experience for rising high school students (and PING continues as a GBO activity).

2017 RAP Students at the VLA

Women in Astronomy IV (WIA IV): The Many Faces of Women Astronomers: Sponsored by the NRAO and the AAS, with support from the NSF, the WIA IV conference took place 9–11 June 2017, following the AAS Summer Meeting in Austin, Texas. Through extensive use of workshops, panels, and small group discussions, WIA IV focused on issues that affect a broad spectrum of women in astronomy. The conference addressed challenges specific to women, and what institutions can do to create welcoming, equitable workplaces. Workshops and breakout sessions were structured to facilitate the production of policy white papers, tool kits, and resource lists.

The WIA IV conference was inclusive in content and participation: all members of the astronomy community were invited. The 177 registered participants included students, administrators, data analysts, software engineers, educators, education and public outreach professionals, engineers, technicians, and others who contribute to the field of astronomy.

Women in Astronomy IV attendees

Internal Programs: Diversity and Cultural Awareness

Online Training: NRAO continues to focus on education and training related to the importance of a diverse workforce and inclusive environment. In 2017, ODI and HR offered an online training module set that includes a Respect and Inclusion series, Diversity in Action, and Unlawful Harassment Prevention. Diversity and Inclusion Advocates, summer student mentors, and hiring managers were assigned sets of courses to take as part of their roles. The courses were made available to all members of NRAO staff.

Diversity and Inclusion Advocates: 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, serve as role models and facilitators, and have a commitment to supporting a culture that values diversity and fosters inclusion. In 2017, D&I Advocates provided advice and assistance to the ODI Director, as well as critical support by facilitating local training.

Speaker Series: In 2017, the NRAO Diversity and Inclusion Speaker Series included presentations about LGBTQ Safe Space/ Cultural Competency, Diversity and Inclusion, Everyday Sources of Bias, Achieving Mindful Diversity and Attentive Inclusion, and Recovering from Trauma and Grief. Partnering with HR, the series included presentations on strategies to enhance diversity and excellence in the hiring process.

International Partnerships

The NRAO International Exchange Program (NINE): The NINE Program continued under the leadership of Program Manager Lory Wingate in 2017. The NINE hosted a nine-week Train-the-Trainer event. Two candidates from South Africa completed the program, along with an embedded NAC student who participated as a representative from the Hampton University NINE Hub that was established in 2016. These visits resulted in the approval of an exchange hub at SKA South Africa (SKA SA), and commitment to long-term mentoring relationships between SKA SA and NRAO staff. In 2017, an Introduction to Radio Astronomy distance-learning course was offered at Hampton University, Howard University, and Norfolk State University. As part of the NINE program's development of distance-learned material, Radio JOVE training materials were developed for use by the NINE hubs.

Graphical description of major components of the NINE Professional Experience.

Local/Regional Programs

NC-VA Louis Stokes Alliance for Minority Participation (LSAMP): In 2017, NRAO became an official partner of the NC-VA Alliance (LSAMP) program under the University of Virginia's successful proposal to NSF for a five-year program. Additionally, NRAO sponsored a day-long field trip for the LSAMP students to the Green Bank facility for a tour of the telescope and observing opportunity.

African-American Teaching Fellows (AATF): NRAO supports AATF's mission to recruit, support, develop, and retain a cadre of African-American teachers within our local community. In 2017, ODI co-sponsored the annual AATF Summit. The summit featured NRAO EPO staff presentations, hands-on activities, classroom materials for teachers, and opportunities for regional schools to tap into NRAO EPO expertise.

Hampton University Hub (HU Hub): The HU Hub expanded in 2017 to include the Radio Astronomy Middle-High School Physics to Undergrad (RAMP-UP)/Astro-Kids program. RAMP-UP exposes high school students to radio astronomy; in 2017, high school students from Hampton City High Schools participated, building and observing with an optical telescope and a Radio Jove.

Communications

The NRAO Communications Office (COM) organized the NRAO presence at the winter American AAS meeting, 3–7 January 2017 in Grapevine, Texas, including an NRAO Town Hall, and Observatory participation in the meeting's multi-day exhibition. A new NRAO exhibit set, designed by COM with external contractor assistance, debuted at this AAS meeting. 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, 4–8 June 2017 in Austin, Texas, including NRAO participation in the meeting's multi-day exhibition and local public outreach events organized by the AAS and sponsored by AUI.

New NRAO-GBO-LBO-ngVLA exhibit set at the January 2017 AAS meeting.

COM submitted a proposal in April 2017 for a science symposium at the 2018 Annual Meeting of the AAAS. Titled *The Chemistry and Physics of Nascent Planetary Systems,* this symposium will describe how the 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 planet formation. The COM proposal was peer-reviewed and accepted by the AAAS for the 2018 AAAS Annual Meeting to take place on 15-19 February 2018 in Austin, Texas. The presenters who will describe the state-of-the-art observing campaigns being crafted by astronomers to probe planet formation at radio wavelengths will be Karin Öberg (Harvard), Meredith Hughes (Wesleyan), and David Wilner (Harvard-Smithsonian Center for Astrophysics).

COM continued to edit and publish the monthly NRAO electronic newsletter, eNews, each issue of which was distributed to more than 9,000 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. COM also edited and published two issues of the CASA News. The NRAO Research Facilities brochure was updated and published immediately prior to the January 2017 AAS meeting.

COM and CIS collaborated on the NRAO exhibit at the SC17 International Conference for High Performance Computing, Networking, Storage, and Analysis conference, 12–17 November 2017 in Denver, Colorado, an annual gathering of more than 10,000 scientists, engineers, software developers, CIOs, and IT administrators from universities, industry, and government agencies.

COM and CDL collaborated on the first-ever NRAO exhibit at a tri-annual General Assembly of the International Union of Radio Science (URSI), 22–25 August 2017 in Montreal, Canada.

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 2017 Users Committee (UC), which met in Charlottesville 1–2 June 2017. The ALMA North American Science Advisory Committee (ANASAC) met on 31 May as a standing sub-committee of the Users Committee.

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

Domestic Spectrum Management

Satellite Coordination–Iridium: Iridium is launching replacement satellites under a Federal Communications Commission (FCC) order not to interfere with radio astronomy. Testing at Germany's Leeheim satellite monitoring station is underway. The 20 year struggle to contain Iridium's radio frequency interference (RFI) into the radio astronomy band around 1612 MHz has moved to the International Telecommunication Union-Radio communications sector (ITU-R) where Iridium is seeking to offer a maritime safety-of-life service. This raises the worry that their signal would achieve a privileged status that they would try to use to excuse their interference. NRAO is supporting a Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) effort to change some of the underlying ITU-R regulatory language that Iridium cites to shield their RFI from criticism by the radio astronomy community. This involved a deep dive into the ITU-R archives extending back to radio astronomy's earliest days as a newly created radio service in 1959, when the concept of passive use of the radio spectrum was first introduced at ITU-R.

Satellite Coordination–OneWeb, SpaceX: At separate meetings hosted by NSF in the spring of 2016, NRAO supplied background material and explained the accepted compatibility criteria to SpaceX and OneWeb, who are separately proposing constellations of 1,000–4,000 satellites using 10.7–12.75 GHz downlinks for global wireless broadband. This is immediately adjacent to a passive service band at 10.68–10.7 GHz in which all emissions are prohibited, imposing strong constraints on the down-link.

Subsequently in 2017, at NRAO urging, OneWeb engaged a spectrum consultant sympathetic to radio astronomy, who convinced OneWeb to modify their operations to be compatible with existing radio astronomy operations. OneWeb was granted authority to operate in the U.S., subject to successful coordination with radio astronomy.

SpaceX did simulations and realized the implications of avoiding interference into the passive band and, unlike OneWeb, suggested that the burden of achieving compatibility should rest largely on radio astronomy's modifications of its own operations. This approach was rejected by NRAO on the basis of impracticality and its resemblance to the unfortunate historical events associated with Iridium's attempts to evade the consequencies of its own interference. Further discussions with SpaceX and NSF are underway.

International Mobile Telecommunication (IMT) and vehicular radar: NRAO commented on and strongly participated in compatibility studies on bith these issues in 2018.

FCC largely pre-empted discussion by opening up spectrum for the U.S. wireless industry when it issued an order concerning spectrum above 24 GHz. Current consensus in U.S. and E.U. seems to be coalescing around use of 26–28 GHz as the first millimeter-wave band for IMT. Use of this band does not directly threaten radio astronomy spectrum allocations, but 26 GHz is heavily used for radiosonde in the remote sensing community, which foresees rather dire consequences if the band is widely adopted for IMT.

The FCC issued rules for 76–81 GHz car radar operation, permitting power levels 10–20 dB above what had been used in prior compatibility studies, and 40 dB higher than those used in tests at the Arizona Radio Observatory 12m telescope in 2010. The FCC ignored CORF and NRAO requests for an off-switch, citing industry's beliefs about the lack of susceptibility of radio astronomy operations to interference and the impracticality of accommodating the small number of radio astronomy sites operating in the band.

International Spectrum Management

ITU-R and World Radio Conference (WRC)-19: There were the usual rounds of ITU-R meetings in 2017 during the current WRC cycle, and studies are barely underway. NRAO, acting as Chair of IUCAF, remains the main source of radio astronomy input documents for most issues at ITU-R.

Space Frequency Coordination Group: NRAO, on behalf of IUCAF, attended the 37th meeting of the Space Frequency Coordination Group at the Canadian National Space Agency near Montreal in September 2017, where operators of remote sensing active (transmitting) satellites held their annual ten-day meeting. IUCAF has been attempting to conclude an agreement whereby operators of high-power orbiting radars would avoid illuminating radio astronomy sites; currently they avoid illuminations only at 9.2–10.4 GHz. This effort has produced useful information clarifying which missions and types of missions emit at threatening levels, but is unlikely to reach a broader agreement regarding illumination of radio astronomy sites and will probably be abandoned.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24
NO PARKING
WITHIN 50FT

Observing Hours

Telescope performance for the VLA 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.

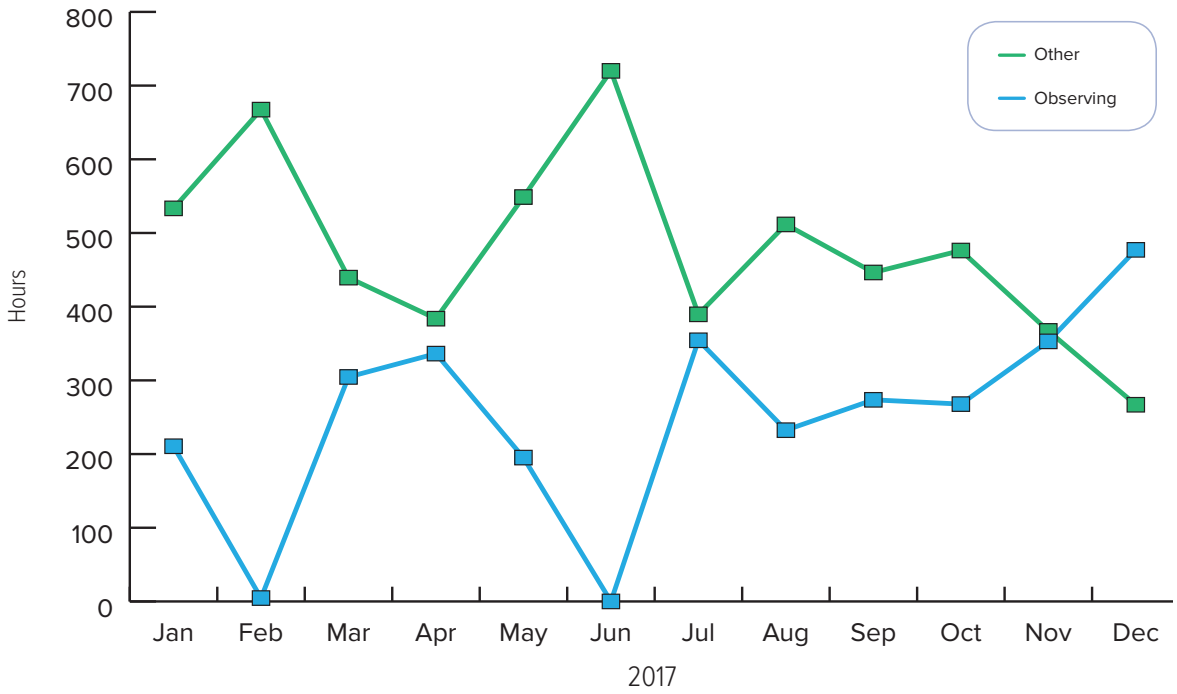
Test: Actual hours for test observations rather than peer-reviewed science proposals.

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

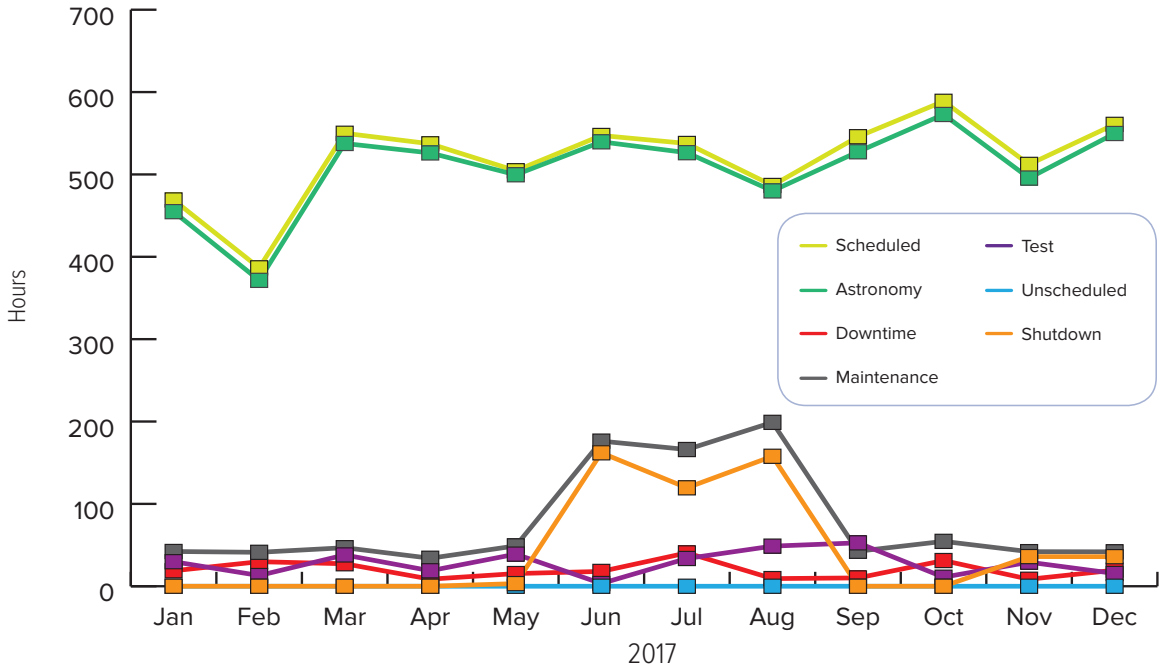
Shutdown: Actual shutdown hours, usually for a holiday. Other major shutdowns occur for major equipment work.

ALMA photograph by Pablo Carrillo

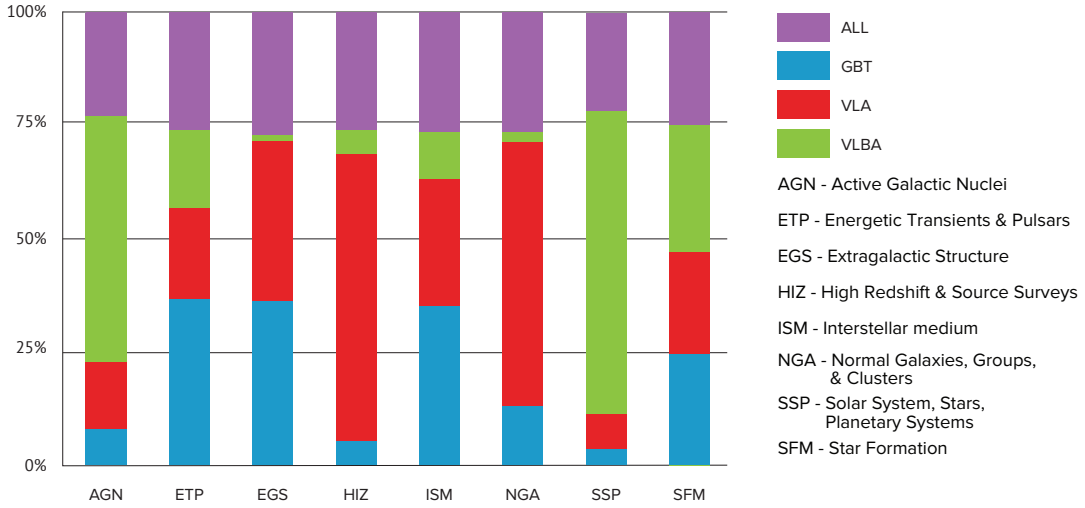
ALMA Observing



VLA Observing

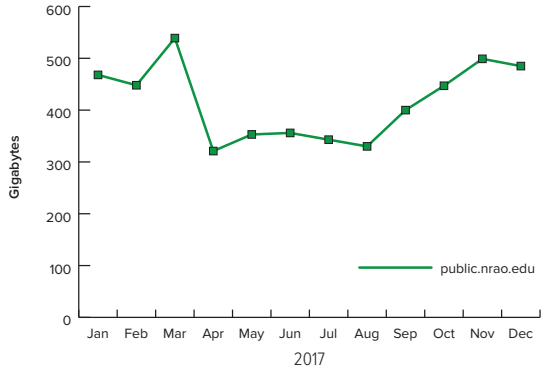


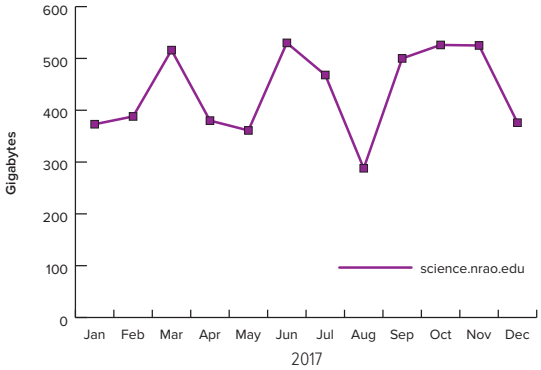
Observing Hours by Science Category

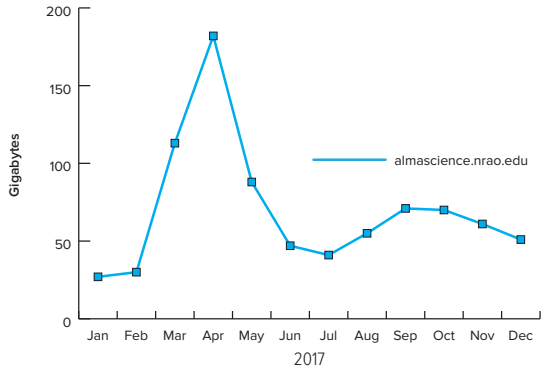


Observing hours for each of the GBT, VLA, and VLBA are tracked in the eight science categories defined in the NRAO proposal evaluation and time allocation process.

NRAO Website Volume

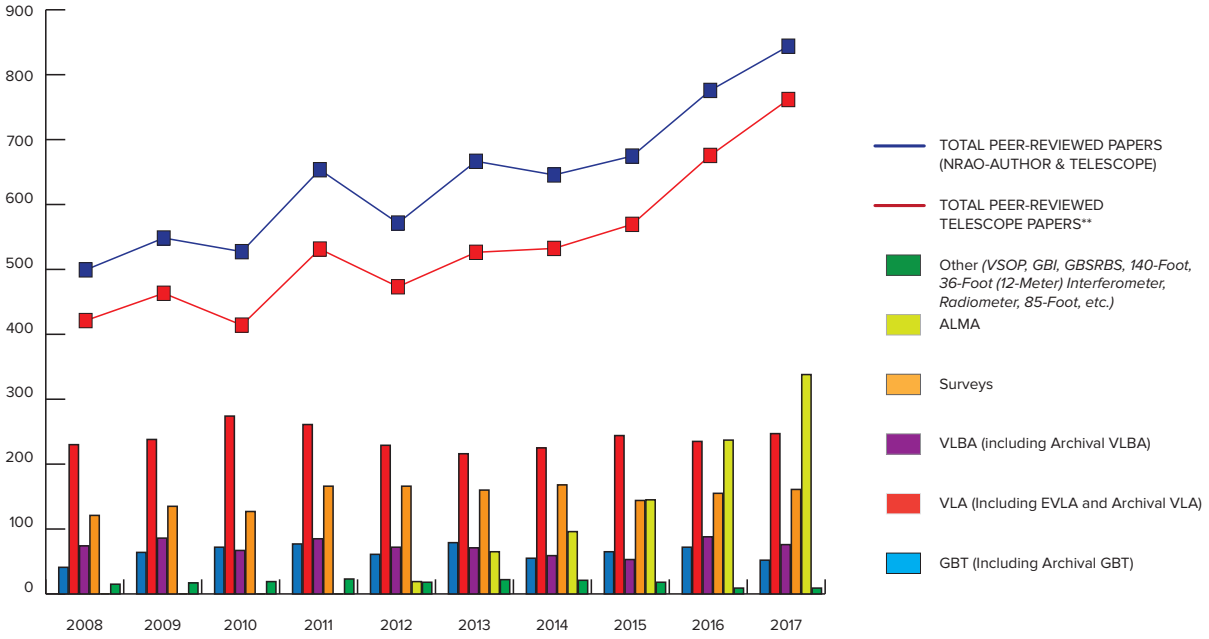






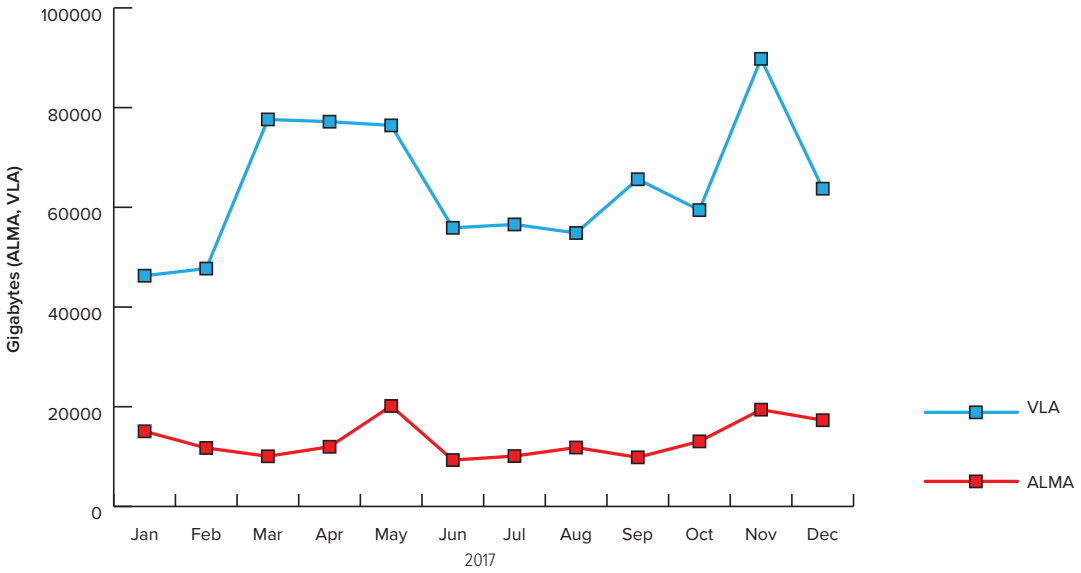
The *public.nrao.edu* website volume reflects activity for press releases and other online public information. The *science.nrao.edu* website volume reflects activity by scientists interested in submitting observing proposals or seeking other professional astronomical information about GBT, VLA, and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

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



APPENDIX A: PUBLICATIONS

2017 NRAO REFEREED PUBLICATIONS

Aalto, S.; Muller, S.; Costagliola, F.; Sakamoto, K.; Gallagher, J. S.; Falstad, N.; König, S.; Dasyra, K.; Wada, K.; Combes, F.; García-Burillo, S.; Kristensen, L. E.; Martín, S.; Van Der Werf, P.; Evans, A. S.; Kotilainen, J. "Luminous, pc-scale CO 6-5 emission in the obscured nucleus of NGC 1377" Astronomy and Astrophysics 608: A22 (8 pp), 2017.

Abbott, B. P.; Abbott, R.; Abbott, T. D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; Adya, V. B.; Affeldt, C.; Afrough, M.; Agarwal, B.; Agathos, M.; Agatsuma, K.; Aggarwal, N.; Aguiar, O. D.; Aiello, L.; Ain, A.; Ajith, P.; Allen, B.; Allen, G.; Allocca, A.; Altin, P. A.; Amato, A.; Ananyeva, A.; Anderson, S. B.; Anderson, W. G.; Angelova, S. V.; Antier, S.; Appert, S.; Arai, K.; Araya, M. C.; Areeda, J. S.; Arnaud, N.; Arun, K. G.; Ascenzi, S.; Ashton, G.; Ast, M.; Aston, S. M.; Astone, P.; Atallah, D. V.; Aufmuth, P.; Aulbert, C.; Aultoneal, K.; Austin, C.; Avila-Alvarez, A.; Babak, S.; Bacon, P.; Bader, M. K. M.; Bae, S.; Baker, P. T.; Baldaccini, F.; Ballardin, G.; Ballmer, S. W.; Banagiri, S.; Barayoga, J. C.; Barclay, S. E.; Barish, B. C.; Barker, D.; Barkett, K.; Barone, F.; Barr, B.; Barsotti, L.; Barsuglia, M.; Barta, D.; Barthelmy, S. D.; Bartlett, J.; Bartos, I.; Bassiri, R.; Basti, A.; Batch, J. C.; Bawaj, M.; Bayley, J. C.; Bazzan, M.; Bécsy, B.; Beer, C.; Bejger, M.; Belahcene, I.; Bell, A. S.; Berger, B. K.; Bergmann, G.; Bero, J. J.; Berry, C. P. L.; Bersanetti, D.; Bertolini, A.; Betzwieser, J.; Bhagwat, S.; Bhandare, R.; Bilenko, I. A.; Billingsley, G.; Billman, C. R.; Birch, J.; Birney, R.; Birnholtz, O.; Biscans, S.; Biscoveanu, S.; Bisht, A.; Bitossi, M.; Biwer, C.; Bizouard, M. A.; Blackburn, J. K.; Blackman, J.; Blair, C. D.; Blair, D. G.; Blair, R. M.; Bloemen, S.; Bock, O.; Bode, N.; Boer, M.; Bogaert, G.; Bohe, A.; Bondu, F.; Bonilla, E.; Bonnand, R.; Boom, B. A.; Bork, R.; Boschi, V.; Bose, S.; Bossie, K.; Bouffanais, Y.; Bozzi, A.; Bradaschia, C.; Brady, P. R.; Branchesi, M.; Brau, J. E.; Briant, T.; Brillet, A.; Brinkmann, M.; Brisson, V.; Brockill, P.; Broida, J. E.; Brooks, A. F.; Brown, D. A.; Brown, D. D.; Brunett, S.; Buchanan, C. C.; Buikema, A.; Bulik, T.; Bulten, H. J.; Buonanno, A.; Buskulic, D.; Buy, C.; Byer, R. L.; Cabero, M.; Cadonati, L.; Cagnoli, G.; Cahillane, C.; Calderón Bustillo, J.; Callister, T. A.; Calloni, E.; Camp, J. B.; Canepa, M.; Canizares, P.; Cannon, K. C.; Cao, H.; Cao, J.; Capano, C. D.; Capocasa, E.; Carbognani, F.; Caride, S.; Carney, M. F.; Casanueva Diaz, J.; Casentini, C.; Caudill, S.; Cavaglià, M.; Cavalier, F.; Cavalieri, R.; Cella, G.; Cepeda, C. B.; Cerdá-Durán, P.; Cerretani, G.; Cesarini, E.; Chamberlin, S. J.; Chan, M.; Chao, S.; Charlton, P.; Chase, E.; Chassande-Mottin, E.; Chatterjee, D.; Chatziioannou, K.; Cheeseboro, B. D.; Chen, H. Y.; Chen, X.; Chen, Y.; Cheng, H.-P.; Chia, H.; Chincarini, A.; Chiummo, A.; Chmiel, T.; Cho, H. S.; Cho, M.; Chow, J. H.; Christensen, N.; Chu, Q.; Chua, A. J. K.; Chua, S.; Chung, A. K. W.; Chung, S.; Ciani, G.; Ciolfi, R.; Cirelli, C. E.; Cirone, A.; Clara, F.; Clark, J. A.; Clearwater, P.; Cleva, F.; Cocchieri, C.; Coccia, E.; Cohadon, P.-F.; Cohen, D.; Colla, A.; Collette, C. G.; Cominsky, L. R.; Constancio, M., Jr.; Conti, L.; Cooper, S. J.; Corban, P.; Corbitt, T. R.; Cordero-Carrión, I.; Corley, K. R.; Cornish, N.; Corsi, A.; Cortese, S.; Costa, C. A.; Coughlin, M. W.; Coughlin, S. B.; Coulon, J.-P.; Countryman, S. T.; Couvares, P.; Covas, P. B.; Cowan, E. E.; Coward, D. M.; Cowart, M. J.; Coyne, D. C.; Coyne, R.; Creighton, J. D. E.; Creighton, T. D.; Cripe, J.; Crowder, S. G.; Cullen, T. J.; Cumming, A.; Cunningham, L.; Cuoco, E.; Dal Canton, T.; Dálya, G.; Danilishin, S. L.; D'antonio, S.; Danzmann, K.; Dasgupta, A.; Da Silva Costa, C. F.; Dattilo, V.; Dave, I.; Davier, M.; Davis, D.; Daw, E. J.; Day, B.; De, S.; Debra, D.; Degallaix, J.; De Laurentis, M.; Deléglise, S.; Del Pozzo, W.; Demos, N.; Denker, T.; Dent, T.; De Pietri, R.; Dergachev, V.; De Rosa, R.; Derosa, R. T.; De Rossi, C.; Desalvo, R.; De Varona, O.; Devenson, J.; Dhurandhar, S.; Díaz, M. C.; Di Fiore, L.; Di Giovanni, M.; Di Girolamo, T.; Di Lieto, A.; Di Pace, S.; Di Palma, I.; Di Renzo, F.; Doctor, Z.; Dolique, V.; Donovan, F.; Dooley, K. L.; Doravari, S.; Dorrington, I.; Douglas, R.; Dovale Álvarez, M.; Downes, T. P.; Drago, M.; Dreissigacker, C.; Driggers, J. C.; Du, Z.; Ducrot, M.; Dupej, P.; Dwyer, S. E.; Edo, T. B.; Edwards, M. C.; Effler, A.; Ehrens, P.; Eichholz, J.; Eikenberry, S. S.; Eisenstein, R. A.; Essick, R. C.; Estevez, D.; Etienne, Z. B.; Etzel, T.; Evans, M.; Evans, T. M.; Factourovich, M.; Fafone, V.; Fair, H.; Fairhurst, S.; Fan, X.; Farinon, S.; Farr, B.; Farr, W. M.; Fauchon-Jones, E. J.; Favata, M.; Fays, M.; Fee, C.; Fehrmann, H.; Feicht, J.; Fejer, M. M.; Fernandez-Galiana, A.; Ferrante, I.; Ferreira, E. C.; Ferrini, F.; Fidecaro, F.; Finstad, D.; Fiori, I.; Fiorucci, D.; Fishbach, M.; Fisher, R. P.; Fitz-Axen, M.; Flaminio, R.; Fletcher, M.; Fong, H.; Font, J. A.; Forsyth, P. W. F.; Forsyth, S. S.; Fournier, J.-D.; Frasca, S.; Frasconi, F.; Frei, Z.; Freise, A.; Frey, R.; Frey, V.; Fries, E. M.; Fritschel, P.; Frolov, V. V.; Fulda, P.; Fyffe, M.; Gabbard, H.; Gadre, B. U.; Gaebel, S. M.; Gair, J. R.; Gammaitoni, L.; Ganija, M. R.; Gaonkar, S. G.; Garcia-Quiros, C.; Garufi, F.; Gateley, B.; Gaudio, S.; Gaur, G.; Gayathri, V.; Gehrels, N.; Gemme, G.; Genin, E.; Gennai, A.; George, D.; George, J.; Gergely, L.; Germain, V.; Ghonge, S.; Ghosh, Abhirup; Ghosh, Archisman; Ghosh, S.; Giaime, J. A.; Giardina, K. D.; Giazotto, A.; Gill, K.; Glover, L.; Goetz, E.; Goetz, R.; Gomes, S.; Goncharov, B.; González, G.; Gonzalez Castro, J. M.; Gopakumar, A.; Gorodetsky, M. L.; Gossan, S. E.; Gosselin, M.; Gouaty, R.; Grado, A.; Graef, C.; Granata, M.; Grant, A.; Gras, S.; Gray, C.; Greco, G.; Green, A. C.; Gretarsson, E. M.; Griswold, B.; Groot, P.; Grote, H.; Grunewald, S.; Gruning, P.; Guidi, G. M.; Guo, X.; Gupta, A.; Gupta, M. K.; Gushwa, K. E.; Gustafson, E. K.; Gustafson, R.; Halim, O.; Hall, B. R.; Hall, E. D.; Hamilton, E. Z.; Hammond, G.; Haney, M.; Hanke, M. M.; Hanks, J.; Hanna, C.; Hannam, M. D.; Hannuksela, O. A.; Hanson, J.; Hardwick, T.; Harms, J.; Harry, G. M.; Harry, I. W.; Hart, M. J.; Haster, C.-J.; Haughian, K.; Healy, J.; Heidmann, A.; Heintze, M. C.; Heitmann, H.; Hello, P.; Hemming, G.; Hendry, M.; Heng, I. S.; Hennig, J.; Heptonstall, A. W.; Heurs, M.; Hild, S.; Hinderer, T.; Hoak, D.; Hofman, D.; Holt, K.; Holz, D. E.; Hopkins, P.; Horst, C.; Hough, J.; Houston, E. A.; Howell, E. J.; Hreibi, A.; Hu, Y. M.; Huerta, E. A.; Huet, D.; Hughey, B.; Husa, S.; Huttner, S. H.; Huynh-Dinh, T.; Indik, N.; Inta, R.; Intini, G.; Isa, H. N.; Isac, J.-M.; Isi, M.; Iyer, B. R.; Izumi, K.; Jacqmin, T.; Jani, K.; Jaranowski, P.; Jawahar, S.; Jiménez-Forteza, F.; Johnson, W. W.; Jones, D. I.; Jones, R.; Jonker, R. J. G.; Ju, L.; Junker, J.; Kalaghatgi, C. V.; Kalogera, V.; Kamai, B.; Kandhasamy, S.; Kang, G.; Kanner, J. B.; Kapadia, S. J.; Karki, S.; Karvinen, K. S.; Kasprzack, M.; Katolik, M.; Katsavounidis, E.; Katzman, W.; Kaufer, S.; Kawabe, K.; Kéfélian, F.; Keitel, D.; Kemball, A. J.; Kennedy, R.; Kent, C.; Key, J. S.; Khalili, F. Y.; Khan, I.; Khan, S.; Khan, Z.; Khazanov, E. A.; Kijbunchoo, N.; Kim, Chunglee; Kim, J. C.; Kim, K.; Kim, W.; Kim, W. S.; Kim, Y.-M.; Kimbrell, S. J.; King, E. J.; King, P. J.; Kinley-Hanlon, M.; Kirchhoff, R.; Kissel, J. S.; Kleybolte, L.; Klimenko, S.; Knowles, T. D.; Koch, P.; Koehlenbeck, S. M.; Koley, S.; Kondrashov, V.; Kontos, A.; Korobko, M.; Korth, W. Z.; Kowalska, I.; Kozak, D. B.; Krämer, C.; Kringel, V.; Krishnan, B.; Królak, A.; Kuehn, G.; Kumar, P.; Kumar, R.; Kumar, S.; Kuo, L.; Kutynia, A.; Kwang, S.; Lackey, B. D.; Lai, K. H.; Landry, M.; Lang, R. N.; Lange, J.; Lantz, B.; Lanza, R. K.; Larson, S. L.; Lartaux-Vollard, A.; Lasky, P. D.; Laxen, M.; Lazzarini, A.; Lazzaro, C.; Leaci, P.; Leavey, S.; Lee, C. H.; Lee, H. K.; Lee, H. M.; Lee, H. 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I.; Magaña-Sandoval, F.; Magaña Zertuche, L.; Magee, R. M.; Majorana, E.; Maksimovic, I.; Man, N.; Mandic, V.; Mangano, V.; Mansell, G. L.; Manske, M.; Mantovani, M.; Marchesoni, F.; Marion, F.; Márka, S.; Márka, Z.; Markakis, C.; Markosyan, A. S.; Markowitz, A.; Maros, E.; Marquina, A.; Marsh, P.; Martelli, F.; Martellini, L.; Martin, I. W.; Martin, R. M.; Martynov, D. V.; Mason, K.; Massera, E.; Masserot, A.; Massinger, T. J.; Masso-Reid, M.; Mastrogiovanni, S.; Matas, A.; Matichard, F.; Matone, L.; Mavalvala, N.; Mazumder, N.; Mccarthy, R.; Mcclelland, D. E.; Mccormick, S.; Mcculler, L.; Mcguire, S. C.; Mcintyre, G.; Mciver, J.; Mcmanus, D. J.; Mcneill, L.; Mcrae, T.; Mcwilliams, S. T.; Meacher, D.; Meadors, G. D.; Mehmet, M.; Meidam, J.; Mejuto-Villa, E.; Melatos, A.; Mendell, G.; Mercer, R. A.; Merilh, E. L.; Merzougui, M.; Meshkov, S.; Messenger, C.; Messick, C.; Metzdorff, R.; Meyers, P. M.; Miao, H.; Michel, C.; Middleton, H.; Mikhailov, E. E.; Milano, L.; Miller, A. L.; Miller, B. B.; Miller, J.; Millhouse, M.; Milovich-Goff, M. C.; Minazzoli, O.; Minenkov, Y.; Ming, J.; Mishra, C.; Mitra, S.; Mitrofanov, V. P.; Mitselmakher, G.; Mittleman, R.; Moffa, D.; Moggi, A.; Mogushi, K.; Mohan, M.; Mohapatra, S. R. P.; Montani, M.; Moore, C. J.; Moraru, D.; Moreno, G.; Morriss, S. R.; Mours, B.; Mow-Lowry, C. M.; Mueller, G.; Muir, A. W.; Mukherjee, Arunava; Mukherjee, D.; Mukherjee, S.; Mukund, N.; Mullavey, A.; Munch, J.; Muñiz, E. A.; Muratore, M.; Murray, P. G.; Napier, K.; Nardecchia, I.; Naticchioni, L.; Nayak, R. K.; Neilson, J.; Nelemans, G.; Nelson, T. J. N.; Nery, M.; Neunzert, A.; Nevin, L.; Newport, J. M.; Newton, G.; Ng, K. K. Y.; Nguyen, P.; Nguyen, T. T.; Nichols, D.; Nielsen, A. B.; Nissanke, S.; Nitz, A.; Noack, A.; Nocera, F.; Nolting, D.; North, C.; Nuttall, L. K.; Oberling, J.; O'dea, G. D.; Ogin, G. H.; Oh, J. J.; Oh, S. H.; Ohme, F.; Okada, M. A.; Oliver, M.; Oppermann, P.; Oram, Richard J.; O'reilly, B.; Ormiston, R.; Ortega, L. F.; O'shaughnessy, R.; Ossokine, S.; Ottaway, D. J.; Overmier, H.; Owen, B. J.; Pace, A. E.; Page, J.; Page, M. A.; Pai, A.; Pai, S. A.; Palamos, J. R.; Palashov, O.; Palomba, C.; Pal-Singh, A.; Pan, Howard; Pan, Huang-Wei; Pang, B.; Pang, P. T. H.; Pankow, C.; Pannarale, F.; Pant, B. C.; Paoletti, F.; Paoli, A.; Papa, M. A.; Parida, A.; Parker, W.; Pascucci, D.; Pasqualetti, A.; Passaquieti, R.; Passuello, D.; Patil, M.; Patricelli, B.; Pearlstone, B. L.; Pedraza, M.; Pedurand, R.; Pekowsky, L.; Pele, A.; Penn, S.; Perez, C. J.; Perreca, A.; Perri, L. M.; Pfeiffer, H. P.; Phelps, M.; Piccinni, O. J.; Pichot, M.; Piergiovanni, F.; Pierro, V.; Pillant, G.; Pinard, L.; Pinto, I. M.; Pirello, M.; Pitkin, M.; Poe, M.; Poggiani, R.; Popolizio, P.; Porter, E. K.; Post, A.; Powell, J.; Prasad, J.; Pratt, J. W. W.; Pratten, G.; Predoi, V.; Prestegard, T.; Price, L. R.; Prijatelj, M.; Principe, M.; Privitera, S.; Prodi, G. A.; Prokhorov, L. G.; Puncken, O.; Punturo, M.; Puppo, P.; Pürrer, M.; Qi, H.; Quetschke, V.; Quintero, E. A.; Quitzow-James, R.; Raab, F. J.; Rabeling, D. S.; Radkins, H.; Raffai, P.; Raja, S.; Rajan, C.; Rajbhandari, B.; Rakhmanov, M.; Ramirez, K. E.; Ramos-Buades, A.; Rapagnani, P.; Raymond, V.; Razzano, M.; Read, J.; Regimbau, T.; Rei, L.; Reid, S.; Reitze, D. H.; Ren, W.; Reyes, S. D.; Ricci, F.; Ricker, P. M.; Rieger, S.; Riles, K.; Rizzo, M.; Robertson, N. A.; Robie, R.; Robinet, F.; Rocchi, A.; Rolland, L.; Rollins, J. G.; Roma, V. J.; Romano, R.; Romel, C. L.; Romie, J. H.; Rosinska, D.; Ross, M. P.; Rowan, S.; Rüdiger, A.; Ruggi, P.; Rutins, G.; Ryan, K.; Sachdev, S.; Sadecki, T.; Sadeghian, L.; Sakellariadou, M.; Salconi, L.; Saleem, M.; Salemi, F.; Samajdar, A.; Sammut, L.; Sampson, L. M.; Sanchez, E. J.; Sanchez, L. E.; Sanchis-Gual, N.; Sandberg, V.; Sanders, J. R.; Sassolas, B.; Sathyaprakash, B. S.; Saulson, P. R.; Sauter, O.; Savage, R. 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APPENDIX A: PUBLICATIONS

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APPENDIX B: EVENTS & MILESTONES

3-7 January
229th AAS meeting
Grapevine, Texas
NRAO Town Hall
NRAO Exhibit
Summer Student Presentations
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

4 January
NRAO Semester 2017B Call for Proposals opened

16-18 January
ALMA Band 1 Science Workshop
Taipei, Taiwan

25-27 January
ALMA Data Reduction Party
Charlottesville, Virginia

1 February
NRAO Semester 2017B Call for Proposals deadline

9-10 February
AUI Board of Trustees meeting
Houston, TX

21 March
ALMA Cycle 5 Call for Proposals published
Joint ALMA Observatory, Chile

27-28 March
2017 NRAO Postdoctoral Fellows Symposium
Charlottesville, Virginia

31 March
NRAO / LBO Community Day
University of Michigan
Ann Arbor, Michigan

20 April
ALMA Cycle 5 Call for Proposals deadline
Joint ALMA Observatory, Chile

25-26 April
NRAO / LBO Community Day
UNAM - Morelia
Morelia, Mexico

27 April
AUI Executive Committee meeting
Washington, D.C.

31 May
ALMA North American Science Advisory Committee (ANASAC) meeting
Charlottesville, Virginia

1-2 June
NRAO Users Committee Meeting
Charlottesville, Virginia

4-8 June
230th AAS meeting
Austin, TX
NRAO Exhibit
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

4-8 June
Astrobiology Graduate Conference
Charlottesville, Virginia

9-11 June
Women in Astronomy IV
Austin, TX

22-23 June
AUI Board of Trustees meeting
Socorro, New Mexico

26-29 June
Developing the ngVLA Science Program Workshop
Socorro, New Mexico

30 June
NRAO Semester 2017A Call for Proposals opened

10-11 July
Community Day - Cornell University
Ithaca, New York

24-26 July
Fred Lo Science Symposium
Charlottesville, Virginia

27-29 July
5th U.S. – China Workshop on Radio Astronomy Science & Technology
Charlottesville, Virginia

1 August
NRAO Semester 2018A Call for Proposals deadline

2-4 August
U.S. Radio–Millimeter–Submillimeter Futures III
Berkeley, California

19-26 August
International Union of Radio Science General Assembly & Scientific Symposium
Montreal, Canada

14 September
AUI Executive Committee meeting
Washington, D.C.

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

30 September
ALMA Cycle 4 science observations ended
Joint ALMA Observatory, Chile

1 October
ALMA Cycle 5 science observations began
Joint ALMA Observatory, Chile

3-5 October
ALMA Long Baseline Workshop
Mielparque Kyoto, Japan

19-20 October
AUI Board of Trustees meeting
Washington, D.C.

23-27 October
6th VLA Data Reduction Workshop
Socorro, New Mexico

24 October
Jansky Lecture
Charlottesville, Virginia

3 November
33rd New Mexico Symposium & Jansky Lecture
Socorro, New Mexico

13-16 November
SuperComputing17 (SC17) exhibition
Denver, Colorado

29 November
AUI Executive Committee meeting
Washington, D.C.

29 November – 2 December
The Origin of Galaxies, Stars, and Planets in the Era of ALMA
Pasadena, California

6-7 December
NSF Program Review
Charlottesville, Virginia

18 December
ALMA Cycle 6 Pre-Announcement
Joint ALMA Observatory, Chile

APPENDIX C: ADVISORY COMMITTEES

Pablo Carrillo

ALMA North American Science Advisory Committee (ANASAC)

Subcommittee of Users Committee

ANASAC members who are also a member of the ALMA Science Advisory Committee (ASAC) are indicated along with finl year of ANASAC service.

Laura Chomiuk
Michigan State University, 2017

Shih-Ping Lai
National Tsing-Hua University, 2018

Dan Marrone
University of Arizona, 2019

Giles Novak (ASAC)
Northwestern University, 2020

Karin Öberg
Harvard-Smithsonian Center for Astrophysics, 2018

Douglas Scott (ASAC)
Univ. British Columbia, 2017

Stephen White (ASAC)
AFRL Space Vehicles Directorate, 2020

Christine Wilson (ASAC)
McMaster University, 2020

NRAO Users Committee

Users Committee members who are also members of the ALMA North American Science Advisory Committee (ANASAC), the ALMA Science Advisory Committee (ASAC), and the Common Astronomy Software Applications (CASA) Users Committee are indicated, along with the final year of UC service.

Loren D. Anderson, Chair
West Virginia University, 2018

Laura Chomiuk (ANASAC)
Michigan State University, 2017

Steven W. Ellingson
Virginia Tech, 2018

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

Dan Marrone (ANASAC)
University of Arizona, 2019

Christine Wilson (ANASAC/ASAC)
McMaster University, 2020

Shami Chatterjee
Cornell University, 2017

Christopher De Pree (CASA)
Bradley Observatory, 2021

Karin Öberg (ANASAC)
Harvard-Smithsonian Center for Astrophysics, 2018

Joseph Lazio
JPL/CIT, 2017

Giles Novak (ANASAC/ASAC)
Northwestern University, 2020

Trish Henning
University of New Mexico, 2019

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

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

Fabian Walter, UC Co-Chair
Max Planck Inst. für Astronomie, 2019

Stephen White (ANASAC/ASAC)
AFRL Space Vehicles Directorate, 2020

AUI Visiting Committee

Final year of VC service is indicated.

Edwin (Ted) Bergin
University of Michigan, Chair, 2018

Rachel Akeson
IPAC/Caltech, 2020

Katherine Blundell
Oxford University, 2018

James Jackson
Boston University, 2020

Luis Felipe Rodriguez Jorge
Instituto de Radioastronomia y Astrofisica, 2020

Patricia L. McBride
Fermi National Accelerator Laboratory, 2021

Margaret Meixner
Space Telescope Science Institute, 2020

David Reitze
LIGO Laboratory, 2021

Greg Taylor
University of New Mexico, 2018

Dan Werthimer
University of California – Berkeley, 2018

Belinda Wilkes
Chandra X-Ray Center, 2021

Time Allocation Committee

Semester 2017B

Kristine Spekkens
Extragalactic Structure (EGS)
Queen's University

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

Mark Whittle
Active Galactic Nuclei (AGN)
University of Virginia

Russ Taylor
Normal Galaxies, Groups and Clusters (NGA)
University of Cape Town

Dominik Riechers, Chair
High Redshift and Source Surveys (HIZ)
Cornell University

Ron Allen
Interstellar Medium (ISM)
Space Telescope Science Institute

Lee Mundy
Star Formation (SFM)
University of Maryland

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

Semester 2018A

Kristine Spekkens
Extragalactic Structure (EGS)
Queen's University

Anita Richards
Solar System, Stars, and Planetary Systems (SSP)
University of Manchester

Mark Whittle
Active Galactic Nuclei (AGN)
University of Virginia

Russ Taylor
Normal Galaxies, Groups and Clusters (NGA)
University of Cape Town

Dominik Riechers, Chair
High Redshift and Source Surveys (HIZ)
Cornell University

Ron Allen
Interstellar Medium (ISM)
Space Telescope Science Institute

Lee Mundy
Star Formation (SFM)
University of Maryland

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

APPENDIX D: FISCAL YEAR 2017 FINANCIAL SUMMARY

(all figures are $k USD)

Functional Work Breakdown Structure Element	GBO	VLA	LBO	ALMA	GB Ops	NM Ops	HQ & CV Ops	CDL	External Grants	Total
Administrative Services	$4,767.03	$2,120.34	$1,845.01	$10,986.18	$845.04	$1,991.35	($1,335.27)	$0.00	$0.00	$21,219.68
Development Programs	$0.00	$514.48	$0.00	$2,220.42	$0.00	$0.00	$156.57	$3,240.84	$0.00	$6,132.30
Director's Office	$704.36	$0.00	$381.12	$5,550.49	$0.00	$2.04	$3,843.65	$0.00	$0.00	$10,481.65
Education & Public Outreach	$361.93	$0.00	$0.00	$542.72	$0.00	$0.00	$552.28	$0.00	$0.00	$1,456.93
Science Operations	$530.47	$23.18	$11.01	$9,256.33	$0.00	$0.00	$7,742.96	$0.00	$0.00	$17,563.95
Telescope Operations	$5,011.75	$9,994.89	$3,983.83	$12,478.96	$0.00	$7.29	$985.88	$3.44	$0.00	$32,466.04
External Grants	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$5,480.61	$5,480.61
Grand Total	**$11,375.5**	**$12,652.9**	**$6,221.0**	**$41,035.1**	**$845.0**	**$2,000.7**	**$11,946.1**	**$3,244.3**	**$5,480.6**	**$94,801.2**

Fiscal Year 2017 = 1 October 2016 – 30 September 2017

VLA and Setting Moon
Credit: Jeff Hellerman (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
DMS	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
GBO	Green Bank, West Virginia
GBT	Green Bank Telescope
GHz	Gigahertz
GMVA	Global 3mm VLBI Array
GO	General Observing
HBT	Heterojunction Bipolar Transistors
HERA	Hydrogen Epoch of Reinonization Array
HIZ	High Redshift and Source Surveys
HPC	High Performance Computing
HR	Human Resources
HRIS	HR Information Systems
HSA	High Sensitivity Array
HST	Hubble Space Telescope
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IfA	Institute for Astronomy
IGM	Intergalactic Medium
IPAC	Infrared Processing and Analysis Center
IPT	Integrated Product Team
ISM	Interstellar Medium

ITU-R . . . . . International Telecommunication Union – Radiocommunication
IUCAF . . . . . Inter-Union Committee on the Allocation of Frequencies
JAO . . . . . Joint ALMA Observatory
JPL. . . . . Jet Propulsion Laboratory
kHz . . . . . kiloHertz
KFPA . . . . . K-band Focal Plane Array
Kpc . . . . . kiloparsec
LBC . . . . . Long Baseline Campaign
LBC . . . . . Long Baseline Observatory
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
MWA . . . . . 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 (Japan)
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

APPENDIX E: ACRONYMS

RF . . . . . Radio Frequency
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
STEAM . . . . . Science, Technology, Engineering, Art, and Mathematics
STScI . . . . . Space Telescope Science Institute
SUS . . . . . Scientific User Support
SWG. . . . . Science Working Group
TAC . . . . . Time Allocation Committee
TES . . . . . Transition Edge Sensor
THz . . . . . TeraHertz
TTA . . . . . Telescope Time Allocation
UVML. . . . . University of Virginia Microfabrication Laboratory
VA . . . . . Virginia
VEGAS . . . . . Versatile Green Bank Astronomical Spectrometer
VLA . . . . . Very Large Array
VLASS . . . . . Very Large Array Sky Survey
VLBA . . . . . Very Long Baseline Array
VLBI . . . . . Very Long Baseline Interferometry
VLITE . . . . . VLA Ionospheric and Transient Experiment
WIDAR . . . . . Wideband Interferometric Digital Architecture Correlator
WMAP . . . . . Wilkinson Microwave Anisotropy Probe
WV . . . . . West Virginia
WV SPOT . . . . . West Virginia Space Public Outreach Team
XSEDE . . . . . Extreme Science and Engineering Discovery Environment

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