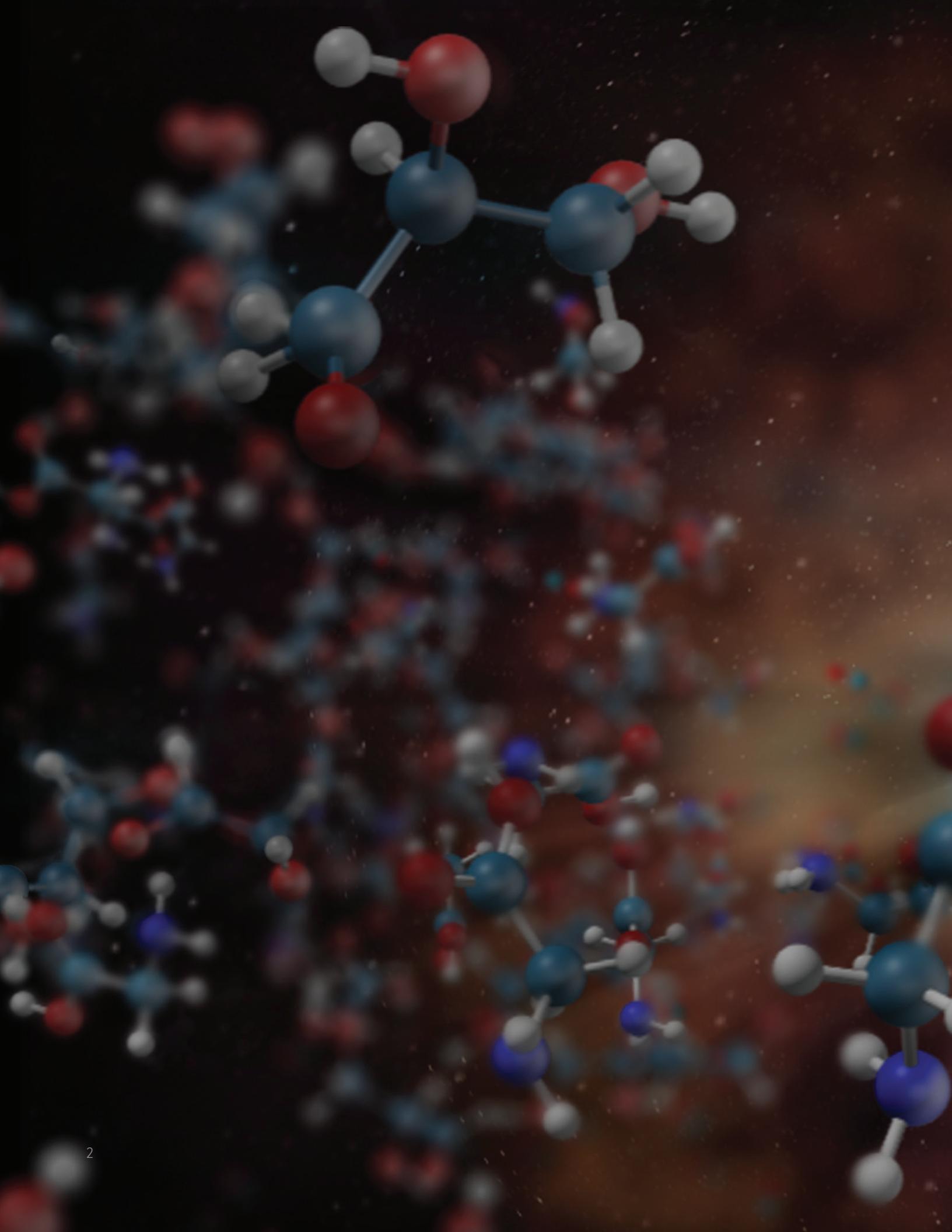


2018 ANNUAL REPORT



NATIONAL RADIO
ASTRONOMY OBSERVATORY



Contents

DIRECTOR'S REPORT	4
NRAO IN BRIEF	6
SCIENCE HIGHLIGHTS	8
NORTH AMERICAN ALMA OPERATIONS	20
NEW MEXICO OPERATIONS	26
SCIENCE SUPPORT & RESEARCH	36
DATA MANAGEMENT & SOFTWARE	44
CENTRAL DEVELOPMENT LABORATORY	50
EDUCATION & PUBLIC OUTREACH	60
MANAGEMENT & ADMINISTRATION	66
PERFORMANCE METRICS	76
APPENDICES	
A. PUBLICATIONS	80
B. EVENTS & MILESTONES	122
C. ADVISORY COMMITTEES	124
D. FINANCIAL SUMMARY	126
E. ACRONYMS	128

NRAO FACTS & FIGURES

436
EMPLOYEES



57
MEDIA RELEASES



889
REFEREED
SCIENCE PUBLICATIONS



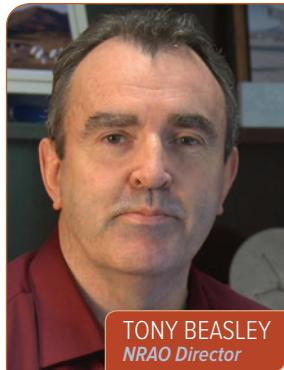
COVER AND LEFT: Stills from ngVLA science case video featured at AAS meeting.

Credit: NRAO/AUI/NSF, S. Dagnello



The Very Large Array. Credit: NRAO/AUI/NSF, B. Kent

DIRECTOR'S REPORT



TONY BEASLEY
NRAO Director

The NRAO and our community enjoyed an excellent year in 2018. More than 889 scientific papers were published by our user community, and the Observatory distributed more than 57 press releases that described cutting-edge science crafted with the Atacama Large Millimeter/submillimeter Array (ALMA), the Karl G. Jansky Very Large Array (VLA), and the Very Long Baseline Array (VLBA). Highlights included ALMA surveying planet-forming disks in nearby stars; ALMA detecting oxygen in the early Universe; the VLA Sky Survey revealing an “orphan gamma-ray burst” and helping to pinpoint the source responsible for an energetic cosmic neutrino detection at the South Pole; and the VLBA detecting a jet of superfast material emerging from a neutron star merger detected by the Laser Interferometer Gravitational-Wave Observatory. ALMA’s productivity is setting new records, and the proposals received for all NRAO instruments suggest that we are delivering data to the scientific community of outstanding scientific impact.

After the National Science Foundation (NSF) Portfolio Review in 2012, the Green Bank Telescope (GBT) and the VLBA were administratively separated from NRAO into the Green Bank Observatory (GBO) and Long Baseline Observatory (LBO), respectively. A major VLBA partnership with the U.S. Naval Observatory was established in 2017, and thereafter the NSF determined that reintegrating the VLBA with NRAO was in the community’s best interests. The VLBA also secured funding to install optical fiber to all antennas, greatly enhancing their data capabilities. The VLBA future seems very bright.

Each of the key NRAO strategic initiatives for the next decade are now underway. The design and development requisite to a next-generation VLA is making great progress with substantial input from the community. ALMA development continues, with a correlator upgrade underway and new Band 6 cartridge run in planning. Growth of the Central Development Lab and connection to ngVLA and ALMA needs is continuing. In Education and Public Outreach, Diversity and Broadening Participation, NRAO is leading the NSF astronomy community. Our 2018 Jansky Lecturer was Prof. Roger Blandford (Stanford), who gave an excellent public lecture on key aspects of radio astronomy history and their relevance to current research.

Our community’s data needs are becoming more complex, and we are responding. The Science-Ready Data Products (SRDP) initiative is leading the field down ALMA’s proven path, enabling scientists to focus on the science, and removing much of the burden of big data and complex processing. In 2019, we will begin to see substantial SRDP benefits.

The Observatory is also helping to train the next generation of professional staff and researchers. Through our student programs, funding to support science visits to our sites, our highly successful National Astronomy Consortium (NAC) and National and International Non-Traditional Exchange (NINE) programs, Reber Fellowships, Jansky Fellows and many other training and award programs, we engage with people from all walks of life, develop new talent, and nurture a lifelong interest in science for many.

The next two years – 2019 and 2020 – will be particularly exciting. We have a clear strategic plan, exciting challenges, and the best staff in the business. Together, we operate one of the world’s great observatories. I am proud of what we do and feel privileged to work here. Stay tuned.

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



ALMA



VLA

Created in 1956 by the NSF and AUI, the NRAO designs, builds, and operates the most capable astronomical telescopes and instruments at radio wavelengths. In 2018, the NRAO operated a complementary suite of three world-class telescopes, each the world leader in its domain: the international **Atacama Large Millimeter/submillimeter Array (ALMA)**, the **Karl G. Jansky Very Large Array (VLA)**, and the **Very Long Baseline Array (VLBA)**.

ALMA is the largest ground-based global astronomy endeavor in history. Composed of 66 high-precision antennas on an excellent 5000+ meter elevation site in northern Chile, ALMA is delivering orders of magnitude improvements in millimeter-wave 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 planet formation, and studying the energy output from supermassive black holes in starburst galaxies. The community's strong interest in

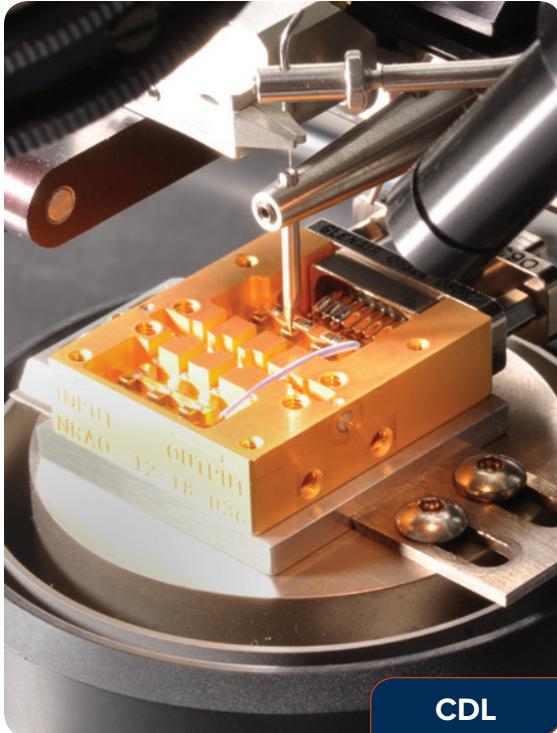
ALMA has been repeatedly demonstrated by the substantial oversubscription of each Call for Proposals and the available observing time.

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-wavelength imaging array and is yielding dramatic new science results that range from Galactic protostellar clouds to the molecular gas in early galaxies.

The **VLBA** is the premier dedicated Very Long Baseline Interferometer (VLBI) array. Astrometry with the VLBA has



VLBA



CDL

reached the precision of a few micro-arcseconds, supporting distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and moving with the Hubble flow. When used in conjunction with the phased VLA and GBT, the resultant High Sensitivity Array (HSA) vastly enhances the sensitivity of VLBI observations and broadens the range of novel scientific research.

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 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.

NRAO telescopes, operated individually and synergistically throughout 2018 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; fundamental physics; molecular gas in early galaxies; the environments of supermassive black holes; cosmology; and much more.

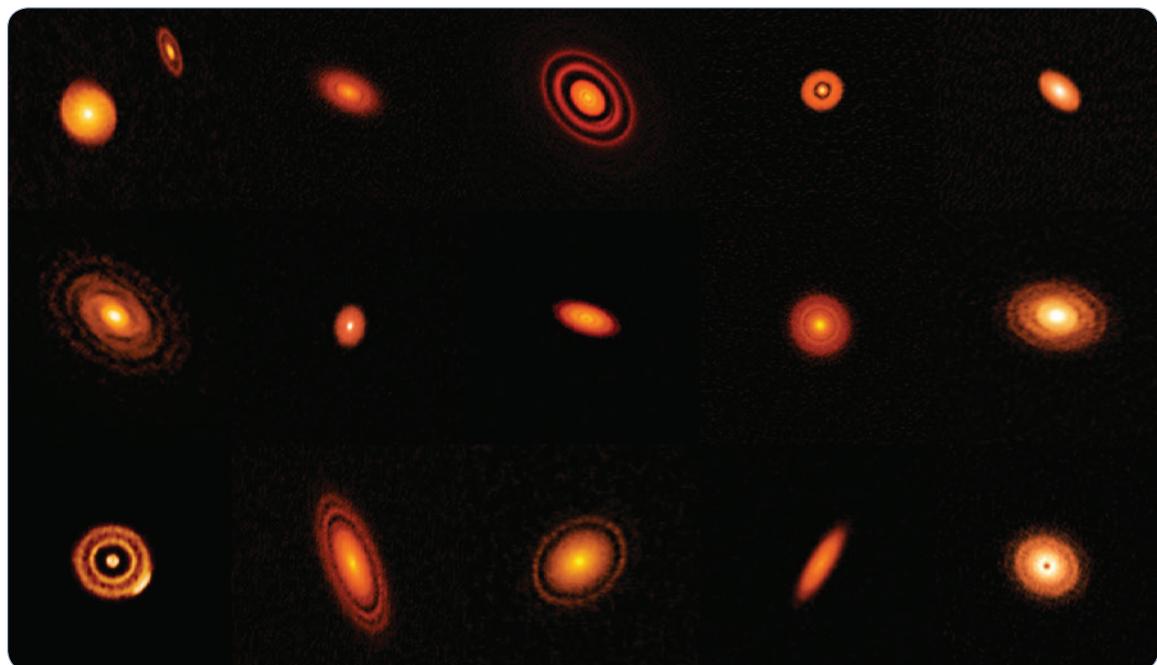
In addition to research, the NRAO broadly impacts science and society via its education and public outreach programs. A diverse program of compelling science, technology, engineering, art, and mathematics (STEAM) education programs are introducing young people every year to the excitement and opportunities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

SCIENCE HIGHLIGHTS

Disk Substructures at High Angular Resolution

The Disk Substructures at High Angular Resolution Project (DSHARP) is one of the initial Large Programs conducted with ALMA. The primary goal of DSHARP is to find and characterize substructures in the spatial distributions of solid particles for a sample of 20 nearby protoplanetary disks, using very high resolution – approximately 0.035 arcseconds or 5 Astronomical Units (AU), Full Width at Half Maximum (FWHM) – observations of their 240 GHz (1.25 mm) continuum emission. These data provide a first homogeneous look at the small-scale features in disks that are directly relevant to the planet formation process, quantifying their prevalence, morphologies, spatial scales, spacings, symmetry, and amplitudes, for targets with a variety of disk and stellar host properties. The authors find that these substructures are ubiquitous in this sample of large, bright disks. They are most frequently manifested as concentric, narrow emission rings and depleted gaps, although large-scale spiral patterns and small arc-shaped azimuthal asymmetries are also present in some cases. These substructures are found at a wide range of disk radii (from a few AU to more than 100 AU), are usually compact (≤ 10 AU), and show a wide range of amplitudes (brightness contrasts). In this overview contribution, the authors discuss the motivation for the DSHARP project, describe the survey design and the sample properties, detail the observations and data calibration, highlight some basic results, and provide a general overview of the key conclusions that are presented in more detail in a series of accompanying articles, also published in *Astrophysical Journal Letters*. The DSHARP data – including visibilities, images, calibration scripts, and more – are released for community use at <https://almascience.org/alma-data/lp/DSHARP>.

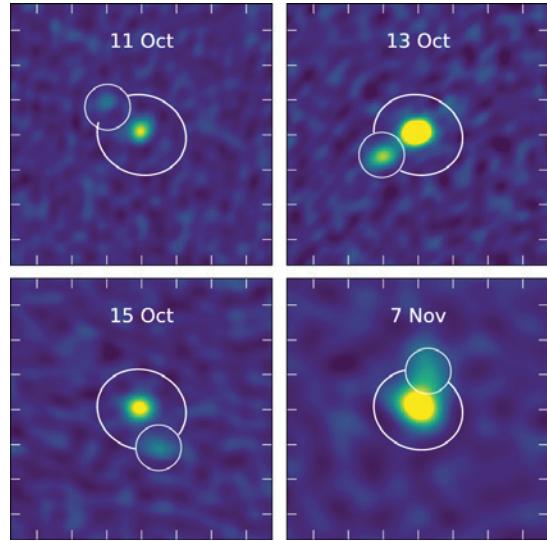


ALMA's high-resolution images of nearby protoplanetary disks from the Disk Substructures at High Angular Resolution Project (DSHARP). Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello.

Publication: Sean M. Andrews (Harvard-Smithsonian Center for Astrophysics) et al., *The Disk Substructures at High Angular Resolution Project (DSHARP): I. Motivation, Sample, Calibration, and Overview*, *Astrophysical Journal Letters*, 869, L41, 20 December 2018.

Kuiper Belt Objects & Their Moons

Most of the largest objects in the Kuiper Belt are known to have one or more satellites orbiting the parent body. The majority of these satellites have a small fractional brightness compared to their parent body. Even before the discovery of any of these small satellites, models predicted that giant impacts onto differentiated bodies would preferentially form icy satellites with a small fractional mass. Many of the known satellites to large Kuiper Belt objects (KBOs) appear consistent with this paradigm. While satellites of mid- to small-Kuiper Belt objects tend to be similar in size and brightness to their primaries, the largest Kuiper Belt objects preferentially have satellites with small fractional brightness. In the two cases where the sizes and albedos of the small faint satellites have been measured, these satellites are seen to be small icy fragments consistent with collisional formation. In this research, the authors examine Dysnomia and Vanth, the satellites of Eris and Orcus, respectively. Using ALMA, the authors obtained the first spatially resolved observations of these systems at thermal wavelengths. Vanth is easily seen in individual images, and Dysnomia was detected at the 3.5σ level by stacking all the available data on the known position of the satellite. The diameter of Dysnomia and Vanth were calculated to be 700 ± 115 km and 475 ± 75 km, respectively, with albedos of 0.04 and 0.08, respectively. Both Dysnomia and Vanth are indistinguishable from typical Kuiper Belt objects of their size.



ALMA observations of the Orcus–Vanth system. The images are centered on Orcus, and the predicted position of Vanth is circled. Tick marks in the images are 200 milli-arcseconds. Vanth is clearly detected even in the lower-resolution November 7 data.



ALMA Photo by Pablo Carillo

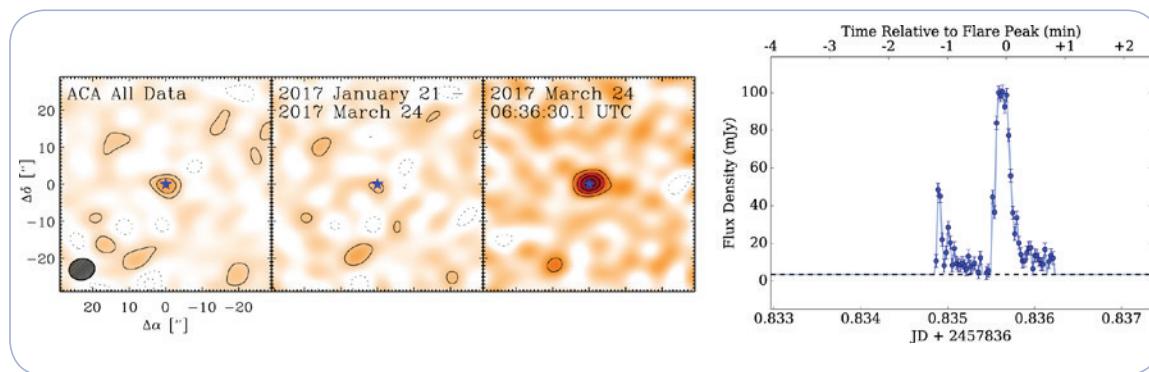
Publication: Michael E. Brown (California Institute of Technology) & Bryan J. Butler (NRAO), *Medium-sized satellites of Large Kuiper Belt Objects*, Astronomical Journal, 156, 164 (October 2018).

SCIENCE HIGHLIGHTS

Capturing a Flare of Proxima Centauri

Low mass M-type stars are the most common stars in the Galaxy and have a high frequency of Earth-sized planets. There is debate, however, as to what extent planets around M dwarfs would be amenable to life. Late M-type stars have long pre-main sequence phases during which the stellar luminosity can change significantly, as well as high stellar activity throughout their lifetimes. Proxima Centauri (spectral type M5.5V) has garnered tremendous recent interest due to the radial velocity detection of a potentially Earth-mass planet within the habitable zone and a new candidate transit event. At a distance of just 1.3 parsecs, Proxima Centauri b ($m_p \sin i = 1.3 M_{\oplus}$, $a = 0.05$ AU) is the closest extrasolar planet to the Solar System. Proxima Centauri has long been known as a flare star.

MacGregor et al. present new analyses of ALMA 12 m and Atacama Compact Array (ACA) observations at 233 GHz (1.3 mm) of the Proxima Centauri system acquired 21 January – 25 April 2017. These analyses reveal that the star underwent a significant flaring event during one of the ACA observations on 24 March 2017. The event lasted ~1 minute and reached a peak flux density nearly 1000X times brighter than the star's quiescent emission. At the flare peak, the continuum emission is characterized by a steeply falling spectral index with frequency $F(\nu) \propto \nu^{\alpha}$ with $\alpha = -1.77 \pm 0.45$, and a lower limit on the fractional linear polarization of $|Q|/|I| = 0.19 \pm 0.02$. Because the ACA observations do not show any quiescent excess emission, the authors conclude that there is no need to invoke the presence of a dust belt at 1–4 AU. They also posit that the slight excess flux density of 101 ± 9 μ Jy observed in the 12m observations, compared to the photospheric flux density of 74 ± 4 μ Jy extrapolated from infrared wavelengths, may be due to coronal heating from continual smaller flares, as is seen for AU Mic, another nearby well-studied M dwarf flare star.



Millimeter emission from Proxima Centauri is detected only in a small subset of the ACA data. [Left] The image at far left combines all 13 ACA observations. The middle image panel shows the first 12 observations combined. The right image panel shows only the final ACA observation. A point source is clearly detected at the stellar location only in the final observation. The blue star indicates the stellar position. The 7.27×5.51 arcsec synthesized beam is indicated by the ellipse in the lower-left corner. [Right] A light curve of the transient point source detected in the second to last scan of the observation on 2017 March 24. Flux densities (blue points) are only plotted when a central point source was detected. For all other times, the flux density is less than the 3σ detection threshold (3.5 mJy) indicated by the dashed black line. A series of small oscillations in flux density was followed by a much larger flare-like event.

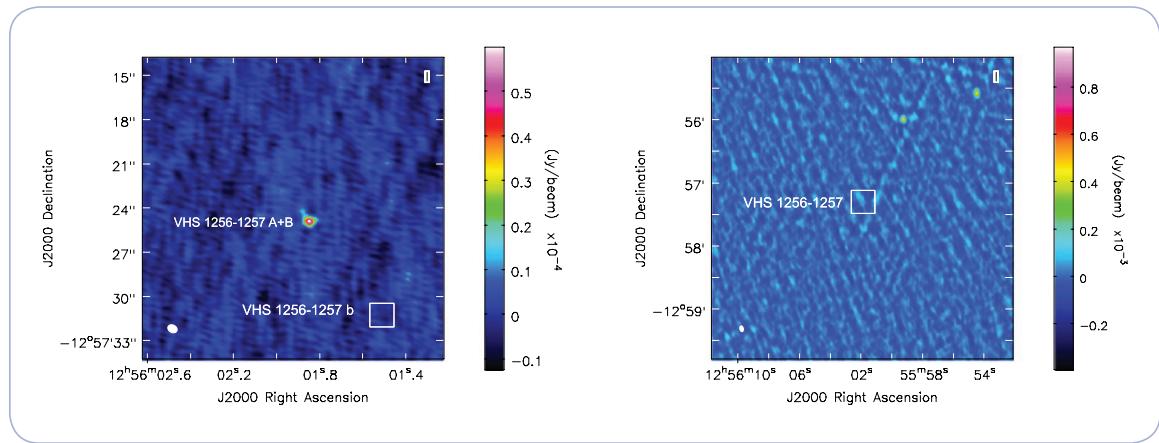
Publication: Meredith MacGregor (Carnegie) et al., *Detection of a Millimeter Flare from Proxima Centauri*, *Astrophysical Journal Letters*, 855, L2 (1 March 2018).

Radio Emission in Ultracool Dwarfs

Cool dwarf stars are the most common planetary hosts. They are also very active in radio flaring, and hence provide the best means to study star–planet magnetospheric interactions, and possibly their influence on the development of life.

To investigate the radio emission of ultracool objects, Guirado et al. carried out a targeted search in the recently discovered system VHS J125601.92–125723.9 (hereafter simply VHS 1256–1257). This system is composed of an equal-mass M7.5 binary and a L7 low-mass substellar object located at only 15.8 pc. The research team observed the VHS 1256–1257 system with the Karl G. Jansky Very Large Array in phase-reference mode at X-band and L-band, and with the European Very Long Baseline Interferometry Network at L band in several epochs during 2015 and 2016.

Radio emission was discovered at X band that is spatially coincident with the equal-mass M7.5 binary with a flux density of 60 μJy . The measured spectral index was $\alpha = -1.1 \pm 0.3$ between 8 and 12 GHz, suggesting that non-thermal, optically thin, synchrotron, or gyrosynchrotron radiation is responsible for the observed radio emission. Interestingly, no signal is seen at L band to a 3σ upper limit of 20 μJy . This might be explained by strong variability of the binary or self-absorption at this frequency. By adopting the latter scenario and gyrosynchrotron radiation, the authors constrain the turnover frequency to be in the interval 5–8.5 GHz, from which they infer the presence of kiloGauss-intense magnetic fields in the M7.5 binary. These data impose a 3σ upper bound to the radio flux density of the L7 object of 9 μJy at 10 GHz.

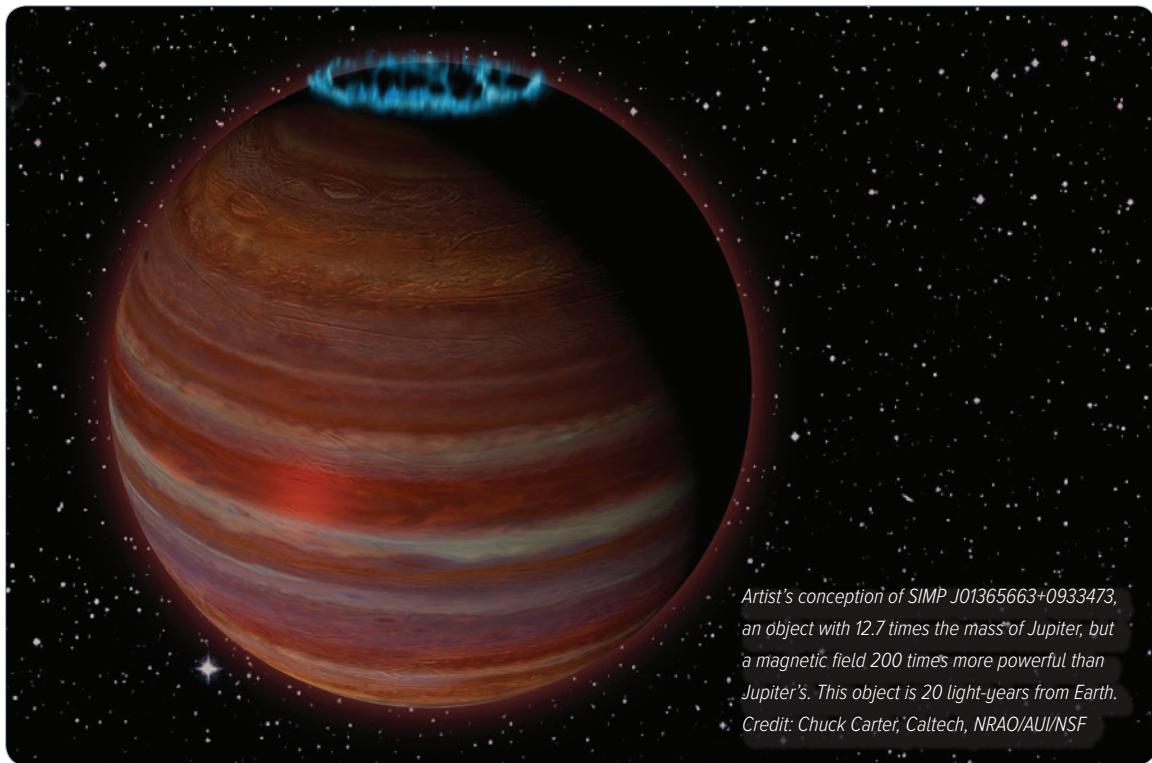


[Left] VLA image of the VHS 1256–1257 field at X-band. The detected source is readily assigned to the M7.5 binary. The (undetected) L7-object location is at the solid white box. The 3σ threshold detection is 9 μJy . At 15.8 pc, the separation between components AB and b corresponds to 128.4 AU. **[Right]** VLA image of the VHS 1256–1257 field at L-band. A solid box, with size that of the X-band image, is centered at the position of the X-band detection. None of the VHS 1256–1257 components is detected. The 3σ threshold detection is 20 μJy . The two bright knots seen in the map at the NW correspond to known extragalactic radio sources.

SCIENCE HIGHLIGHTS

Spotting a Rogue, Giant Magnetized Planet

Characterizing magnetic fields in the coolest dwarfs and eventually exoplanets can provide valuable insight into the formation, emission, and evolution of planets through stars. Kao et al. used the Karl G. Jansky Very Large Array to observe a sample of five known radio-emitting late-L and T dwarfs ranging in age from ~0.2 to 3.4 Gigayears (Gyr). Each target was observed for seven hours, extending to higher frequencies than previously attempted and establishing proportionally higher limits on maximum surface magnetic field strengths. Detections of circularly polarized pulses at 8–12 GHz yield measurements of 3.2–4.1 kG localized magnetic fields on four targets, including the archetypal planetary-mass object T2.5 dwarf SIMP J01365663+0933473. A pulse at 15–16.5 GHz was also detected for the T6.5 dwarf 2MASS 10475385+2124234, corresponding to a localized 5.6 kG field strength. For the same object, a 16.5–18 GHz pulse was tentatively detected, corresponding to a localized 6.2 kG field strength. Rotation periods were measured between ~1.47 – 2.28 hours for 2MASS J10430758+2225236, 2MASS J12373919+6526148, and SDSS J04234858–0414035, supporting: (a) an emerging consensus that rapid rotation may be important for producing strong dipole fields in convective dynamos; and/or (b) rapid rotation is a key ingredient for driving the current systems powering auroral radio emission. The authors observe evidence of variable structure in the frequency-dependent time series of targets on timescales shorter than a rotation period, suggesting a higher degree of variability in the current systems near the surfaces of brown dwarfs. Age, mass, and temperature together cannot account for the strong magnetic fields produced by these targets.

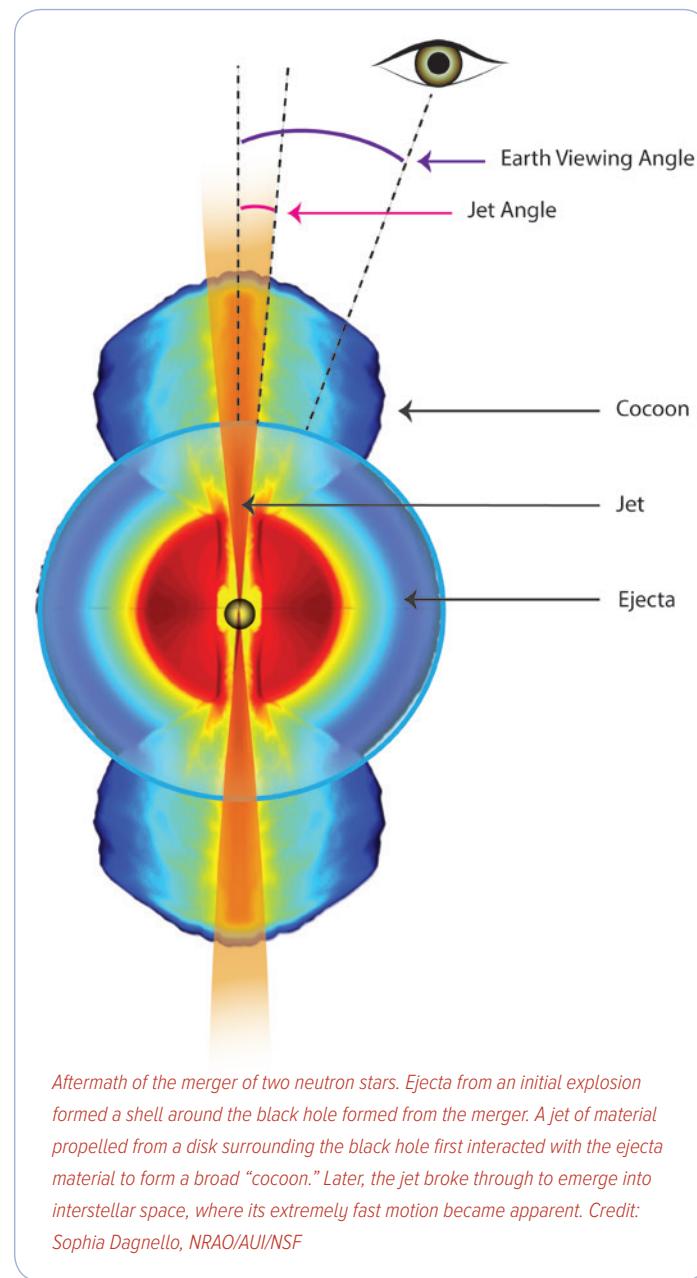


Artist's conception of SIMP J01365663+0933473, an object with 12.7 times the mass of Jupiter, but a magnetic field 200 times more powerful than Jupiter's. This object is 20 light-years from Earth.
Credit: Chuck Carter, Caltech, NRAO/AUI/NSF

Publication: Melodie M. Kao (California Institute of Technology, Arizona State University) et al., *The Strongest Magnetic Fields on the Coolest Brown Dwarfs*, *Astrophysical Journal Supplement Series*, 237, 25 (August 2018).

Superluminal Motion of a Relativistic Jet in a Neutron Star merger

The binary neutron-star merger GW170817 was accompanied by radiation across the electromagnetic spectrum and localized to the galaxy NGC 4993 ($d \sim$ about 41 Mpc). The radio and X-ray afterglows of GW170817 exhibited delayed onset, a gradual increase in the emission with time (proportional to $t^{0.8}$) to a peak \sim 150 days after the merger event, followed by a relatively rapid decline. Models have been proposed to explain the afterglow emission, including a choked-jet cocoon and a successful-jet cocoon / structured jet. However, the observational data have remained inconclusive regarding whether GW170817 launched a successful relativistic jet. Mooley et al. report radio observations acquired via Very Long Baseline Interferometry conducted with the Very Long Baseline Array, the Karl G. Jansky Very Large Array, and the Green Bank Telescope. The authors find that the compact radio source associated with GW170817 exhibits superluminal apparent motion between 75 days and 230 days after the merger event. This measurement breaks the degeneracy between the choked- and successful-jet cocoon models and indicates that, although the early-time radio emission was powered by a wide-angle outflow (a cocoon), the late-time emission was likely dominated by an energetic and narrowly collimated jet with an opening angle of less than five degrees, observed from a viewing angle of \sim 20 degrees. The imaging of a collimated relativistic outflow emerging from GW170817 adds substantial weight to the evidence linking binary neutron-star mergers and short γ -ray bursts.

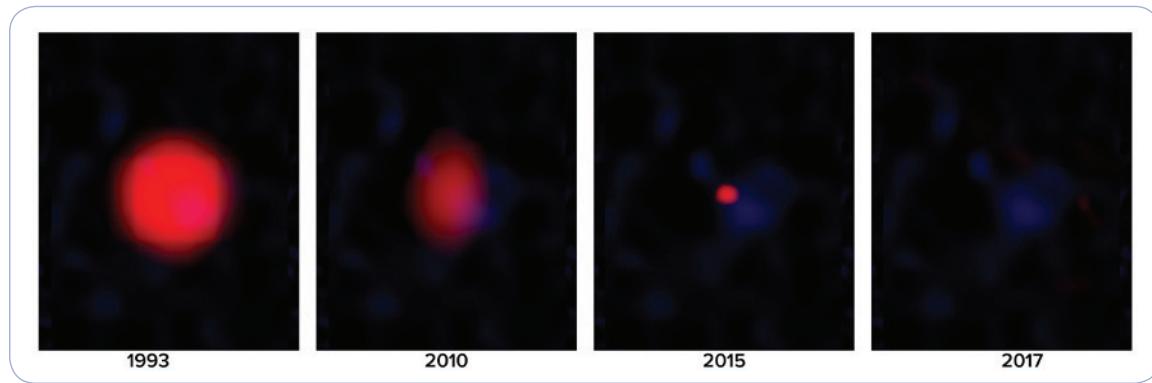
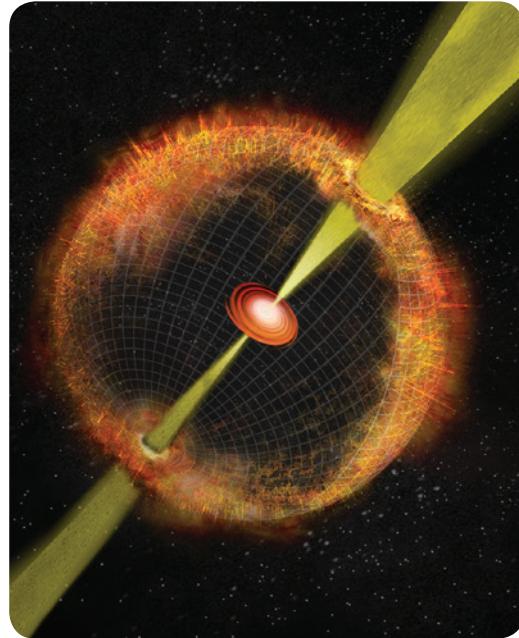


Publication: K. P. Mooley (NRAO, Caltech) et al., *Superluminal motion of a relativistic jet in the neutron-star merger GW170817*, Nature, 561, 355-359 (2018).

SCIENCE HIGHLIGHTS

An Orphan Gamma-ray Burst

Casey Law et al. present the discovery of a slowly evolving, extragalactic radio transient, FIRST J141918.9+394036, identified by comparing a catalog of radio sources in nearby galaxies against new observations from the Very Large Array Sky Survey. Analysis of other archival data shows that FIRST J1419-3940 faded by a factor of ~ 50 over 23 years, from a flux of ~ 26 mJy at 1.4 GHz in 1993 to an upper limit of 0.4 mJy at 3 GHz in 2017. FIRST J1419+3940 is likely associated with the small star-forming galaxy SDSS J141918.81+394035.8 at a redshift $z = 0.01957$ ($d = 87$ Mpc), which implies a peak luminosity $\nu L_\nu \gtrsim 3 \times 10^{38}$ erg/sec. If interpreted as an isotropic synchrotron blast wave, the source requires an explosion of kinetic energy $\sim 10^{51}$ erg some time prior to the authors' first detection in late 1993. This explosion is most likely associated with a long gamma-ray burst (GRB), but the radio source could also be interpreted as the nebula of a newly-born magnetar. The radio discovery of either of these phenomena would be unprecedented. Joint consideration of the event light curve, host galaxy, lack of a counterpart GRB, and volumetric rate suggests that FIRST J1419+3940 is the afterglow of an off-axis ("orphan") long GRB. The long time baseline of this event offers the best available constraint in afterglow evolution as the bulk of shock-accelerated electrons become non-relativistic. The proximity, age, and precise localization of FIRST J1419+3940 make it a key object for understanding the aftermath of rare classes of stellar explosion.



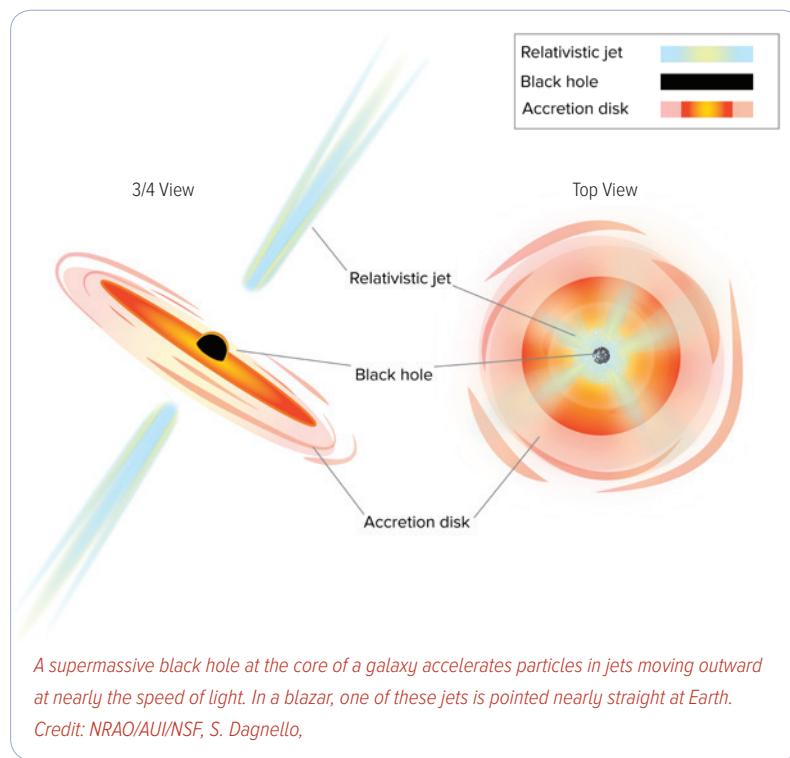
[Top] Artist's conception of a gamma ray burst. Jet of fast-moving material is propelled outward through spherical shell of ejected material from initial explosion of a massive star and its collapse into a black hole. Credit: B. Saxton, NRAO/AUI/NSF [Above] Series of radio images of FIRST J1419+3940 from 1993 to 2017 show its slow fade. Credit: Law et al., B. Saxton, NRAO/AUI/NSF.

Publication: C.J. Law (University of California, Berkeley) et al., *Discovery of the Luminous, Decades-long, Extragalactic Radio Transient FIRST J141918.9+394036*, *Astrophysical Journal Letters*, 866, L22 (20 October 2018).

Identifying the Source of a High-energy Neutrino

Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and Supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, the IceCube Neutrino Observatory sensors, distributed throughout a cubic kilometer of ice under the South Pole, detected a high-energy neutrino, IceCube-170922A. Its arrival direction was consistent with the location of a γ -ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ -rays. These observations characterized the variability and energetics of the blazar. This observation of a neutrino in spatial coincidence with a γ -ray-emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos. Following the IceCube detection, astronomers looked at TXS 0506+056 with numerous telescopes and found that it had brightened in gamma rays, X-rays, and visible light. Tracking the high-energy neutrino detected by IceCube to TXS 0506+056 marks the first time a specific object has been identified as the probable source of such a high-energy neutrino.

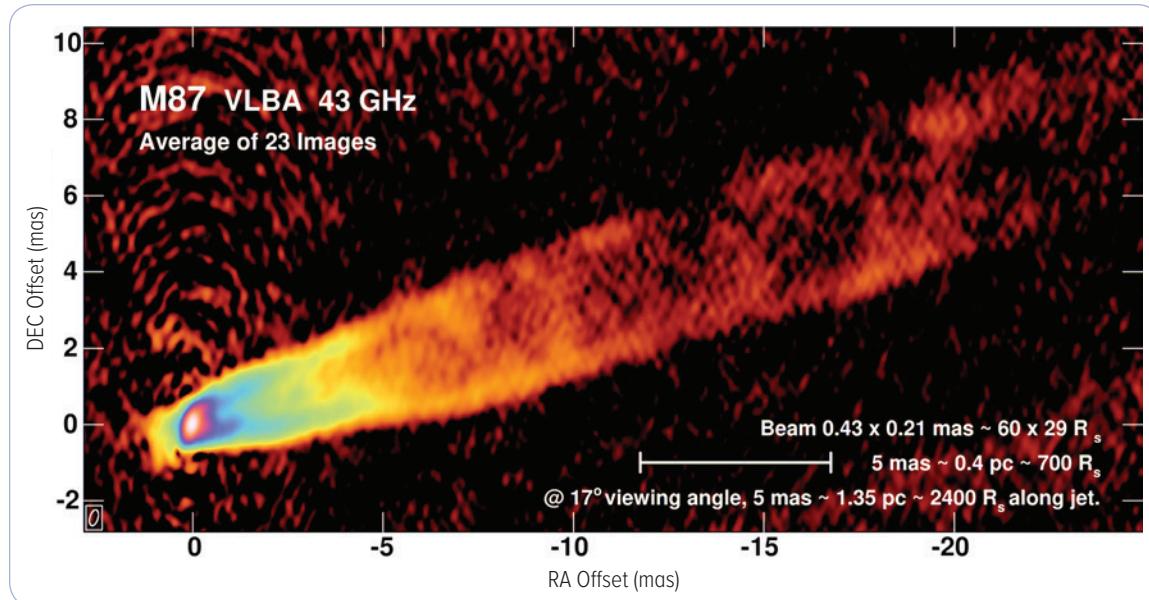
The Very Large Array (VLA) observed TXS 0506+056 in several radio bands from 2 to 12 GHz, beginning two weeks after the alert, detecting significant radio flux variability and some spectral variability of this source. The source is also in the long-term blazar monitoring program of the Owens Valley Radio Observatory 40m telescope at 15 GHz. The light curve shows a gradual increase in radio emission during the 18 months preceding the neutrino alert. TXS 0506+056 has also been monitored for years with the Very Long Baseline Array (VLBA). VLBA images have shown bright knots of radio emission that travel outward within the jets at nearly the speed of light. The knots presumably are caused by denser material ejected sporadically through the jet.



Publication: The IceCube Collaboration et al., *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, Science, 361, 146 (No. 6398, 11 July 2018).

The Physics of Jet Formation

The central radio source in Messier 87 (M87) provides the best opportunity to study jet formation owing to its large angular size for the gravitational radius of the black hole and its bright jet that is well resolved by very long baseline interferometry observations. Walker et al. present intensive monitoring observations from 2007 and 2008, plus approximately annual observations that span 17 years, all conducted with the Very Long Baseline Array (VLBA) at 43 GHz with a resolution of $\sim 30 R_s \times 60 R_s$. The high dynamic range of these images clearly show the wide opening angle structure and the counterjet. The jet and counterjet are nearly symmetric in the inner 1.5 milli-arcseconds (0.12 parsec in projection), with both being edge brightened. Both show deviations from parabolic shape in the form of an initial rapid expansion and subsequent contraction followed by further rapid expansion and, beyond the visible counterjet, subsequent collimation. Proper motions and counterjet / jet intensity ratios both indicate acceleration from apparent speeds of $\leq 0.5c$ to $\geq 2c$ in the inner ~ 2 milli-arcseconds and suggest a helical flow. The jet displays a sideways shift with an $\sim 8\text{--}10$ year quasi-periodicity. The shift propagates outward nonballistically and significantly more slowly than the flow speed revealed by the fastest-moving components. Polarization data show a systematic structure with magnetic field vectors that suggest a toroidal field close to the core.

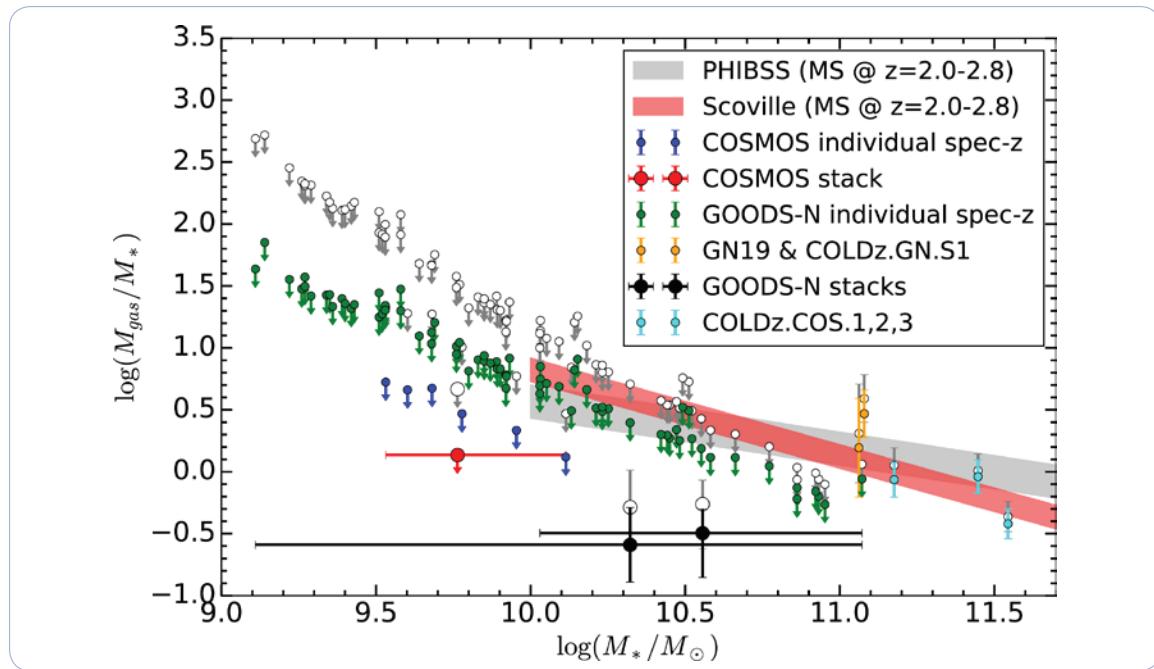


The 23-epoch average radio image of the jet and counterjet in M87 based on data from 2007 and 2008. Angular to linear scales (in parsecs and Schwarzschild radii, R_s) are indicated for distances in the sky plane and for distances along the axis of the jet assuming that it is oriented at 17° to the line-of-sight. The beam with resolution 0.43×0.21 milli-arcsecond elongated in position angle -16° is at lower left. The off-source noise level is $62 \mu\text{Jy}/\text{beam}$; the image peak is 0.83 Jy .

Publication: R. Craig Walker (NRAO) et al., *The Structure and Dynamics of the Subparsec Jet in M87 Based on 50 VLBA Observations over 17 Years at 43 GHz*, *Astrophysical Journal*, 855, 128 (10 March 2018).

The Dense Gas History of the Universe

The authors describe the *CO Luminosity Density at High-z* (COLDz) survey, the first spectral line deep field targeting CO(1–0) emission from galaxies at $z = 1.95 – 2.85$ and CO(2–1) at $z = 4.91–6.70$. The main goal of COLDz is to constrain the cosmic density of molecular gas at the peak epoch of cosmic star formation. By targeting both a wide ($\sim 51 \text{ arcmin}^2$) and a deep ($\sim 9 \text{ arcmin}^2$) area, the survey is designed to robustly constrain the bright end and the characteristic luminosity of the CO(1–0) luminosity function. An extensive analysis of the reliability of the survey’s line candidates and new techniques provides detailed completeness and statistical corrections as necessary to determine the best constraints to date on the CO luminosity function. The blind search for CO(1–0) uniformly selects starbursts and massive main-sequence galaxies based on their cold molecular gas masses. The search also detects CO(2–1) line emission from optically dark, dusty star-forming galaxies at $z > 5$. Pavesi et al. find a range of spatial sizes for the CO-traced gas reservoirs up to ~ 40 kiloparsecs, suggesting that spatially extended cold molecular gas reservoirs may be common in massive, gas-rich galaxies at $z \sim 2$. Through CO line stacking, they constrain the gas mass fraction in previously known typical star-forming galaxies at $z = 2 – 3$. The stacked CO detection suggests lower molecular gas mass fractions than expected for massive main-sequence galaxies by a factor of $\sim 3–6$. The authors find total CO line brightness at ~ 34 GHz of $0.45 \pm 0.2 \mu\text{K}$, which constrains future line intensity mapping and Cosmic Microwave Background experiments.



The molecular gas mass fraction constraints for galaxies with spectroscopic redshifts for which the CO(1–0) emission can be constrained by the COLDz data. The color points assume $\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$; the gray points correspond to adopting the metallicity-dependent α_{CO} from Genzel et al. (2015). Upper limits are 3σ and assume a line FWHM of 300 km/sec. The gray and red shaded regions correspond to the reported average expected gas mass fraction in the range $z \sim 2.0–2.8$ for main-sequence galaxies.

Publication: Riccardo Pavesi (Cornell University) et al., *The CO Luminosity Density at High-z (COLDz) Survey: A Sensitive, Large-area Blind Search for Low-J CO Emission from Cold Gas in the Early Universe with the Karl G. Jansky Very Large Array*, *Astrophysical Journal*, 864, 49 (1 September 2018).

A Massive Galaxy in the Early Universe

According to our current understanding of cosmic structure formation, the precursors of the most massive structures in the Universe began to form shortly after the Big Bang, in regions corresponding to the largest fluctuations in the cosmic density field. Observing these structures during their period of active growth and assembly—the first few hundred million years of the Universe—is challenging because it requires surveys that are sensitive enough to detect the distant galaxies that act as signposts for these structures and wide enough to capture the rarest objects. As a result, very few such objects have been detected to date.

In this contribution, Marrone et al. report observations of a far-infrared-luminous object at redshift 6.900—just 780 million years after the Big Bang—that was discovered in a wide-field survey. This object, SPT0311–58, was originally identified in the 2,500-deg² South Pole Telescope survey as a luminous source with a steeply increasing spectrum, indicative of thermal dust emission. Observations with ALMA provide the redshift of the source.

High-resolution imaging shows it to be a pair of extremely massive star-forming galaxies. The larger is forming stars at a rate of 2,900 M_⦿ per year, contains 270 billion M_⦿ of gas and 2.5 billion M_⦿ of dust, and is more massive than any other known object at a redshift of more than 6. Its rapid star formation is probably triggered by its companion galaxy at a projected separation of 8 kiloparsecs. This merging companion hosts 35 billion M_⦿ of stars and has a star-formation rate of 540 M_⦿ per year, but has an order of magnitude less gas and dust than its neighbor and physical conditions akin to those observed in lower-metallicity galaxies in the nearby Universe. These objects suggest the presence of a dark-matter halo with a mass of more than 100 billion M_⦿, making it among the rarest dark-matter haloes that should exist in the Universe at this epoch.

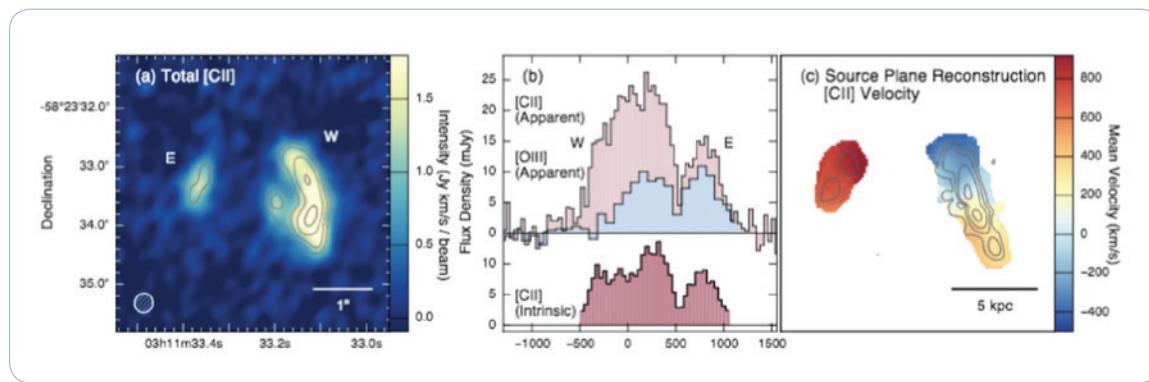
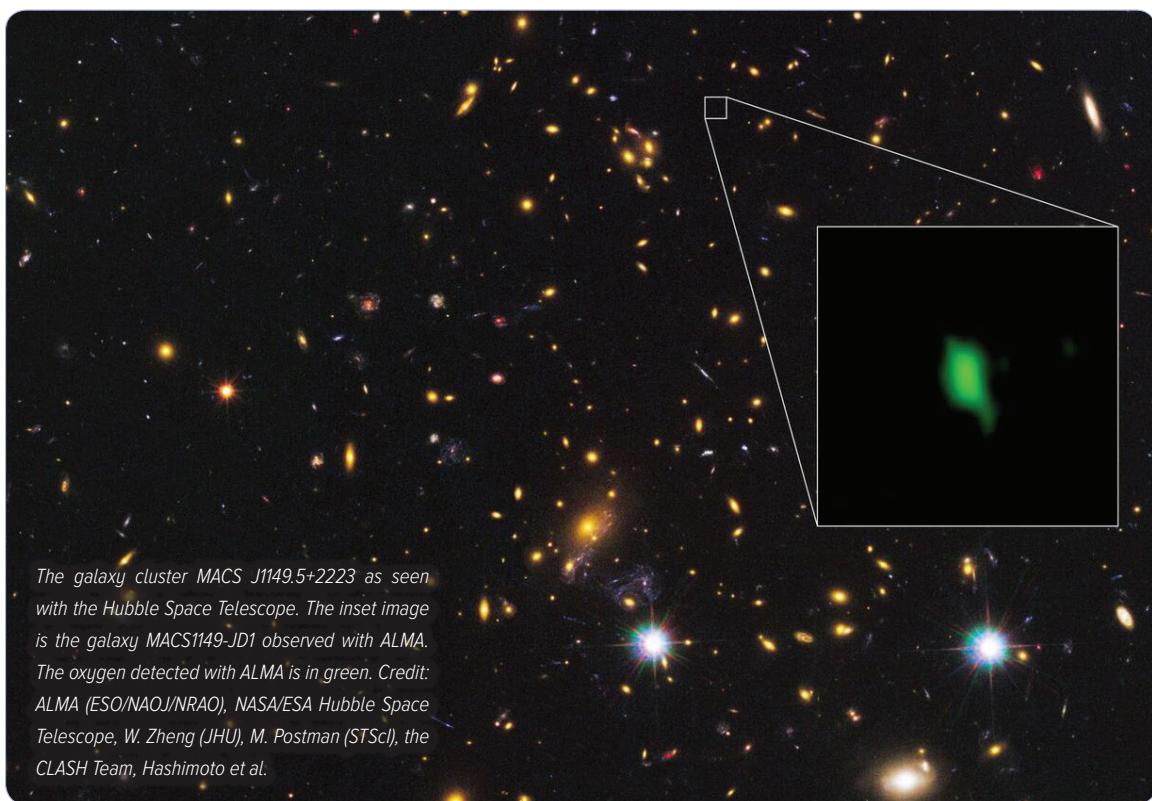


Image & spectra of the [CII] and [OIII] emission from the z=6.9 lensed starburst galaxy SPT0311–58.

D.P. Marrone (Steward Observatory, University of Arizona) et al., *Galaxy Growth in a Massive Halo in the First Billion Years of Cosmic History*, Nature, 553, 51 (4 January 2018).

The Onset of Star Formation after the Big Bang

A fundamental quest of modern astronomy is to locate the earliest galaxies and study how they influenced the intergalactic medium a few hundred million years after the Big Bang. The abundance of star-forming galaxies is known to decline from redshifts of about 6 to 10, but a key question is the extent of star formation at even earlier times, corresponding to the period when the first galaxies might have emerged. In this paper, Hashimoto et al. report spectroscopic observations of MACS1149–JD1, a gravitationally-lensed galaxy observed when the Universe was less than four per cent of its present age. Between March 2016 and April 2017, the team performed observations of MACS1149–JD1 at the Atacama Large Millimeter/submillimeter Array, targeting the far-infrared oxygen line, [O III] at a wavelength of 88 μm , and dust continuum emission over a broad wavelength range consistent with its photometric redshift range ($z \sim 9.0\text{--}9.8$). An emission line of doubly ionized oxygen was detected at a redshift of 9.1096 ± 0.0006 , with an uncertainty of one standard deviation. This precisely determined redshift indicates that the red rest-frame optical color arises from a dominant stellar component that formed about 250 million years after the Big Bang, corresponding to a redshift of ~ 15 . These results indicate that it may be possible to detect such early episodes of star formation in similar galaxies with future telescopes.



The galaxy cluster MACS J1149.5+2223 as seen with the Hubble Space Telescope. The inset image is the galaxy MACS1149-JD1 observed with ALMA. The oxygen detected with ALMA is in green. Credit: ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

Publication: T. Hashimoto (Osaka Sangyo University, National Astronomical Observatory of Japan) et al., *The onset of star formation 250 million years after the Big Bang*, Nature, 557, 392 (17 May 2018).

NORTH AMERICAN ALMA OPERATIONS



Photo by Arne Marinovic – ALMA (ESO/NAOJ/NRAO)

North American ALMA Science Center

The North American ALMA Science Center (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 operated efficiently and effectively in 2018 as the North American scientific community's interface to the ALMA Observatory for expert advice and assistance in the use of ALMA, including proposal preparation and submission, data reduction and processing, ALMA documentation, and online tools and resources. The North American ALMA Regional Center (NA ARC) is embedded within the NAASC and provides the core services specified by the ALMA Observatory for scientific support in the regions, and contributed support for Chile operations.

The **Telescope Interface and Diagnostics Team** functioned as the technical and diagnostic liaison to the Joint ALMA Observatory (JAO) in 2018. This team performed critical tasks, such as identifying issues with the array or in data collection and analysis. The team was also responsible for testing the new functionality of the ALMA Observing Tool and worked with the integrated NAASC teams on a new data processing workflow for Cycle 6. This effort successfully implemented a more robust and efficient workflow for data processing operations. The team's responsibilities in 2018 also included: (a) support of telescope operations in Chile, such as staffing 17 Astronomy-on-Duty shifts at the JAO; (b) active participation in the JAO technical and diagnostics-related meetings and teleconferences, such as the JAO Science and Engineering Coordination; (c) providing technical expertise to the ALMA proposal review process, such as the Proposal Handling Tool technical assessment; (c) critically reviewing all Phase 2 materials (scheduling blocks) submitted by North American Principal Investigators, ensuring they all were ready to run on the telescope; and (d) a leadership role in the annual process that prioritizes the ALMA Extension and Optimization of Capabilities activities.

The **ALMA Software Support and Testing Team** provided expert scientific support for the development and validation of ALMA software in 2018, including validation and analysis of existing or proposed tools; research in support of requirements definition; testing and requirements definition; and coordination of NRAO-wide software testing. Additional activities included: testing new Common Astronomy Software Application (CASA) package releases; CASA development support; and ALMA calibration and imaging pipeline test and development.

The **Science Data Services and Archive Team** are the NAASC staff responsible for the calibration, imaging, and delivery of Principal Investigator science data to the community, and contribute to ALMA archive improvements and deployment testing. Throughout 2018, these staff took a lead role in the development and testing of the end-to-end Cycle 6 ALMA data processing workflow including ALMA archive access.

The **Science Community Interface Team** enacted the strategic plans and initiatives to grow and educate the ALMA user community in 2018, including the planning and execution of NAASC-sponsored schools, tutorials, and workshops. The team was responsible for face-to-face visitor support such as data reduction visitors to the NAASC, visiting scientists, diversity initiatives and broadening participation, and coordination with the Education & Public Outreach and Science Communication offices. In 2018, the team reviewed and collaborated with the international ALMA working groups in the preparation of nearly all ALMA Cycle 6 end user documentation such as the Call for Proposals, Proposers/Users Guide, ALMA Primer, ALMA Technical Handbook, Guide to the NA ARC, software user guides, and additional documentation describing NAASC services access. The team also prepared the ALMA Science Portal for the Cycle 6 Call for Proposals. The NAASC provided a Contact Scientist (CS) for each PI project, assisting with Schedule Blocks, data reduction and analysis, and supporting remote requests for pipeline re-processing. In 2018, Contact Scientists supported 282 Cycle 5 programs and began the preparations for supporting 248 Cycle 6 programs.

NORTH AMERICAN ALMA OPERATIONS

ALMA Ambassadors

The 2018 North American ALMA Science Center (NAASC) – ALMA Ambassadors program is at the core of NAASC efforts to reach out to potential proposal Principal Investigators. ALMA Ambassadors receive intensive training at NRAO headquarters prior to an ALMA Call for Proposals on topics related to ALMA proposal writing, including interferometry basics, ALMA science capabilities, recent ALMA headlines, use of the Observing Tool, and guidance with speaking on these topics. Each of the 2018 ALMA Ambassadors hosted a local proposal preparation workshop at their home institution in advance of the Cycle 6 ALMA proposal deadline.



2018 ALMA Ambassadors

(pictured left to right)

Dary Ruiz-Rodriguez

Ian Czekala

Loreto Barcos

Nicholas Ballering

Steve Ertel

Patrick Sheehan

Kate Rowlands

Deanne Coppejans

Meredith MacGregor

Katie Jameson

Irene Shivaei

Stacia Cook

Rui Xue (not pictured)

Rochester Institute of Technology

Stanford University

Joint ALMA Observatory

University of Arizona – Steward Observatory

University of Arizona – Steward Observatory

The University of Oklahoma

Johns Hopkins University

Northwestern University

Carnegie Institution

Australian National University

University of Arizona – Steward Observatory

Columbia University

University of Iowa

Cycle 5

As ALMA Cycle 5 science observing drew to a close in mid-2018, a gap was identified in the Atacama Compact Array observing schedule between Local Sidereal Time of 22 hours and 1.5 hours. Scientists at the Joint ALMA Observatory (JAO) and the ALMA Regional Centers proposed a number of filler programs. These proposals were reviewed by the ALMA Integrated Science Team and the ALMA Director approved four that addressed a wide range of scientific interests. The data from the observations was quality assessed by the JAO and released through the ALMA Archive with no proprietary period.

Cycle 6

The ALMA Director, on behalf of the Joint ALMA Observatory and the partner organizations in East Asia, Europe, and North America, announced that the ALMA Cycle 6 Call for Proposals was open effective 21 March 2018, with a submission deadline of 15:00 Universal Time on 19 April 2018. ALMA observing proposals were solicited for scientific observations to be scheduled from October 2018 through September 2019. The Call for Proposals announced that Cycle 6 would allocate 4000 hours of 12-m Array time and 3000 hours of Atacama Compact Array (ACA) time to successful proposals.



Photo by Pablo Carillo

In Cycle 6, ALMA provided continuum and spectral-line capabilities for wavelengths from 0.32 to 3.6 mm, and angular resolutions from 0.018 to 3.4 arcseconds on the 12-m Array. Cycle 6 offered several new ALMA observational capabilities, including full circular polarization observations, reduced restrictions for simultaneous observations with the 12-m Array and the ACA, Band 8 stand-alone ACA observations, and an increase of the Band 6 Intermediate Frequency bandwidth.

In response to the Cycle 6 Call for Proposals, the JAO received a record 1836 proposals from the international community that requested 19,690 hours of observing time. Of the proposals submitted, 100 received the highest priority of Grade A, 269 received Grade B, and 292 received Grade C. The Grade A and B proposals requested an estimated 3840 hours of observing time on the 12-m Array. Together with the estimated 180 hours of Cycle 4 Grade A proposals carried forward to Cycle 6, this constitutes the 4000 hours of 12-m Array time available for Cycle 6. Additionally, of the 18 Large Programs that were submitted, four were scheduled for Cycle 6 that were collectively assigned 446 hours on the 12-m Array and 46 hours on the 7-m Array, the largest time allocation to ALMA Large Programs to date.

The international ALMA team closed out Cycle 5 and began Cycle 6 observations on schedule on 1 October 2018 with all 66 ALMA antennas available.

Cycle 7

A pre-announcement for the ALMA Cycle 7 Call for Proposals was published to the ALMA Science Portal on 19 December 2018. The Call will be released on 19 March 2019, with a planned proposal submission deadline of 15:00 Universal Time on 17 April 2019.

The following ALMA technical capabilities will be available for the first time in Cycle 7:

- Observations in Band 7 in configurations C43-9 and C43-10;
- Solar observations in Band 7 in configurations C43-1 and C43-2;
- Solar observations in one additional configuration (C43-4) in Band 3;
- Improved sensitivity limit for full spectral resolution linear polarization observations.

In addition, spectral scans will become a standard mode. Observations in Band 7 at baselines longer than 5 km will become a standard mode if there is a suitable phase calibrator within 5 degrees of the science target. The data rate limitation from previous cycles will be significantly relaxed so that Principal Investigators will be able, for example, to place high spectral resolution windows in long baseline configurations that were previously hampered due to high data rates.

NORTH AMERICAN ALMA OPERATIONS

ALMA Development

ALMA will sustain its cutting-edge transformational science through 2030 via an aggressive series of upgrades, guided by the ALMA Development Roadmap (ALMA Memo 612) that was approved in 2018 by the ALMA Board and released by the ALMA Director, Sean Dougherty, and ALMA Board Chair, Toshikazu Onishi. The Roadmap, achieved through community consultation, is guided by fundamental science drivers for ALMA development over the next decade, as described below.

Origins of Galaxies

Trace the cosmic evolution of key elements from the first galaxies ($z > 10$) through the peak of star formation ($z = 2 - 4$) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.

Origins of Chemical Complexity

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales ($\sim 10 - 100$ AU) by performing full-band frequency scans at a rate of 2 – 4 protostars per day.

Origins of Planets

Image protoplanetary disks in nearby (150 parsec) star formation regions to resolve the Earth forming zone (~ 1 AU) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

According to the vision in the Roadmap, the current development priorities as based on scientific merit and technical feasibility, are:

- broaden the receiver intermediate frequency (IF) bandwidth by at least a factor of two; and
- upgrade the associated electronics and correlator.

NRAO leads the approved Correlator Upgrade Project, a North American project that is the first step along the Roadmap.

In order of scientific priority, receiver upgrades are recommended for intermediate (200 – 425 GHz), low (< 200 GHz), and high (> 425 GHz) frequencies. NRAO built the widest IF band receiver currently available on ALMA, the 211 – 280 GHz Band 6. Development Studies to result in upgrades are being pursued.

The *ALMA Development Plan* includes provision for Projects and Studies. An ALMA Development Project is a large-scale (typically \$1M+ USD), multi-year initiative involving relatively mature technology which may lead to full implementation in the ALMA Observatory. Projects must be approved by the ALMA Board. An ALMA Development Study is a small-scale ($\leq \$0.2M$ USD), one-year investigation of an emerging technology of general interest which may lead to a Development Project.

A Call for Proposals for ALMA Development Studies was released 3 December 2018. The deadline for proposals is 1 May 2019 for funding during Fiscal Year 2020, depending on the U.S. federal budget process. Members of the North America ALMA Operations Partnership were invited to submit proposals to investigate a potential ALMA upgrade (hardware, software, or advanced techniques), especially those that address the goals described in the *ALMA Development Roadmap*.



Photos by Pablo Carrillo

A large yellow satellite dish antenna is positioned in the foreground, angled towards the right. Behind it, several smaller blue satellite dishes are scattered across a dark, star-filled landscape. The background features a large, bright yellow and orange celestial body, possibly a planet or a massive firework, with a visible ring. A thin red horizontal line runs across the top of the image.

NEW MEXICO OPERATIONS

Karl G. Jansky Very Large Array

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.

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.

VLA Sky Survey

The VLA Sky Survey (VLASS) is a new 2-4 GHz, multi-epoch, all-sky radio survey. It is the highest resolution all-sky radio survey ever undertaken, and is being observed in the VLA B and BnA configurations. The first half of the first epoch (VLASS1.1) was observed between September 2017 and February 2018, after which the VLA continued through the regular A, D, and C configuration cycle. Observing for the second half of the sky (VLASS1.2) will begin in March 2019 after moving back to the B configuration and continue through July 2019, to complete the almost 34,000 square degrees of sky accessible to the VLA.

Table 5.1: VLASS Goals

Frequency	2-4 GHz
Resolution	2.5 arcseconds
Sky coverage	All Sky North of Dec. -40 deg. (33,885 deg ²)
Sensitivity per epoch	120 μJy RMS
Combined (3 epoch) sensitivity	69 μJy RMS
Polarization	I, Q, U
Cadence	3 epochs each separated by 32 months
Start Date	15 September 2017
Expected number of sources	~5,000,000



NRAO will make Basic Data Products available through the NRAO archive, including:

- Raw visibility data (available immediately);
- Calibration tables (within 1-2 weeks of observation);
- “Quick Look” 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 ~106 bright sources;
- Fine resolution (16 MHz channel, IQU polarization) cubes around the ~50,000 brightest sources;
- Catalogs of source components from both the 2D images and the cubes.

Community groups will produce Enhanced Data Products to supplement the Basic Data Products produced by NRAO, for example rotation measure maps and event brokers for transients.

NEW MEXICO OPERATIONS

Realfast

The field of Fast Radio Burst (FRB) detection has experienced an explosion of interest in recent years. Re-analyses of large, single-dish pulsar survey data have discovered new classes of transients, of as-yet unknown origin. These discoveries show that these transients exist, but are difficult to interpret given the poor localization of single-dish telescopes, highlighting the potential for interferometers to revolutionize this field of study. A single FRB has been localized with the VLA, but there are questions as to its uniqueness, as it is the only known FRB repeater. The *realfast* development project seeks to design and implement a commensal fast transient system for the VLA, and to investigate options for searching for these events.



A proposal was successfully submitted to the NSF Advanced Technologies and Instrumentation program in FY2017–2019 to support development of such a system. In FY2017, the basic software architecture was developed, and major subsystems were implemented. In 2018, the major software subsystems were refined, and the interfaces to other NRAO software were defined. The development of some interfaces began. Prototype hardware was purchased, and after testing, the final cluster order was placed. Limited regular operations will begin 2019.

Science Operations

NRAO continued to offer three types of observing programs to VLA users in the Calls for Proposals issued in 2018: General Observing (GO), Shared Risk Observing (SRO) and Resident Shared Risk Observing (RSRO). In the Semester 2018B Call for Proposals, three capabilities were promoted from RSRO to SRO: Solar observing, frequency averaging, and P-band spectroscopy. In the Semester 2019A Call for Proposals, phase-binned pulsar observing was promoted from RSRO to SRO, and two capabilities were promoted from SRO to GO: Solar observing; and On-The-Fly Mosaicing observing for P-, L-, S-, and C-bands. RSRO programs supported in FY2018 included coherent-dedispersion pulsar, fast-dump, and P-band polarization observations.

A large fraction of the scientific support in 2018 went toward maintaining receiver, antenna, and array performance and ensuring that the NRAO user community had access to quality instrumentation and updated information to effectively use the VLA. Operational tasks carried out by the scientific staff in support of these functions are listed below.

Support Calls for Proposals: Define capabilities to be offered in the 2018B and 2019A semesters, and then update user documentation for all capabilities for the relevant Call for Proposals; scientific testing of user tools needed to prepare proposals (e.g., Proposal Submission Tool (PST), General Observing Setup Tool (GOST), Exposure Calculator Tool); technical reviews for proposals and evaluation of proposals for RSRO contributions.

Hardware, Software, and Operational Documentation: Technical documentation detailing hardware and software functionality for staff and users, operational procedures and documentation for the operations staff. The VLA Observational Status Summary was updated before the 2018B and 2019A Call for Proposals, along with the online Guide to Observing with the VLA.

Track and Measure VLA Performance

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

Scientific Testing of Antennas Completing Major Maintenance:

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

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

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

Array Operations

Array reconfigurations completed in 2018 included the moves into the BnA- (for VLASS observing only), A-, and D-configurations. The start of observing in the D-configuration was delayed by the extended outage associated with a major electrical infrastructure upgrade, so the subsequent move to the C-configuration was pushed into FY2019 to ensure the completion of high-priority D-configuration science.

In 2018, a succession plan was implemented to reassign duties within the Array Operations division to fill gaps when key personnel are absent. This activity involved getting operators to learn new processes for data reports and assist with data quality assurance. A new VLA Technical Manager was identified to help coordinate between science support and technical groups, and to improve communication on maintenance issues.



Next Generation Very Large Array

Throughout 2018, the NRAO engaged the broad science and technical community in the design of a next-generation Very Large Array (ngVLA), an interferometric array with 10X the sensitivity and 10X higher spatial resolution than the VLA and ALMA, optimized for 1.2 – 116 GHz operations. The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, and unprecedented broad-band continuum polarimetric imaging of non-thermal processes. These capabilities are required to address a broad range of critical questions in modern astronomy, including direct imaging of planet formation in the terrestrial zone, studies of dust-obscured star formation, and making a cosmic census of the molecular gas which fuels star formation back to first light and cosmic reionization. The ngVLA will be optimized for observations at wavelengths between ALMA at submillimeter wavelengths, and the future Phase 1 Square Kilometre Array (SKA-1) at decimeter and longer wavelengths.



The ngVLA project goal is to craft a submission to the Astro2020 Decadal Survey, including a compelling science case, and a rationally costed and realizable design for all major telescope elements. This effort is being driven by the community and coordinated via the NRAO.

Science Goals

The ngVLA science case and reference design are being developed via a close collaboration between the NRAO and the international astronomy community. This effort is led by the ngVLA Science Advisory Council (SAC), whose goal is the clear elucidation of the most compelling science case. The SAC, in collaboration with the broader international astronomy community, developed 80+ science cases requiring ~200 unique observations between ~1.2 – 116 GHz with sensitivity, angular resolution, and mapping capabilities far beyond those provided by the VLA, VLBA, ALMA, and SKA-1. Input following this science use case exercise indicated a strong interest in an ngVLA capable of addressing a broad range of topics in planetary science, star formation, Galactic and extragalactic astronomy, fundamental physics, and much more. These form the basis for developing the Key Science Goals (KSGs) for the ngVLA and drive the corresponding reference design.

Each of the ngVLA science cases was reviewed and discussed by Science Working Groups within the SAC. Ultimately, five KSGs were chosen to satisfy three criteria: (1) each addresses an important, unanswered astrophysics question that has broad scientific and societal implications; (2) progress can be uniquely addressed by the ngVLA; and (3) each exhibits key synergies with science goals being pursued by existing or planned facilities in the 2025+ time frame. The resulting five highest-priority ngVLA KSGs to be carried out across the lifetime of the ngVLA are:

1. Unveiling the formation of Solar System analogs on terrestrial scales;
2. Probing the initial conditions for planetary systems and life with astrochemistry;
3. Characterizing the assembly, structure, and evolution of galaxies from the first billion years to the present;
4. Using Galactic Center pulsars to make fundamental tests of gravity;
5. Understanding the formation and evolution of stellar and supermassive black holes in the era of multi-messenger astronomy.

Technical Concept

NRAO sponsored science and technical community meetings to define the science mission and concept for ngVLA, building on the ALMA and VLA legacies. This concept matured appreciably in 2018, incorporating top-down feedback from the radio astronomy community and bottom-up design feasibility feedback from the engineering team.

The ngVLA technical concept is an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, 1.2 –116 GHz). The observatory will be a synthesis radio telescope:

- A main array of 214 reflector antennas, each 18m diameter, operating in a phased or interferometric mode and distributed to sample scales from tens of meters to 1000 km. A dense core and spiral arms provide high surface brightness sensitivity, with mid-baseline stations enhancing angular resolution.;
- A Short Baseline Array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales undetected by the main array. The SBA may be combined with four 18m (main-array) antennas used in a total power mode to completely fill in the central hole in the (u,v)-plane left by the 6m dishes.;
- A Long Baseline Array (LBA) will add an additional 30 reflector antennas each of 18m diameter in 10 clusters providing continental scale baselines (~8860 km). The LBA is designed to sample a broad range of scales for stand-alone sub-array use, as well as for integrated operation with the main array.

The complete ngVLA will have ~10X the sensitivity of the VLA and ALMA, continental-scale baselines providing sub-millarcsecond-resolution, and a dense core on km-scales for high surface brightness sensitivity.

The dense core and the signal processing center of the array will be located at the Very Large Array site, on the plains of San Agustin, New Mexico. The high desert plains of the southwest U.S., at 2000m+ elevation, provide excellent observing conditions, including reasonable phase stability and opacity at 3mm wavelength over much of the year.

The main array will include stations outside New Mexico, in west Texas, eastern Arizona, and northern Mexico. Long baseline stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the U.S. Virgin Islands, and Canada.

Operations will be conducted from the VLA site and the array operations and repair centers in Socorro, New Mexico. A science operations center and data center will likely be collocated in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split amongst these centers as appropriate.

The facility will be operated as a PI-driven instrument. The fundamental data products for ngVLA users will be Science-Ready Data Products (i.e., images and cubes) generated using calibration and imaging pipelines created and maintained by the observatory. Both the pipeline products and the raw visibilities and calibration tables will be archived, retaining the option of future re-processing and archival science projects.

Schedule and Budget

Project planning and the associated scheduling effort progressed significantly for the ngVLA in 2018. A basic project cadence was established with standing and focus meetings and events scheduled by the ngVLA Project Office. The ngVLA project timeline depicts the project phases from initial design and development to array transition to full scientific operations. In addition, a rudimentary Integrated Master Schedule has been created and aligned with the baselined project Work Breakdown Structure. The Project Office continues to gather inputs from various stakeholders on the feasibility, assessment of resource availability, timing, successors, predecessors and constraints required to establish a robust schedule.

The 2018 budget baselined for ngVLA reference design work totaled \$7M USD, comprised of a \$6M supplemental NSF allocation, and nearly \$1M in reallocated resources within the current NSF cooperative agreement funding, and a small non-federal supplement. The project engaged ~18 FTEs, providing project and scientific leadership, project management and costing support, scientific program

NEW MEXICO OPERATIONS

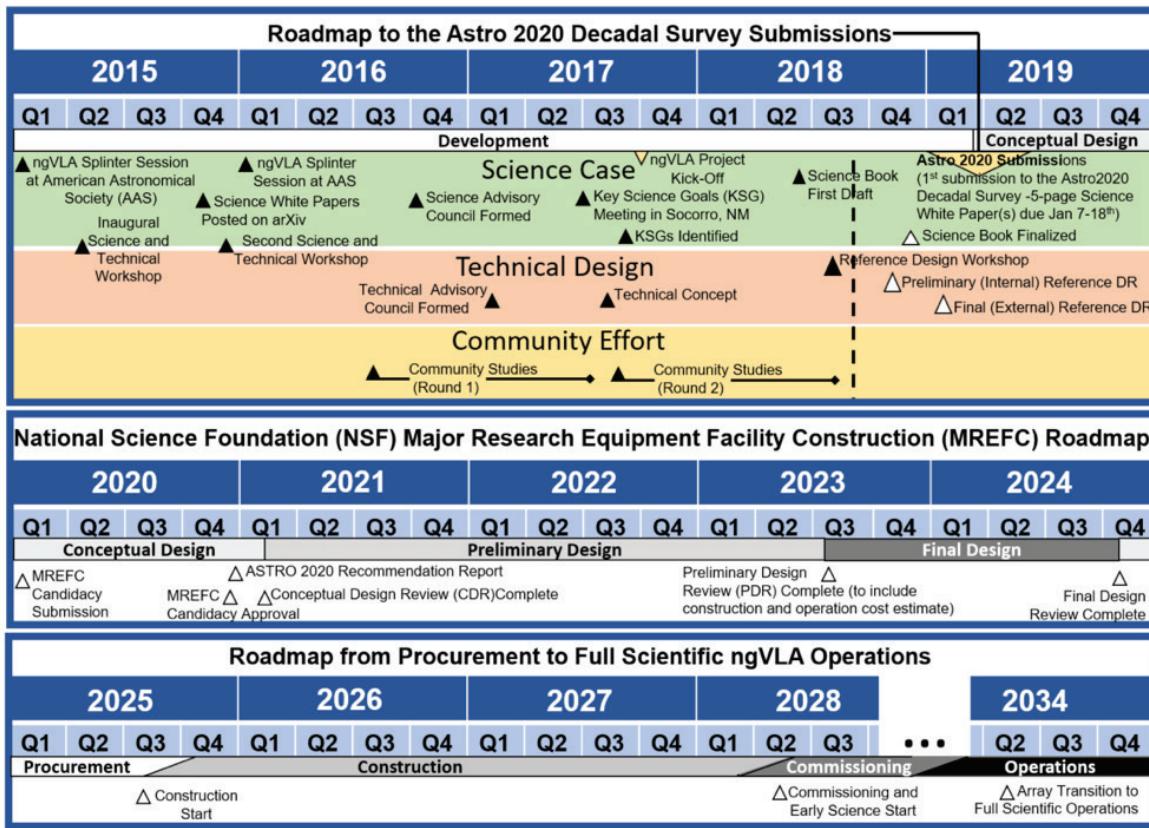


Figure: ngVLA project timeline (2018).

development, and technical definition. The majority of the 2018 expenditures were for additional project staff, prototyping activities, community engagement activities, and an antenna reference design study performed by an external engineering company.

Astro2020 Preparations

Following guidance provided by the NSF, NRAO continues to engage the astronomy community to obtain further consensus on the needs, priorities, and requirements for the proposed telescope. A key opportunity to showcase ngVLA alignment with community priorities is through the exploration of ngVLA scientific goals and open review of the development and design efforts at the Astro2020 Decadal Survey. The Decadal Surveys conducted by the U.S. National Academy of Sciences (NAS) assess the current state of the field and make research priority recommendations. These recommendations inform the decisions for future funding of new instrument construction.

The ngVLA Project Office is responsible for developing a sound, strongly supported submission to the Astro2020 Decadal Survey. Preparations for Astro2020 include coordination of community white paper submissions, development of a reference design for the facility, submission of requisite additional information to a Program Prioritization Panel, and active participation in Astro2020-sponsored events.

While the NAS organization committee has called for science white papers to be submitted in January 2019, it has yet to formalize the timeline for submitting additional project documents. However, the ngVLA Project Office expects the submission process to begin in early 2019.

ngVLA Reference Design

The ngVLA reference design is a low technical risk, costed concept that supports the Key Science Goals, and is the technical and cost basis of the Astro2020 Decadal Survey submission. This design was developed to satisfy the Cost and Technical Evaluation process within the Survey that ranks projects on their technical risk and construction cost realism, favoring projects at a higher level of design maturity.

As the ngVLA is in the development stage, it is too early to complete a full conceptual design down-select of all major subsystems. The reference design is one plausible implementation that supports the instrument requirements and provides a baseline for evaluating the associated cost realism and technical risk. The project is pursuing technology development in parallel with this design, with the goal of maturing leading-edge technologies to an appropriate technical readiness level before a conceptual design down-select. These development efforts are intended to exploit opportunities to reduce cost or improve performance as the design effort progresses.

Based on a preliminary system architecture, requirements and concepts for each major element are described in a series of technical reports with supporting engineering analysis and models where appropriate. A workshop was conducted in 2018 to review the status of the design and supporting materials, and identify the most significant gaps and inconsistencies. These gaps have since been addressed and the updated design documentation is presently under project review, ensuring that all quality checks are completed prior to the decadal submission in 2019.

Antenna Reference Design

The antennas comprise approximately half the construction budget estimate, and historical analogs vary widely in cost. Initial attempts at parametric cost modeling displayed a wide variance and poor fit, so the project has pursued a contract with General Dynamics Mission Systems (GDMS) for a reference design to the project specifications to better determine the likely cost of ngVLA antennas. A secondary goal of this work is to refine the requirements and architecture for future stages of the design.

The project issued a Request for Proposal for the costed conceptual design in late 2017 and issued a contract to GDMS in early 2018. Preliminary results were received at the conceptual design review milestone in mid-2018, and have been reflected in the system-level reference design.

The antenna design has proved challenging to keep affordable while meeting the key performance requirements. GDMS has struggled with specifications for surface accuracy and pointing accuracy, which in turn impact system sensitivity and dynamic range.

In parallel to the reference design exercise, NRAO has been collaborating with the National Research Council of Canada (NRCC) on a higher-risk, leading-edge concept employing single piece, rim-supported composite technology to provide a high-performance antenna that can be built at lower cost than traditional steel and aluminum structures. As the difficulties of meeting performance and cost targets with traditional technologies became apparent, we have refocused this development study to be able to provide a second costed concept for inclusion in the reference design. This provides two concepts, with different degrees of technical risk and performance that can be submitted to better inform the reference design.

Community Engagement

Over the past year, the ngVLA has remained heavily engaged with the scientific community via a number of scientific and technical workshops, as well as other initiatives. This effort is critical. First, it is through this engagement with the scientific community that they are able to contribute to the development of the ngVLA science case, which in turn drives the science and technical requirements of the telescope. Second, it is a critical means for raising awareness about the project as the Astro2020

NEW MEXICO OPERATIONS

Decadal Survey approaches. Community engagement will ultimately help to ensure that the ngVLA appears in a large fraction of Astro2020 science white papers that are due in January 2019.

NRAO launched the ngVLA Community Studies program in 2016, encouraging members of the scientific and engineering communities to become major contributors. Given the success of the first round of ngVLA Community Studies, a second round was initiated during 2017–2018.

Aimed at tackling some of the most pressing questions unveiled by the initial studies, the primary objective for the second round of community studies is to further develop the Key Science Goals outlined in ngVLA Memorandum #19. Community studies and simulations were asked to focus on addressing these key science goals while better quantifying the expected performance of the array to provide additional supporting technical requirements. During this second round, a total of 12 studies were approved, and of these seven received substantial funding to support their efforts. Each of the community studies reported their findings at the June 2018 Science Meeting in Portland, OR. The funded community studies will document their final reports as ngVLA memoranda.

Astrophysical Frontiers in the Next Decade and Beyond

This ambitious science conference was organized by the NRAO and took place 26–29 June 2018, bringing a broad cross-section of the astronomy community to Portland, Oregon to discuss the most pressing astrophysical questions for the Astro2020 Decadal Review. With 200+ registrants, including 70+ students, the conference showcased strong community support from users to pursue cutting-edge space and ground-based facilities to tackle the most pressing questions in astrophysics, with a special emphasis on the ngVLA.

The science program featured invited plenary speakers and parallel sessions of invited and contributed presentations covering: (a) Origins of Exoplanets and Protoplanetary Disks; (b) Mechanisms of Galaxy Evolution; and (c) Black Holes and Transient Phenomena. These science areas are multi-wavelength and multi-messenger. Given this conference's success, a comparable cross-discipline conference is being planned for 2020.

Science Book

The ngVLA Science Book published in the Astronomical Society of the Pacific Monograph series in 2018 features peer-reviewed research papers supporting the ngVLA development that were prepared by members of the astronomy community and compiled by the NRAO. With 88 chapters (850+ pages) from over 285 unique authors, this volume highlights key areas of astrophysics that are ripe for major breakthroughs and underscores the broad U.S. and international support for pursuing the ngVLA. While this volume will serve as a snapshot for the ngVLA project and a vision for ngVLA transformational science, NRAO envisages this science book as a living document that will be periodically updated until the initiation of construction. <https://ngvla.nrao.edu/page/scibook>

Project Outreach

Given the scale of the ngVLA and the broad interest in it, strategic partnerships with domestic and international institutions, as well as industry, are needed to advance the project. Connections have been established because technical and scientific colleagues from the U.S. and from around the world already participate in the ngVLA science and technical advisory councils, science working groups, science and technical workshops, and community studies. Potential industry partners also participate in community studies and technical workshops. Discussions were held in 2018 with potential domestic and international partners to determine if they can undertake suitable work packages in the ngVLA design.

Very Long Baseline Array

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

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



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

VLBA Re-integration with NRAO

On 1 October 2016, the Very Long Baseline Array (VLBA) was extracted from the NRAO and placed under the management of the Long Baseline Observatory. Shortly thereafter, the U.S. Naval Observatory became a 50% funding partner of the LBO, ensuring the near-term vitality of the VLBA.

On 23 October 2018, the NRAO received an award from the NSF for reintegration of the VLBA with the NRAO and continued operation through 30 September 2026, at which point the entirety of NRAO will again be due for management recompetition. With this chapter of the VLBA history behind us, attention will turn to its future development.

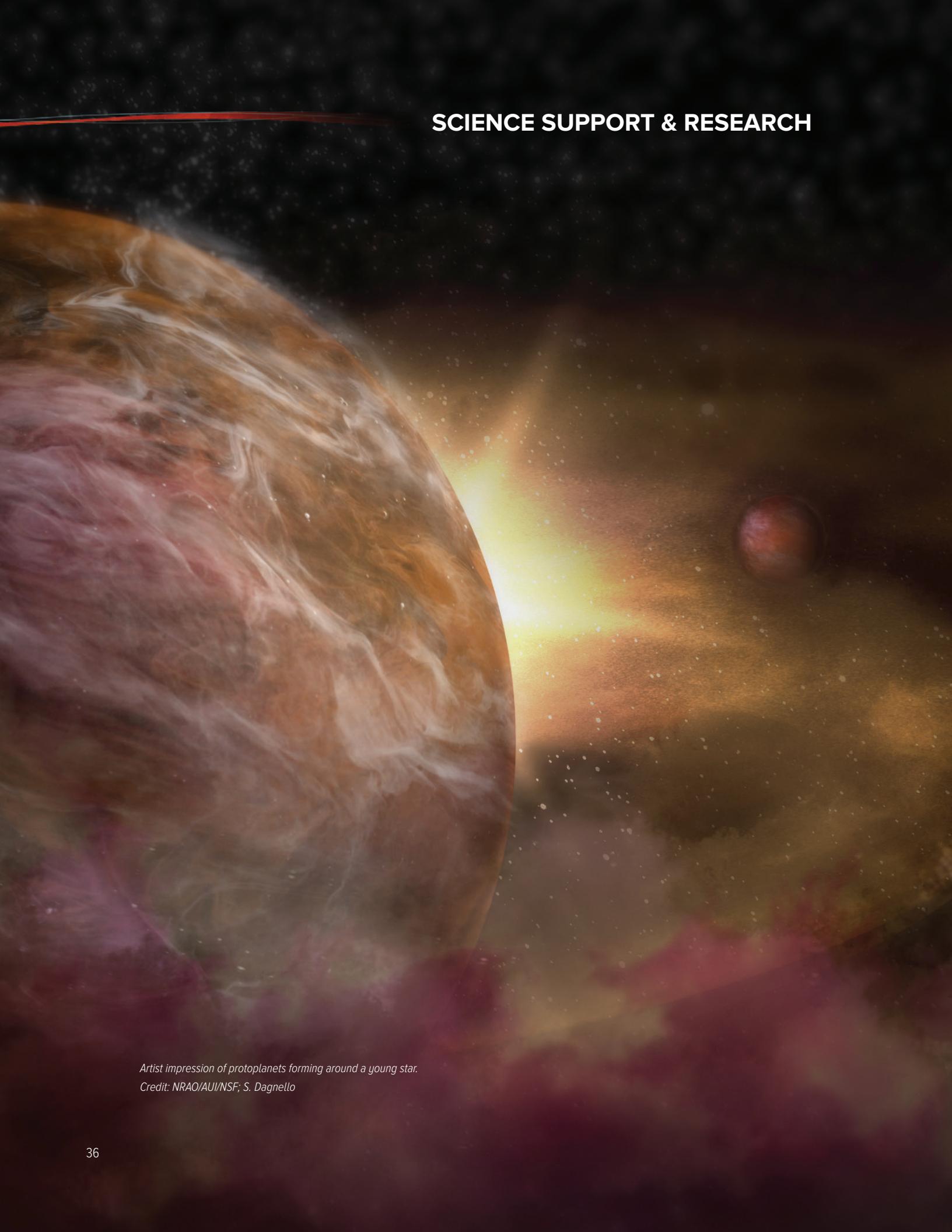
St. Croix VLBA Station Repairs

The NSF provided \$2 million in 2018 to repair damage to the easternmost VLBA station, located on St. Croix in the U.S. Virgin Islands, caused by Hurricane Maria in September 2017. The St. Croix telescope is a key VLBA component. The repairs afforded by the hurricane relief funds ensure that the facility will continue to serve as the easternmost element of the VLBA.

Hurricane Maria formed in the western Atlantic, then entered the Caribbean Sea, devastating the island of Dominica before striking Puerto Rico and skirting the U.S. East Coast, in addition to its destruction on St. Croix. Maria struck St. Croix as a Category 5 storm, with recorded wind gusts up to 137 mph. Officials estimated that 90% of the buildings on St. Croix were damaged or destroyed. The St. Croix VLBA station sustained damage to its 240-ton antenna and the building that houses its electronic equipment.

This NSF funding enables the NRAO to bring the important St. Croix station back to a state of full health so it can continue to support the forefront scientific work of the VLBA.

SCIENCE SUPPORT & RESEARCH

An artist's impression of a protoplanetary system. A large, reddish-brown planet with prominent white and grey cloud bands dominates the left side of the frame. In the background, a bright yellow star is visible, partially obscured by a large, luminous, multi-colored nebula of red, orange, and yellow. A smaller, dark brown sphere, representing another protoplanet, is positioned in the upper right quadrant. The overall scene is set against a dark, star-filled space.

Artist impression of protoplanets forming around a young star.

Credit: NRAO/AUI/NSF; S. Dagnello

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) and Scientific User Support (SUS).

Telescope Time Allocation (TTA) manages the process and tools by which users prepare and submit proposals for use of the VLA and VLBA, and through Service Level Agreements with the GBO, the GBT. 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.

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 programs and various other scientific activities such as the Jansky Lectureship, 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. Four new Jansky Fellows joined NRAO in 2018.



Nolan Denman received his Ph.D. at the University of Toronto – Dunlap Institute for Astronomy and Astrophysics, where he worked with Keith Vanderlinde. Nolan brings expertise in correlator design, Graphic Processing Units (GPUs), high-performance computing, and instrumentation associated with the Canadian Hydrogen Intensity Mapping Experiment (CHIME) to the Central Development Laboratory.

Lisa Locke was a postdoctoral research engineer in the Millimetre Instrumentation Group at National Research Council – Herzberg Astronomy and Astrophysics Research Centre. Lisa has extensive experience in phased array feed design, most recently working on the Cryogenic Phased Array Feed (CryoPAF) project. Lisa brings her considerable experience in receiver design and development to the Central Development Laboratory.



SCIENCE SUPPORT AND RESEARCH



Ryan Loomis received his Ph.D. from Harvard University working with Karin Öberg. Ryan's thesis work on the physical and chemical processes which govern the star formation process in our Galaxy has been complemented by his extensive work on algorithmic improvements to radio astronomical imaging and information extraction. Ryan is hosted at NRAO in Charlottesville.

Brian Svoboda received his Ph.D. at the University of Arizona – Steward Observatory. Brian's thesis work with Yancy Shirley expanded our understanding of the earliest phases of the star formation process through physical and chemical studies of its large-scale structure. Brian will continue his extensive use of NRAO facilities to further our understanding of the star formation process as a Jansky Fellow at NRAO Socorro.



Telescope Time Allocation: Semester 2018B



A total of 149 new VLA proposals were received for the 1 February 2018 submission deadline for Semester 2018B. The oversubscription rate (by proposal number) was 2.5 and the proposal pressure (hours requested over hours available) was 2.2 – only the C configuration was offered in Semester 2018B. This pressure is higher than has been reported for recent semesters – the difference results from the discovery that some proposals were being neglected in calculating the VLA proposal pressure. Correcting this omission indicates that the long-term average proposal pressure for the VLA is between 2 and 3. One large and 20 time-critical (triggered) proposals were received. There was significant demand for the time made available on space observatories through inter-observatory agreements, and nine proposals requesting time on the Hubble Space Telescope, Swift or Chandra were submitted.

The proposals were reviewed for scientific merit by eight Science Review Panels (SRPs) and for technical feasibility by NRAO staff. These reviews were completed in February – March 2018 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 1-2 May 2018 at the Charlottesville offices of NRAO. The TAC – comprising the eight SRP chairs – was charged with recommending a science program for Semester 2018B to the Observatory Director. The recommended program was reviewed and approved on 14 May 2018. 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 30 May 2018 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 has been 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 2019A

A total of 242 new VLA proposals were received for the 1 August 2018 submission deadline for Semester 2019A. The oversubscription rate (by proposal number) was 2.2 and the proposal pressure (hours requested over hours available) for both the A and B configurations was 2.0. This pressure is similar to that for Semester 18B and somewhat higher than has been reported for semesters prior to 18B – the difference results from the discovery that some proposals were being neglected in calculating the VLA proposal pressure. Correcting this omission indicates that the long-term average proposal pressure for the VLA is between 2 and 3. One large and 36 time critical (triggered) proposals were received. There was significant demand for the time made available on space observatories through inter-observatory agreements, and nineteen proposals requesting time on the Hubble Space Telescope, Swift or Chandra (together with AUI/NRAO telescope time) were submitted.

The proposals were reviewed for scientific merit by eight Science Review Panels (SRPs) and for technical feasibility by NRAO staff. These reviews were completed in September – October 2018 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 23-24 October 2018 in Socorro, New Mexico. The TAC – comprising the 8 SRP chairs – was charged with recommending a science program for Semester 2019A to the Observatory Director. The recommended program was reviewed and approved on 6 November 2018.

Proposals submitted to the GBO and LBO were assessed through the same process. Forty-six proposals for the VLBA were received for Semester 2019A, corresponding to an oversubscription rate of 2.1 and a proposal pressure of 2.2.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 13 November 2018 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 has been 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 SOS program supports ~12 students for each ALMA Cycle and about three 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.

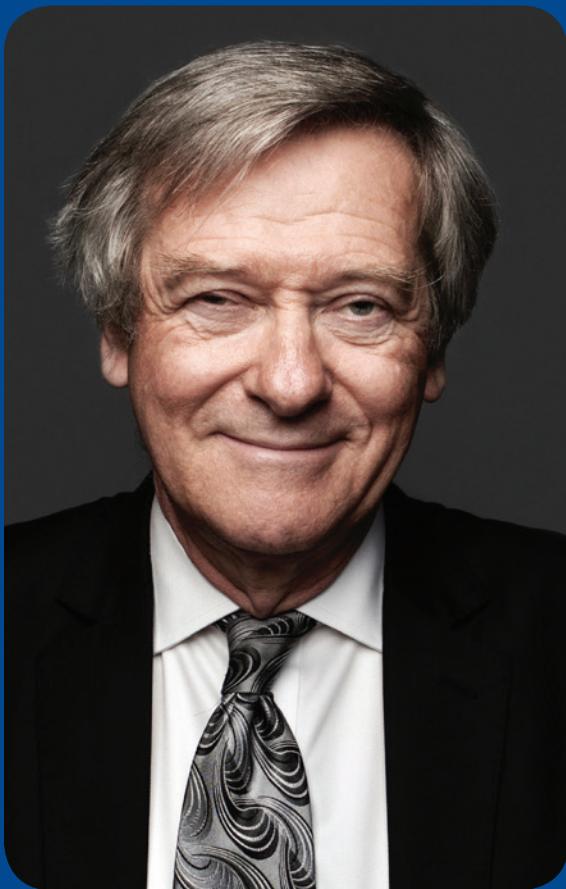
The SOS committee, an external panel, made the following awards for ALMA Cycle 5.

- 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?*

SCIENCE SUPPORT AND RESEARCH

- 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.*

Jansky Lectureship Awarded to Professor Roger D. Blandford



AUI and the NRAO awarded the 2018 Karl G. Jansky Lectureship to Professor Roger D. Blandford of Stanford University. The Jansky Lectureship is an honor established by the AUI trustees to recognize outstanding contributions to the advancement of radio astronomy.

Blandford has a long association with NRAO and the broader astronomy community, is an outstanding scientist and communicator, and has made many theoretical contributions to radio astronomy. In particular, he and his colleagues developed the basic theory behind the formation and propagation of cosmic jets of plasma propelled at nearly the speed of light. He has received many prizes and awards and is arguably the outstanding theoretical astrophysicist in the U.S.

A native of England, Blandford earned his B.A., M.A., and Ph.D. degrees at Cambridge University. He held postdoctoral positions at Cambridge, Princeton, and Berkeley before joining the faculty at Caltech, where he taught astronomy and physics for 25+ years. In 2003, he moved to Stanford to become the first Director of the Kavli Institute for Particle Astrophysics and Cosmology. His research interests

cover many aspects of radio astronomy involving quasars, pulsars and supernova remnants, as well as cosmology using gravitational lensing and the cosmic microwave background.

Blandford has received many honors, including election as a Fellow of the Royal Society and of the American Academy of Arts and Sciences, and is a member of the National Academy of Sciences. He has received the American Astronomical Society's Dannie Heineman Prize, the Crafoord Prize, and the Gold Medal of the Royal Astronomical Society.

Project Scientist Appointed for Science Ready Data Products

Effective 21 August 2018, Dr. John Tobin was appointed as Project Scientist for the Science Ready Data Products (SRDP) project. As project scientist, John leads the SRDP heuristics team in developing and validating the requirements for the SRDP project. John works closely with scientists from the North American ALMA Science Center and the New Mexico Array Science Center to ensure that the SRDP project delivers useful, science quality products, and an archive interface that maximizes the science impact of NRAO telescopes. Additionally, John works with the User Support groups to educate the community about the properties of the science ready data products produced at NRAO. John is the primary contact point between the NRAO SRDP Project and the broad community of NRAO telescope users.



Dr. John Tobin

John comes to NRAO from the University of Oklahoma where he was the Homer L. Dodge Assistant Professor. Previously, John was a Netherlands Organization for Scientific Research Veni Fellow at Leiden Observatory, and a Hubble Fellow, during which he was resident at the NRAO in Charlottesville. John received his Ph.D. in 2011 from the University of Michigan where he studied the morphology and kinematics of protostellar envelopes with Lee Hartmann and Edwin Bergin. John has recently served on the NRAO Users Committee and is an experienced observer on the ALMA and VLA telescopes.

Robert L. Brown Dissertation Award

The Robert L. Brown Outstanding Doctoral Dissertation Award is administered by AUI and NRAO on behalf of Brown's friends and family to honor his 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. Applications are due each year no later than 31 December.



Dr. Claire Murray

Most recently, the Robert L. Brown Outstanding Doctoral Dissertation Award was given to Claire Murray (Space Telescope Science Institute) for her extraordinarily detailed observations of the thermodynamic state of neutral gas in the interstellar medium (ISM), which she describes in her dissertation, *Unveiling the Diffuse, Neutral Interstellar Medium: Absorption Spectroscopy of Galactic Hydrogen*.

Murray's observations along 57 different sight-lines, her painstaking data analyses, and especially the new scientific results derived from her analyses were remarkable. Her work using the VLA, complemented by the Arecibo radio/radar telescope, provided important new insights into the present state of the ISM and revitalized a major field of study in Galactic structure. Additionally, Murray's work establishes a solid factual foundation for probing the complex dynamics of the ISM.

The Robert L. Brown Outstanding Doctoral Dissertation Award was presented to Dr. Murray on 20 September 2018 at NRAO Headquarters in Charlottesville, Virginia, after which she delivered a colloquium based on her thesis research.

Claire Murray received her M.S. (2013) and Ph.D. (2017) in astronomy from the University of Wisconsin. She graduated from Carleton College with a B.A. in physics in 2011. In 2010, Claire was a NSF Research Experiences for Undergraduates student at NRAO – Socorro, where she and Lorant Sjouwerman discovered the first methanol maser in M31. She is currently a postdoctoral fellow at the Space Telescope Science Institute, where she has expanded her dissertation work to study the interplay between neutral gas and dust in the Milky Way and the nearby Magellanic System to aid cosmological experiments by quantifying Galactic dust foregrounds with high precision and to resolve the multidimensional gas flows governing the evolution of star-forming molecular clouds.

SCIENCE SUPPORT AND RESEARCH

From the Archives: NRAO Summer Students

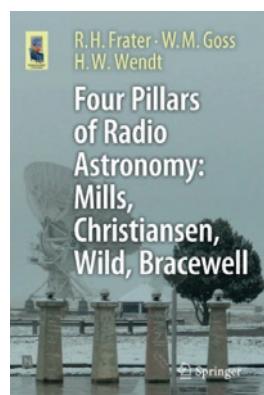


Students participating in NRAO summer student programs arrive each year at their respective NRAO sites in late May and early June. Since its inception in 1959, the summer student program has engaged over 1,000 young people in scientific research, and many NRAO summer students have gone on to distinguished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

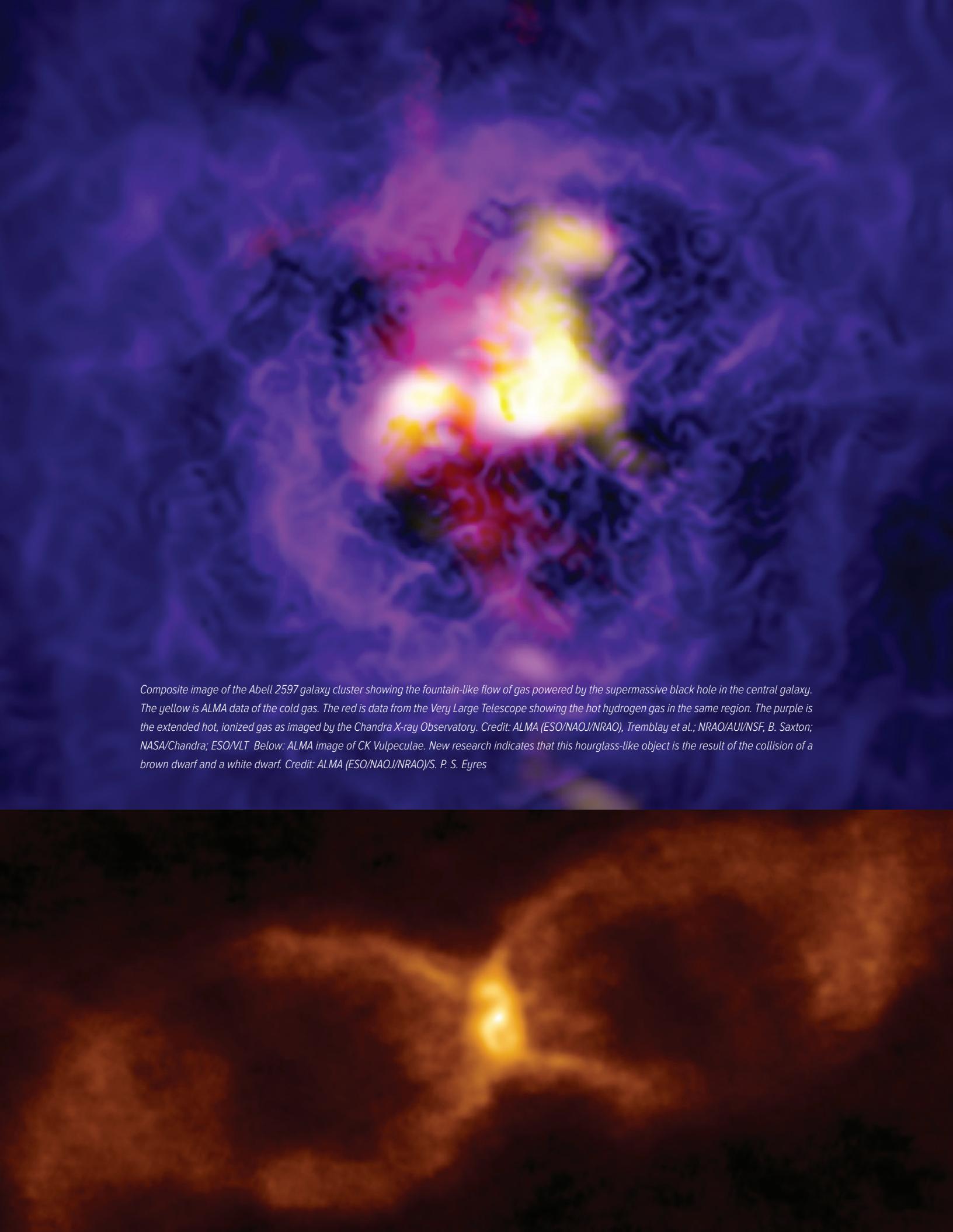
This image shows the 1981 Charlottesville summer students. [Left to right, back] Jim Knoke, Chong-An Chang, Dave Wolpert, Tony Davidov, Roy Nakatsuka, Reinhard Skuppin, Debe Crocker. [Left to right, front] Paul Coleman, Dianne Tucker, Jim Lewis, Elizabeth Sturgis, Carol Bornmann.

New Book Highlights Early Radio Astronomy Pioneers

A new book published by Springer explores the early history of radio astronomy by telling the stories of four pioneers who laid the foundations not only for today's cutting-edge research facilities but also for technologies that have transformed daily life. *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, recounts the saga of a pathfinding team of Australians who made unique contributions in the era following World War II. Their contributions helped build radio astronomy into a worldwide scientific powerhouse that would transform our understanding of the Universe. Along the way they also would pave the way for technologies ranging from Wi-Fi to medical imaging.



In addition, Bernie Mills, Chris Christiansen, Paul Wild, and Ron Bracewell created an environment that encouraged scientific discovery and influenced the careers of many researchers who followed them. Authors R.H. Frater, W.M. Goss, and H.W. Wendt weave the stories of these remarkable pioneers into a narrative aimed at a general, non-specialist audience interested in science and astronomy.



Composite image of the Abell 2597 galaxy cluster showing the fountain-like flow of gas powered by the supermassive black hole in the central galaxy. The yellow is ALMA data of the cold gas. The red is data from the Very Large Telescope showing the hot hydrogen gas in the same region. The purple is the extended hot, ionized gas as imaged by the Chandra X-ray Observatory. Credit: ALMA (ESO/NAOJ/NRAO), Tremblay et al.; NRAO/AUI/NSF, B. Saxton; NASA/Chandra; ESO/VLT. Below: ALMA image of CK Vulpeculae. New research indicates that this hourglass-like object is the result of the collision of a brown dwarf and a white dwarf. Credit: ALMA (ESO/NAOJ/NRAO)/S. P. S. Eyres

DATA MANAGEMENT AND SOFTWARE

The NRAO Data Management and Software (DMS) department made key contributions to the NRAO throughout 2018. DMS deliverables provided vital infrastructure for the VLA Sky Survey, from taking the observations through ingestion into the archive and the workflow to flag, calibrate, image and provide Quality Assurance (QA) information on the observations, as well as software to track the status of the observations and derived products. ALMA pipelining was improved. This work for the VLASS and ALMA will be integrated within the Science Ready Data Products (SRDP) initiative under the leadership of the SSR department.

The new Archive Access Tool steadily improved throughout 2018, most notably with support for access to pipeline products—not just raw telescope data.

DMS staff worked with SSR towards developing requirements for a next-generation Proposal Submission Tool.

DMS strengthened the Algorithm R&D effort inside of the department, and administratively separated it into a distinct group for visibility and tracking purposes.

Scientific Information Services

The Scientific Information Services (SIS) division is matrixed into the Information Technology (IT)-centric Computing Information Services (CIS) division. This enables transparent sharing of highly skilled staff for both telescope-supporting science responsibilities (SIS), as well as general IT support duties (CIS). There are four major functional groups in SIS.

The site-centric Computing Operations groups for the NAASC and New Mexico (NM) Operations directly support day-to-day telescope operations and reliable delivery of data to the archive and the community. They ensure that telescope capability development projects are appropriately staffed, with resources being assigned based on commitments and timelines defined within the Program Management Department and at the site. Project and milestones for these resources are tracked under the appropriate telescope support sections. The DMS department focussed on infrastructure required for CASA Pipeline development for use by the JAO and ARCs as well as the VLA. In FY2018, the planning and delivery of RHEL 6.9 and 7 Operating System (OS) images for testing by the telescope operations and science software development division was completed.

The Archive and Cluster Processing group supports the production archive, parallel processing clusters, and the user-facing storage resources needed in support of pipeline processing and science data analysis. It defines the operational model for these shared resources – e.g., with batch and resource scheduling – and works closely with the Software Division. There is substantial staffing and skill overlap with the Unix Common Computing Environment in CIS. This group ensured sufficient storage was provisioned throughout 2018 to maintain pace with observations. Specific attention was given to large projects such as VLASS and ALMA Cycle 5. Installation of CASA parallel testing resources mitigated the impact of this key work on data reduction operations and PI support. Following the successful upgrade of the NM Lustre system, the NAASC Lustre installed a petabyte storage solution. Due to the age of the first-generation Next Generation Archive Systems, SIS worked with Science Support and Archive and ALMA/JAO to define a data migration utility to decommission low capacity drives and consolidate their records onto higher density storage. The actual migration has been deferred to ensure adequate validation and testing. The NM Lustre solution successfully underwent a system software upgrade with minimal downtime. To better manage the shared Lustre resource, group quotas were enabled for temporary accounts and for projects based on capacity planning and prioritized storage need.

The Science Computing group provided technology-driven advanced computing support, and is tasked with delivering the next generation of data processing solutions, working closely with the Software Division, CDL, and external cyberinfrastructure partners, such as the Extreme Science and Engineering Discovery Environment and national High Performance Computing (HPC) centers. This group is responsible for escalations from Archive and Cluster Processing and Telescope Operations in the event of systematic performance issues with the production infrastructure. In 2018, they worked closely with VLASS and SRDP to ensure

DATA MANAGEMENT AND SOFTWARE

efficient data processing of the first light VLASS products. The Science Computing Group investigated and deployed the Moab cluster scheduler to improve interactive and batch job packing to effectively provide twice the compute capacity for VLASS and ALMA SRDP product generation.

The Wide-Area Networking group is a science data capacity-driven team responsible for provisioning the long-haul, high bandwidth connectivity needed to uplink the telescope and then deliver reliable throughput in support of PI and general data delivery. Operational support for commodity circuits is handed off to Communication Services in CIS once a network service has been accepted into production. A feasibility study for provisioning fiber connectivity to the remaining 6 VLBA sites relying on copper network cabling was a major 2018 initiative. With the re-integration of the Long Baseline Observatory into NRAO, this project is proceeding, contingent upon anticipated infrastructure funding approval.

The Scientific Computing Group now employs Amazon Web Services cloud computing resources in operations support for capacity-on-demand for time critical projects and to ensure that VLASS has the required processing capacity for timely data processing and delivery.

As the reliance of NRAO on high-speed storage arrays increases, the potential for catastrophic data loss must be managed. Thus, SIS expanded the backup solution for the NAASC Lustre to one petabyte in 2018.

ALMA System Software

The Antenna Bus Master computers in the ALMA antennas and Correlator Control Computers in the Baseline Correlator use a Real-Time Operating System (RTOS). The RTOS implementation previously relied on the RealTime Application Interface (RTAI) on 32-bit computers. Serious effort in 2017 was spent developing and testing software so that the 32-bit machines could be updated to 64-bit machines without depending on RTAI. Testing of the RTOS upgrade project on the ALMA telescope was conducted November 2017 – January 2018. The software was delivered as part of the Cycle 6 software in January 2018, to be used on-sky starting October 2018.

In May 2016, a workshop was held in Charlottesville, VA on improvements to the Baseline Correlator. Six areas were defined in which to improve the correlator subarray efficiency, which is critical to avoid delaying observations. The improvement areas involve parallelization, reducing duplication, moving processing to components with a lighter workload, and re-using previously computed results. The parallelization effort was largely completed in 2017. Improving efficiency by re-using previously computed results and reducing duplication was completed in 2018 and delivered in the Cycle 6 software. The remaining tasks for improving efficiency, including improvements to scheduling of calibrations in subarrays, were delivered via a pre-release for the Cycle 7 software.

The Correlator group invested significant effort into better simulations. The simulations progressed on two fronts: replicating subarray functionality in the Correlator Data Processor and recreating execution times. The first task produces simulated correlator output; the second task allows for realistic subarray scheduling. The bulk of these improvements were delivered for Cycle 6. The simulations were upgraded for Cycle 7.

Operational efficiency can be improved by scheduling observations based on atmospheric conditions for a particular ALMA antenna array. The Control group developed a component that takes water vapor radiometer data and telescope calibration results and produces products to optimize telescope scheduling. These products include the highest recommended observing frequency based on phase stability, optimum phase calibration cycle time, and estimated spectral window average sky brightness variability. The observing conditions software was developed in stages starting at the beginning of FY2018 and delivered as part

Photo by P.Carrillo, NRAO/AUI/NSF

of the Cycle 6 software. The algorithms and implementation were refined in 2018 via on-sky testing and day-to-day ops use, and were delivered for the Cycle 7 software.

The focus of the scheduling software team in 2018 was on optimizing the Dynamic Scheduling Algorithm (DSACore) which translates into improved observing efficiency. In FY2017, the infrastructure surrounding DSACore was simplified and formalized, ensuring that DSACore receives reliable and accurate inputs. In 2018, the focus was on the algorithm to produce improved short, mid, and long-term simulations. In addition, the scheduling infrastructure was updated to be more flexible in accepting new inputs and requirements, such as the observing conditions component developed by the Control system, and relaying them to DSACore.

VLA System Software

The responsibilities of this group include the system software – primarily monitor and control, but including other operational functions, notably dynamic scheduling. Much of the work is maintenance, however some new capabilities were provided. Deployments for use during Semester 2017B and 2018A PI observing were made in 2018. In addition, software was incrementally made available for commissioning new Semester 2018A and 2018B capabilities. This group also supports VLBA System Software via an internal Service Level Agreement. Support was provided as required for major VLA projects including fast transient detection (*realfast*), VLASS, and ngVLA.



DATA MANAGEMENT AND SOFTWARE

Software Development

Development of the Common Astronomy Software Applications (CASA) package, the NRAO post-processing software, continued to emphasize support for the VLA and ALMA, unlocking their scientific potential. During 2018, NRAO added capabilities and supported the evolving understanding of the requirements of these forefront telescopes.

CASA version 5.1 was released to the community early in FY2017, providing ALMA Cycle 5 support, as well as VLASS improvements and support. An internal CASA version 5.2 was released in early 2018, implementing parallelization improvements in imaging for the ALMA pipeline. These were validated and later released publicly as part of CASA 5.4 for ALMA Cycle 6. In mid-2018, CASA 5.3 was released with improvements to the ALMA and VLA pipelines for Cycle 6 and VLASS. The Joint Institute for VLBI in Europe added tasks to enable the use of CASA for VLBI data calibration in version 5.3. CASA 5.4, released in late FY2018, included the ALMA Cycle 6 pipeline, parallel imaging, and telemetry recording.

Stability and robustness were addressed in all CASA releases, completing initiatives to address technical debt in the calibration and imaging subsystems. The rollout of new software engineering processes continued in CASA and pipeline throughout 2018.



DMS continued to gather input from the CASA Users Committee to help guide CASA development. This feedback was incorporated in the ongoing development plans.

The international CASA development team, led by NRAO, continued to increase support for single dish data reduction and HPC capabilities working on the integration of those capabilities with the standard reduction pipelines. The team continued to support and develop new imaging and calibration algorithms through a close connection to the NRAO Algorithm Research and Development Group.

Progress on the Cube Analysis and Rendering Tool for Astronomy (CARTA) next-generation visualization software continued through the collaboration with ASIAA CASA Development Center and the South African Institute for Data Intensive Astronomy, with the intention of improving the user interface and expanding capabilities. The CARTA production release is late. Additional resources have been assigned on a temporary basis to help assemble an initial release in FY2019. Through a collaboration with the University of Alberta, software was developed to support interactive clean capabilities in CARTA. This will be integrated and tested as the CARTA software matures.

Additional collaborations extend the use and capabilities of CASA. The Australia Telescope Compact Array and Giant Metrewave Radio Telescope support the use of CASA for reduction of their data products. A staff member from each of those observatories is available through the NRAO helpdesk to answer questions specific to these telescopes. NRAO has started an initiative with the SKA to jointly investigate the definition of a next iteration for the CASA measurement set. If successful, this will be a first step in updating the underpinnings of CASA, parts of which are 25 years old. This would be an important part of the general CASA refurbishment designed to ensure that CASA continues to fill VLA and ALMA needs, and can evolve to be suitable for the ngVLA.

The CASA Pipeline continued to evolve to support ALMA, VLA operations, and VLASS. A major release was delivered to coincide with ALMA Cycle 5. This release included improved imaging along with calibration and flagging improvements to increase process efficiency and support faster delivery of PI data. A subsequent pipeline update was provided internally with CASA version 5.2 to provide parallelized imaging capability in the ALMA pipeline.

The CASA and CASA Pipeline teams iterated with VLASS to provide updates for testing, development of calibration and imaging algorithm improvements, and delivery of calibrated data products.



Version 3.0 of the new Archive Access Tool / Pipeline Processing Interface was released. It supports storing, searching, and retrieving VLA calibration pipeline products. Similar capabilities for images were developed and were delivered in Version 3.5 in late 2018.

The Observation Preparation Tool (OPT), PST, and PHT were updated to support VLA observing. The NRAO Users Committee advised that the PST should get priority over the OPT for significant upgrades. A PST version eliminating sessions from the user interface was delivered as specified. The SSR Telescope Time Allocation group, after some deliberation, chose not to continue development of this version. DMS participated with the SSR department in the requirements gathering process for a potential new tool.

Algorithm Research and Development

To increase the visibility of CASA-based Algorithm R&D, DMS implemented an administrative change so these efforts are now managed by a separate subgroup. A management plan for this newly-organized group was developed. The plan includes a long-term roadmap. The roadmap was developed and reviewed by NRAO scientific staff and other major stakeholders. The roadmap contains items which address efficient scientific use of Observatory instruments that require long-term focus and R&D. These include scientific algorithm development, evaluation of high-performance computing platforms/hardware, and feasibility of deployment on such platforms in production software. The roadmap will be reviewed and updated annually. Early roadmap deliverables include a derivation of antenna parameters from holography data for wide-band imaging and integration of frequency-dependent antenna parameters in the imaging code.

DMS crafted a memo on imaging performance requirements for the ngVLA. This involved simulating data that cover the typical imaging requirements for the ngVLA science drivers. Data was imaged using standard CASA algorithms to estimate the size-of-computing. DMS also provided a memo with possible solutions for the major issues in VLASS imaging, a development roadmap and estimate of size-of-computing for science quality productions for VLASS Epoch-I imaging. This is required to characterize the imaging algorithms and low-level investigations to understand the VLASS data. This led to discovery of a number of previously unknown issues in VLASS data, observing parameters, and bugs in the relevant VLA on-line control software.

CENTRAL DEVELOPMENT LABORATORY

The Central Development Laboratory (CDL) mission is to maintain and support the evolution of existing NRAO facilities and to provide the technology and expertise needed to build the next generation of radio astronomy instruments. Work continued through 2018 in the areas of low-noise amplifiers, millimeter and sub-millimeter detectors, optics and electromagnetic components including feeds, digital signal processing, integrated receiver development, and other new receiver architectures. This was a transitional year for the CDL during which workforce demographics drove succession planning, and the new Laboratory Director, Dr. Bert Hawkins, evaluated and began to refine the CDL long-range technology development strategy.

One significant change was the integration of the Correlator team into a larger Digital Design Team, with the mission to provide digital design and engineering support to projects throughout CDL and to closely collaborate with the Integrated Receiver group and Digital Signal Processing research engineer to help steer the digital way forward for CDL.

In 2018, the CDL successfully conducted the Preliminary Design Review for the ALMA Correlator Upgrade Project (CUP). A Conceptual Design Review for the second generation of the ALMA Band 6 cartridge was also successful. CDL initiated a new development effort – Traveling-wave Kinetic Inductance Parametric (TKIP) amplifiers – as part of an ALMA development grant. The lead research engineer started outfitting a TKIP laboratory, including a milli-kelvin dilution refrigerator.

The Integrated Receiver Development group completed the construction of a dual-polarization, W-band front-end with faster sample rates, broader bandwidth, and greater flexibility than previous prototypes. Other notable milestones included the construction of a mm-wave hot/cold load test set for the calibration and testing of Digital Orthomode Transducers (DOMT), integration of the high-bandwidth unformatted serial link with the integrated front-end, and demonstration of reflectionless filters with active synthetic elements. In 2018, as part of a CDL ngVLA work package, a subcontract to design a custom Serial Analog-to-Digital-Converter (SADC) based on a concept developed by the CDL Integrated Receiver Development (IRD) program was initiated. Prior to the ngVLA funding, prototype circuit boards using the best available off-the-shelf parts were used to provide a proof-of-concept. Now this new contract will implement the design in an Application Specific Integrated Circuit (ASIC), a silicon chip, thereby realizing major benefits in size, pin count, and especially power dissipation—all crucial metrics for the ngVLA conceptual design. The first chips are to be delivered in early 2019.

During 2018, CDL completed and delivered several Work for Others (WFO) projects and continued to make significant technical strides across key technology areas. Production of the ALMA band 1 Local Oscillator system was initiated and is expected to continue through 2019. Construction and delivery of cryogenic low noise amplifiers for the ALMA band 1 receiver project also continued throughout 2018. CDL also provided mission support for the maintenance and operation of NRAO telescopes.

Repair, Maintenance, Production, Support

The core CDL production and support activities for 2018 are described below.

Millimeter and Submillimeter Detectors

CDL continued to support the offsite maintenance of the ALMA band 6 receivers originally built by NRAO, with the focus on maintaining a sufficient quantity of spare mixers and preamps. During the same period, CDL supported millimeter wave community projects, such as the Arizona Radio Observatory (ARO), the South Pole Telescope, and the Taiwanese Greenland Telescope based on the Vertex ALMA prototype antenna. With the exception of the ALMA support, these activities were outside the scope of the NRAO NSF award and were carried out on a Work For Others (WFO) basis and undertaken only when it did not interfere with work required under the NSF award.

Maintenance and production of band 6 (211–275 GHz) mixer-preamps was delayed during the past several years by the inability to reproduce mixer-preamps with the stringent gain flatness of those in the original receiver production run. The

CENTRAL DEVELOPMENT LABORATORY

reasons for this are not completely clear, but likely originated in the need to use commercial components in the preamps that differed from those available when the receivers were first produced. Commercial resistors and capacitors are not specified for operation at 4K, and even slight changes in manufacturing – such as use of a different high relative permittivity dielectric in a capacitor or a change in the resistive film used in a resistor – are typically not indicated by a change of part number as long as the specifications remain unchanged within the normal operating temperature range.

Low Noise Factory (LNF) in Sweden now offers a low-power 4–12 GHz MMIC amplifier which meets or exceeds the ALMA band 6 preamp noise and gain requirements. CDL worked with LNF to produce a direct replacement preamp which included an SIS mixer bias chip. When used with the CDL 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 specification. To remedy this, a passive gain slope equalizer was designed and incorporated. A formal engineering change request was filed with ALMA to seek approval for this component design change, and it was subsequently accepted, enabling subsequent mixer-preamplifier repair/refurbish work, which continued during 2018.

Ten K-band down-converter assemblies were built and qualified at the CDL for use as VLA spares. Two amplifiers for the Focal-plane L-band Array for the Green Bank Telescope were repaired.

Low Noise Amplifiers (LNA)

The CDL Low Noise Amplifier Group continued to produce replacement amplifiers and/or repair amplifiers for the VLA, VLBA, GBO, and ALMA telescopes. Several amplifiers were repaired, more units are in the repair queue, and this work will continue into 2019. During 2018, collaboration with JPL's Deep Space Network continued under a Memorandum of Understanding (MoU). The JPL team visited CDL several times to study the assembly of amplifiers. The modeled and measured results of X-band and Ka-band amplifiers, respectively, were also compared.

Amplifier production work, under the contract to manufacture 160 amplifiers for ALMA band 1 cartridges, continued during FY2018. A quantity of 28 band 1 amplifiers was built and accepted by Academia Sinica Institute for Astronomy and Astrophysics (ASIAA) during the course of this year. Another quantity of 16 band 1 amplifiers has been submitted for acceptance review and await shipping. This multi-year project will conclude in FY2019.

ALMA Offsite Hardware Support

The CDL offsite hardware support team provided extensive support to ALMA Operations during 2018 including: (a) diagnosis consultancy, on-site visits to the OSF by support teams; (b) software and firmware support; and (c) repair and return of malfunctioning line replaceable unit (LRU) hardware. In all, 27 Front End (FE) LRUs (including receiver cartridges), 35 Warm Cartridge Assembly LRUs, and 42 Back End (BE) Local Oscillator (LO) and Photonics LRUs were returned to the ALMA site after repairs. Notable LRUs (not a comprehensive list) that were repaired in 2018 included: band 6 cold cartridge assemblies, FE bias modules, FE M&C modules, warm cartridge/local oscillator assemblies (a mix of various bands), Line Length Correctors, and LO Photonic Receivers. Lower-level hardware repair was carried out on 258 sub-assemblies. Hardware for the FE Test & Measurement Systems, including the IF processor modules and tilt tables, was also repaired/replaced during 2018. A new batch of compressor M&C modules were fabricated, tested, and delivered to the OSF to replace old and obsolete spare units.

In addition to the continuation of the multi-year band 1 amplifier construction work, CDL staff completed the following WFO projects and delivered the requested hardware and/or services to the larger radio astronomy community:

- ALMA FE Components for KASI;
- Band 6 Mixers for Steward Observatory (2x);
- Q band cryogenic low noise amplifiers for MIT Haystack Observatory (2x);

- K band low noise cryogenic amplifier repairs for Torun Observatory (3x);
- ALMA band 10 FE Local Oscillator Power Amplifier for Virginia Diodes Inc. (1x);
- ALMA band 1 FE Local Oscillator assemblies for ASIAA (10x);
- ALMA band 6 receiver chains for East Asia Observatory and ASIAA: Band 6 horn (2x), Band 6 Orthomode Transducer (2x), Band 6 Mixers (4x);
- C band cryogenic low noise amplifiers for Steward Observatory (4x);
- Mini-Circuits' request for new models of reflectionless filter designs.

CDL also constructed and delivered six compact water vapor radiometers for the ngVLA, ten K-band downconverters to VLA, and repaired two Phased Array Feed amps for GBO.

Research & Development

CDL Research and Development (R&D) efforts 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.

The R&D resources remained constrained due to lack of new approved ALMA development projects; nevertheless, the above strategic goals formed the basis for most R&D activity.

Millimeter and Submillimeter Detectors

In 2018, assisted by UVA Microfabrication Laboratory (UVML), the CDL continued to develop components for the next generation of the ALMA band 6 receiver cartridge. This work involved the following main areas:

- The development of SIS junctions with Aluminum Nitride (AlN) tunnel barriers that have high critical current density and sufficient reproducibility to permit receiver production on ALMA scales. This will allow new mixers for band 6 to be produced with flatter noise temperature and gain vs. frequency performance than is currently the case;
- 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.

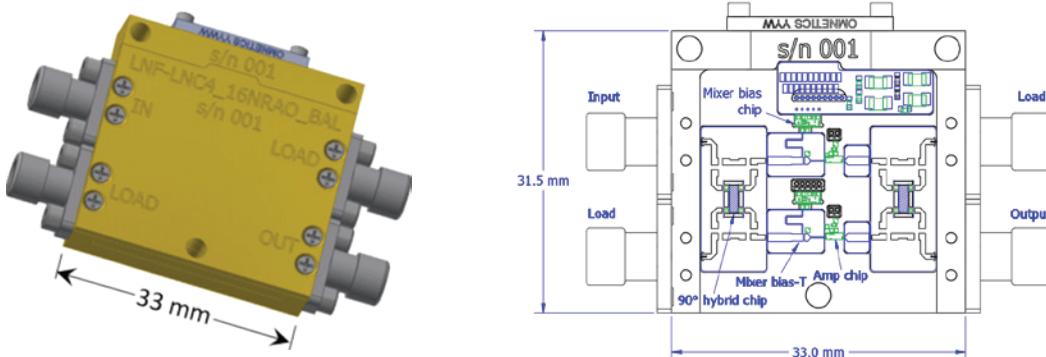


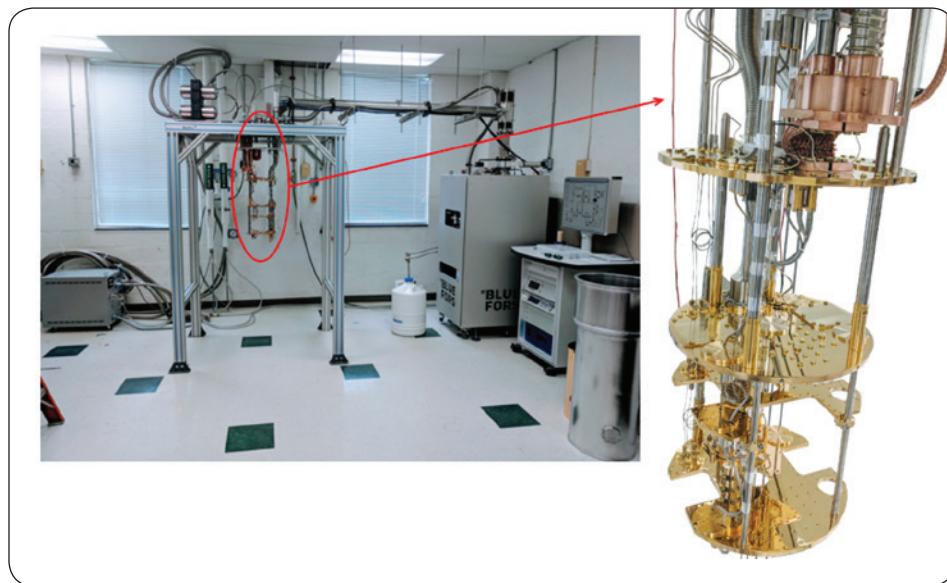
Figure: The balanced 4–12 GHz IF amplifier (left), and the layout of the components within (right). The amplifier is based on a superconducting IF hybrid designed at NRAO and produced by UVML, and Low Noise Factory produced cryogenic amplifier MMICs. The component amplifier MMICs have been evaluated in this package and exhibit good gain and noise temperature performance. Further development work continues to improve the input return loss of the superconducting IF hybrids and to reconfigure the assembly as a balanced amplifier and measure it.

CENTRAL DEVELOPMENT LABORATORY

The test set for evaluating the balanced 4–12 GHz cryogenic IF amplifier at 4K was constructed during 2018, and preliminary measurements made on the prototype balanced amplifiers. The first wafer of 4–12 GHz superconducting quadrature hybrids had a very low yield (root-cause identified), and CDL awaits the delivery of the next wafer with improved devices. Following the delivery of the amplifiers, Low Noise Factory found that the gain of MMIC chips used would change from one cool-down to the next. This is not acceptable for a balanced amplifier, and the manufacturer has proposed to replace the MMICs in these amplifiers with new ones.

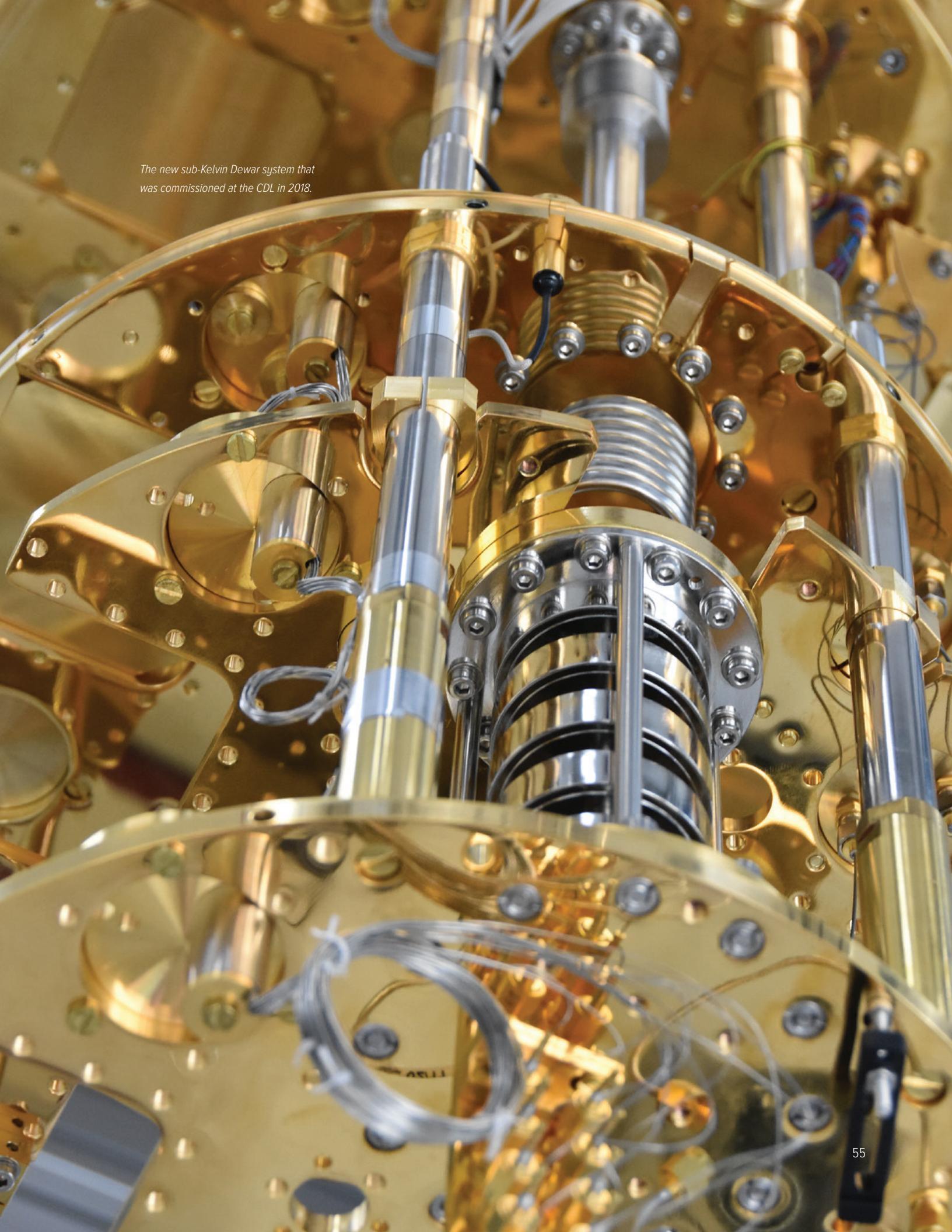
During the year, a band 6 cartridge upgrade plan describing all available options was produced along with development, cost, and schedule estimates. An ALMA Conceptual Design Review was successfully conducted and this should pave the way for funding the continuation of this effort.

TKIP amplifiers developed in recent years by the quantum computing industry have the potential to be a revolutionary technology in radio astronomy instrumentation. The TKIP amplifier is essentially a long superconducting transmission line whose nonlinear kinetic inductance generates gain over a wide frequency band when an appropriate pump signal is present. In addition to their wide bandwidth, TKIP amplifiers have quantum-limited noise. They appear to be equally well-suited for use as RF front-end amplifiers or as IF amplifiers following SIS mixers. As a replacement for the IF amplifiers in the current ALMA SIS receiver (bands 3–10), TKIP amplifiers would result in a reduction of receiver noise temperature of ~10–15 K—the current receiver noise temperatures are 30–50 K in ALMA bands 3 to 6 —thus TKIP could provide a major improvement in sensitivity. This is a new field of development at the CDL. New equipment and instrumentation needs to be installed to enable it. In FY2018, significant progress was made to set up this desired new facility, including the procurement, installation, and commissioning of the BlueFors milli-Kelvin cryostat as well as some necessary test instrumentation. Once the test sets are completed, the evaluation of JPL TKIP devices is expected to commence in FY2019.



A sample housing for the W-band TKIP parametric amplifier was machined at CDL and sent to JPL for an amplifier to be installed. In preparation for the parametric amplifier testing, the W-band waveguide vacuum feedthroughs, and thermal waveguide isolators that are required for building the cryogenic test-bed, were designed, machined, and tested.

*The new sub-Kelvin Dewar system that
was commissioned at the CDL in 2018.*



CENTRAL DEVELOPMENT LABORATORY

Low Noise Amplifiers

Initial results concerning the natural limits of noise performance of microwave Field Effect Transistors (FET) have been published. Theoretical work on this subject continued in 2018, with special emphasis on the limits of the noise performance of Indium Phosphide (InP) high electron mobility FETs. This work focused especially on further scaling of the gate length and will also address the so-called noise cancellation techniques used in Complementary Metal-Oxide Semiconductor transistors. Although this last topic is not expected to significantly impact state-of-the-art low noise receivers for radio astronomy, it may impact the direction of SKA and ngVLA development. CDL experience in building the state-of-the-art amplifiers using chip-and-wire technology will continue to be useful in specific applications where a commercial source cannot deliver state-of-the-art performance.

The amplifier group evaluated sample devices from Diramics Inc., a new Swiss (Zurich-based) commercial source for low noise devices, by installing them in CDL amplifiers, and found the performance to be very close to that obtained using devices from the cryo-3 wafer. This establishes a potential alternate and commercial source for these devices.

Optics and Electromagnetic Components

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

As part of the exercise to iterate upon ngVLA antenna designs, beam patterns of 18m dual-offset Gregorian and Cassegrain antennas with varying subreflector angles were computed. Aperture efficiency from 1.2–2.4 GHz was calculated and compared for the different cases. Integrated phase shifters (with transitions on either end) for the Ka-band were evaluated by measuring the differential phase shift between orthogonal polarizations. This method of fabrication eliminates four extra flanges and are faster to electroform compared to manufacturing three individual pieces. This design could be useful in a future Ka-band receiver.

The General Reflector Antenna Software Package from Ticra was successfully commissioned. This software enables the accurate design and analysis of reflector antennas. A few test cases were modelled and analyzed to assess the accuracy of the software. The Corrugated Horn Analysis by Modal Processing software package was also obtained.

A prototype of the corrugated horn, designed (in the 4–8 GHz band) for the ngVLA reference design optics, was fabricated. This is an axially corrugated horn with a half-flare angle of 55 degrees. Far-field patterns were measured in the Green Bank anechoic chamber range. Patterns were recorded in the principal and the diagonal planes. Measurements were found to be in agreement with simulated results.

A new Jansky Fellow joined the CDL this year and will assist with the re-optimization of the optics for the ALMA band 6 cartridge over the next two years.

Digital Signal Processing (DSP) and Correlators

The CDL Correlator team was integrated into a larger Digital Design Team to provide digital design and engineering support at CDL and to closely collaborate with the Integrated Receiver group and Digital Signal Processing (DSP) research engineer.

In coordination with the National Research Council (NRC) - Canada, the preliminary requirements, reference design and cost estimate of the ngVLA Central Signal Processor have been finalized. Spectral kurtosis has been evaluated as a candidate pre-correlation RFI technique for several types of RFI (narrowband, pulsed, etc.). Full analysis and dissemination of the results are still in progress.

Plans to present the ALMA Correlator Upgrade Proposal to the ALMA Board in November 2017 were scrapped in favor of holding a Preliminary Design Review of the project. A successful PDR was completed in March 2018, following which the project was presented to the ALMA Board. The Correlator Upgrade Project was initiated in April 2018.

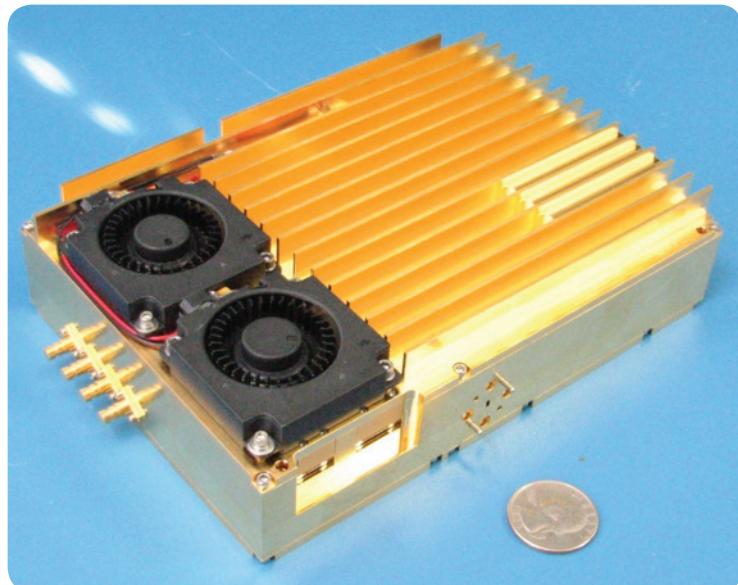
Prototype printed circuit boards for the ALMA Correlator Upgrade Project were fabricated. During the February 2018 ALMA shutdown, these newly designed/fabricated cards were used to test the operation of the interface between Station and Correlator racks in the ALMA correlator at twice the current data rate.

Component shortages and obsolescence issues could impact the Fifth Quadrant effort—consequently, an internal parts review was carried out to identify any potential issues. Further construction of electronic assemblies continued for the Station Cards, Mezzanine Cards, and PCB layout of Final Adder Card. Visits to vendors were part of the effort to finalize the contract for the Application Specific Integrated Circuit (ASIC) physical design services and start the initial design phase. The Correlator ASIC physical design vendor was selected.

Integrated Receiver Development (IRD)

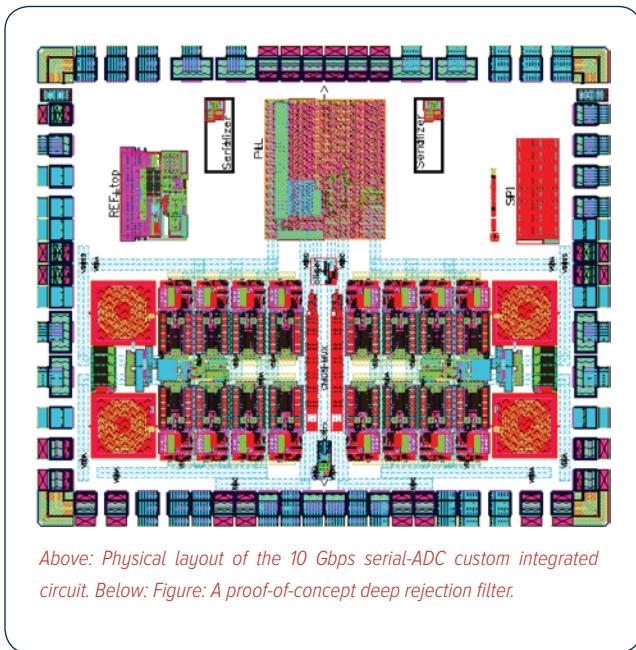
Evaluation of the W-band IRD Front End was started but suffered delays as several technical issues were encountered. A Back End circuit board was damaged, and an unexpected oscillation in an IF signal path module was detected. These issues were successfully resolved. Furthermore, an active doubler in the digital OMT test set failed. An alternate device has been identified and is in the process of being procured. Testing will be resumed once the system is reintegrated.

Right: A dual-polarization, W-band Front End with faster sample rates, broader bandwidth, and greater flexibility than previous prototypes was constructed in 2018.



The IRD group also procured the necessary hardware to implement an unformatted serial link operating at 10 Gbps over 40 km of fiber. Preparations are also underway to demonstrate its operation. This is the longest distance over which this has been ever attempted. Confidence level for a successful test is very high, and this will have positive implications for the ngVLA.

CENTRAL DEVELOPMENT LABORATORY



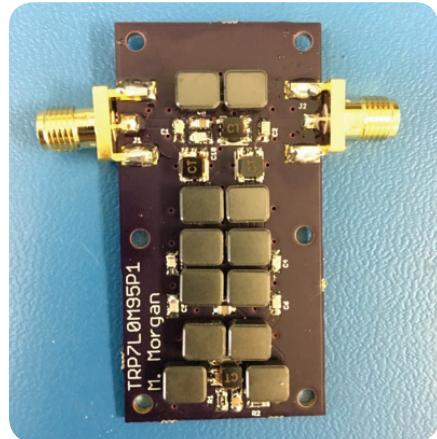
Above: Physical layout of the 10 Gbps serial-ADC custom integrated circuit. Below: Figure: A proof-of-concept deep rejection filter.

Earlier in 2018, a contract was signed with City Semiconductor (San Francisco) for development of a Serial Analog-to-Digital Converter (SADC). Subsequently, architectural and schematic design reviews were held with City Semiconductor for SADC design/fabrication-work, and the prototype chips are expected to be delivered in early 2019 after the final design reviews are completed. This will be the first-article prototype for the ngVLA operating at 10 Gbps.

Reflectionless filter technology has been an offshoot of the CDL IRD. In the past, the CDL has filed for and been awarded patents for several configurations of reflectionless filters. This year, U.S. Patent No. 9,923,540, titled Transmission Line Reflectionless Filters, was issued on 20 March. Also, a new provisional patent application was filed for Deep Rejection Reflectionless Filters (no. 62/652,731). These circumvent a long-standing limitation of previous designs.

Band 2+ Prototype Project Closeout

Since the ALMA Cycle 5 band 2 construction proposal failed to secure funding, the detailed design tasks that were underway following the successful PDR were continued until their next logical stop points and systematically wound down. The pending evaluation of the band 2+ turnstile OMT was completed. The final project report was drafted and submitted to formally halt the band 2 related development. However, a no-cost extension was filed to formally keep the project open to allow continuation of the cryogenic amplifier MMIC wafer run being executed as a sub-award by Cahill Radio Astronomy Laboratory at the Northrop Grumman Aerospace Systems foundry and to enable receipt of the resulting devices at CDL. This task is scheduled to be completed in 2019.



Phased Array Feed (PAF)

As envisaged in the 2018 Program Operating Plan, CDL sought to capitalize on its R&D investments in cryogenic PAFs by seeking potential customers for this technology or partners for further development. Several potential partners approached CDL for PAF projects, but the scope and risk of the projects were not deemed suitable. CDL continues to explore opportunities.

Hydrogen Epoch of Reionization Array (HERA)

The Hydrogen Epoch of Reionization Array (HERA) is a scientific road map investigation aimed at exploring the large-scale structure in the baryonic universe via the 21 cm line of hydrogen. Funding was acquired as a sub-award from the Moore Foundation (via the Massachusetts Institute of Technology, MIT) to help cover the cost of a UVA graduate student and postdoc participation in instrument R&D activities at the CDL. The goals of the three-year work package (June 2017 – May 2020) are: (a) assist MIT researchers to develop designs for a 60–120 MHz narrow band feed and a 60–200 MHz wideband feed for the

existing HERA dishes to extend the frequency range into that required for Epoch of X-ray studies; and (b) make portability, extended frequency coverage, and complex sampling improvements to the antenna beam mapping system that currently makes use of downlink signals from the Orbcomm satellite constellation.

Towards the above goals, the following tasks were completed during this year:

- Assisted MIT with the reflection coefficient measurements in Green Bank;
- Developed the high/low band convertible feed candidate concept for HERA;
- Refurbished several Precision Array for Probing the Epoch of Reionization (PAPER) project antennas for beam pattern development work;
- Developed a pair of dual-channel receivers for 150 MHz (in addition to 137 MHz receivers);
- Performed lost satellite search;
- Developed a new digital back end based on the Ettus Research Universal Software Radio Peripheral Software Defined Radio platform;
- Worked to develop the Orbcomm system with complex sampling (suitable for polarimetry), and to deploy the beam mapping development system at UVA research site. A proposal was made for drone-based beam mapping in collaboration with UVA faculty.

Network for Exploration and Space Science (NESS)

The Network for Exploration and Space Science (NESS) will implement cross-disciplinary partnerships to advance scientific discovery and human exploration at target destinations in the Solar System. NESS includes research in "...astrophysics and heliophysics that is uniquely enabled by human and robotic exploration of Target Bodies." The foundations for the next generation Cosmic Twilight Polarimeter (CTP) is supported by this grant to assist the concept development for a similar instrument on the Moon. Funding was obtained as a sub-award from the NASA Solar System Exploration Research Virtual Institute Program for graduate student support at the University of Virginia, July 2017 through June 2022.

The proof-of-concept CTP was demonstrated in 2018, and work is ongoing on the enhanced version. Improvements in gain tracking stability will be implemented with the goal of maintaining under 10 ppm variation over long integration periods. Backend throughput will be improved via an FPGA-based data acquisition and processing platform. The CTP will be deployed at GBO for stand-alone observations and as an engineering development platform for space-based systems.

Support Facilities

The CDL machine shop provided support for many of the CDL repair, maintenance, production, and support functions and also played a critical role in research and development.

Approximately 100 jobs were completed by the machine shop. A new Matsuura LX-160 precision milling machine was acquired to complement other CDL milling machines. This machine has an X/Y/Z positioning accuracy of ± 0.001 mm ($\pm 0.000039"$) and a repeatability of ± 0.0005 mm ($\pm 0.000019"$).



Above: The new Matsuura LX-160 precision milling machine in the CDL machine shop adds the capability to manufacture sub-mm wave assemblies with stringent tolerance requirements.

EDUCATION & PUBLIC OUTREACH



The Education and Public Outreach (EPO) Department serves the strategic goal of broadening public appreciation of and participation in Science, Technology, Engineering, Arts, and Mathematics (STEAM) through its four divisions: (a) STEAM Education and Outreach; (b) News & Public Information; (c) Multimedia Engagement; and (d) Visitor Center Operations.

STEAM Education and Outreach

Sister Cities and Observatories

The Sister Cities cultural exchange program that had been led by AUI for the previous two years was adopted by EPO in 2018. After evaluating the results of the previous two exchanges, the program was wrapped up and rebranded as the Sister Cities and Observatories exchange. Changes include a redistribution of coordination responsibilities from the schools to EPO staff, reduction of the exchange from 30 to 10 days, and a shift from a cultural exchange with host families to a STEM exchange with a focus on the VLA and ALMA as observatories located in the vicinity of the small towns from where the students are recruited. The first trip with two high school girls and one teacher from San Pedro de Atacama High School took place at the end of FY2018. The in-country host, Business Manager Pablo Vidal, was an adept translator who facilitated a smooth trip for all. In advance of the trip, the students were given an opportunity to define their area of research interest and they chose indigenous astronomy. The exchange included opportunities to observe the northern hemisphere night skies, an introduction to southern hemisphere planispheres, and a session about preserving traditional sky knowledge with Navajo astronomers and founders of the Indigenous Education Institute. The students participated in the VLA Open House in October and provided bilingual astronomy activities for visitors on that day.



Radio Astronomy and Physics in New Mexico (RAP-NM)

The RAP-NM residential summer camp was hosted on the NM Tech campus in early June, immediately after the school year ended. There is fierce competition for summer programs, but the seven rising 9th graders who participated had a unique research experience that included access to NM Tech physics labs, NSF-funded Skynet Junior Scholars remote telescopes for observation in optical and radio bands, and access to the Spider 300 radio telescope installed by EPO on the NM Tech campus. Parents reported it was a transformational experience for their children. A detailed evaluation of the summer camp will inform further fine tuning of the model for 2019.



Virginia and New Mexico Community Outreach

Community outreach events occurred nearly every month. Science nights at local schools and career days are traditional partnerships that NRAO will build on for more strategic expansion of EPO programming.

EDUCATION & PUBLIC OUTREACH

In addition to numerous events, a unique opportunity presented itself as ODI evaluated its relationship with the African American Teaching Fellows (AATF) in Charlottesville. EPO, ODI, and AATF representatives met and devised a plan to leverage efforts from the summer NINE program with the AATF fellows, the Hampton City School system, and the Boys and Girls Club to:

- Develop a set of scaffolded lesson plans and activities for K-12 students, connected to Virginia Standards of Learning and Common Core standards;
- Provide students with a basic understanding of radio astronomy principles;
- Test and evaluate lesson plans/activities in FY2018–2019;
- Eventually deploy this set of plans through all NINE hubs, locally in VA and NM, nationally, and internationally.

News & Public Information

It was a steady year for newsworthy science results with the release of 57 press products inclusive of those for VLA and ALMA, plus LBO and GBO. Regular check-ins with contacts at each observatory assist in the evaluation of research publications as press release candidates.

The Public Information Officers (PIO) worked with the multimedia team to redesign the home page to develop a news and features page for the public web site.

Observatory	Releases	Announcements
ALMA	16	3
VLA	7	0
CDL	1	2
NRAO	4	8
GBO	9	1
VLBA	6	0
Total	43	14

EPO has the capability of posting a feature story along with press releases and image releases that have the full look of press releases, but without the distribution through Newswire, Eureka Alerts, or the AAS. This gives EPO more flexibility to include articles that may summarize several results that alone may not constitute breaking news, but would still be of interest to NRAO's general audience. In the coming year, the PIOs have committed to quarterly news features to fill in the gaps between press releases to ensure frequent updates on the NRAO home page.

The screenshot shows the NRAO website with a dark blue header. The header includes the NSF/NRAO logo, the text "National Radio Astronomy Observatory", and social media links for Facebook, Twitter, and YouTube. Below the header is a navigation bar with links for NEWS, GALLERY, BLOGS, TELESCOPES + TECH, VISIT US, LEARN, and EXPLORE. A search bar is also present. The main content area features a large image of a spiral galaxy with a bright central region. Below this image is a news article titled "New Method May Resolve Difficulty in Measuring Universe's Expansion" dated 8 July 2019. To the right of the main image are five smaller news cards with dates and titles: "20 June 2019 Planetary Rings of Uranus 'Glow' in Cold Light", "12 June 2019 2019 Jansky Lectureship Awarded to Caltech Professor", "5 June 2019 Cool, Nebulous Ring around Milky Way's Supermassive Black Hole", "29 April 2019 Black Hole's Tug on Space Pulls Fast-Moving Jets in Rapid Wobble", and "16 April 2019 The Giant In Our Backyard". At the bottom of the page is a "See All News" link and a set of navigation arrows.

Mentoring Interns

Public information interns serve short, project-based terms, delivering stories and research under supervision and direction of PIOs. This program provides mentorship for future astronomy communicators while advancing NRAO outreach efforts. During the summer of 2018, Adam Gattuso interned at NRAO headquarters and produced a series of blogs, contributed to the hosted videos by working on drafts of the script, and updated a glossary for the NRAO public website.

Multimedia Engagement

The Multimedia team provided original art, science image processing, and video support to the news group, but also took the lead on many projects. For example, the team experimented with a new hosted video format for news stories that tells a compelling video story. ALMA Data Analyst Melissa Hoffman read the part, and had a natural enthusiasm and ease in front of the camera. The full three minute video can be viewed online: <https://vimeo.com/277515054> and the full press release is at <https://public.nrao.edu/news/2018-alma-proto-trio/>.



Figure: ALMA Data Analyst Melissa Hoffman.

Production of a three-minute video requires a minimum of 40 staff-hours (script writing, editing, adapting illustrations, setting up teleprompter, video lighting, rehearsal, shoot and post production). When posted, the press release got 600 hits, but the video, posted a week later, received 1600 hits on Newswise. This experiment has inspired EPO to develop a workflow to include more videos in press releases.

Drone Video

The multimedia group teamed up with NM Ops and Brian Kent, an NRAO scientist who is also a licensed Federal Aviation Administration drone pilot, to acquire high definition aerial footage of the VLA during the scheduled electrical infrastructure upgrade. The complete shutdown of the array during this upgrade is the only feasible time to operate a drone over the array. Over four hours of aerial footage is now on file, and a short compilation is online at <https://vimeo.com/280796493>.



EDUCATION & PUBLIC OUTREACH

Social Media

NRAO EPO continues to maintain an effective social media presence on Facebook and Twitter. Each cultivates a different demographic, Twitter being a younger audience and Facebook an older audience. The Twitter audience is growing by ~43 followers per day and is now at 16,576 followers at the close of FY2018. Facebook has continued to adjust its algorithms to prioritize posts from friends and family and NRAO has seen a steady slow in audience growth, at a healthy 63,583. News and current events play well on Facebook and Twitter. In 2018, EPO launched an Instagram account that is steadily growing in popularity with 1,177 followers by the end of FY2018. It is a distinctly visual platform and photography of the various remote but uniquely photogenic observatory sites is proving popular.



New Web Pages

Two major multimedia projects – creation of a CDL explorer and updating the Basics of Radio Astronomy – were delayed by the loss of a science writer. An ngVLA page was successfully launched using graphics adapted from infographic posters developed for the media reception at the winter AAS meeting. <https://public.nrao.edu/ngvla/>

New Technology, New Capabilities

The next generation Very Large Array

Introducing the next generation Very Large Array (ngVLA) with the technology to dramatically simplify our understanding of the universe and place even more discovery in our reach. Here's how...

IN SYNC WITH SYNERGY

The ngVLA's unique capabilities can supplement and advance the work of other world-class observatories:



A PERFECT HOME IN THE U.S.

Site location: New Mexico, Arizona, Texas, and Mexico

- 2,300 m elevation
- Exceptional location to study cosmic radio light
- 100 km distance between furthest antennas, creating a virtual telescope nearly 2x the width of New Mexico



IMPRESSIVE STRUCTURE

10 m antenna dish diameter—a site that balances sensitivity and cost effectively

- Equal to nearly 10 persons standing together to finger tip



A WHOLE GREATER THAN THE SUM OF ITS PARTS

24 individual antennas that combine to form a single telescope

- Fully coherent
- Incredibly powerful



EXCEPTIONAL POWER

Ability to detect the faintest cosmic light

• 10,000X



• Lightyears 10,000X longer than those visible to the naked eye

• Possess the ability to study all kinds of cosmic events and objects throughout the universe

Ability to capture fine details—even at great distances

- Able to see details about as small as the distance from Mercury to Earth (it's 40 light-years away)
- Gives telescope incredible viewing power
- Imaging 100 times better than the Hubble Space Telescope



CONNECTING THROUGH THE CONSTELLATION—A SPACEDUPERATOR

- Can process 400 channels at 1 millisecond
- Allows on the spot to receive the signal from each individual antenna and combine them into one



Profound Questions, New Answers

The next generation Very Large Array

The most provocative Very Large Array (ngVLA) will revolutionize our research—both through its unique individual capabilities and through synergistically building off the power of current and future next-generation arrays, leading our understanding of the universe to new insights.

The ngVLA has the potential to answer questions in key areas, including...

SAVING MORE ENERGY AND RESOURCES

• Studying more phenomena more thoroughly

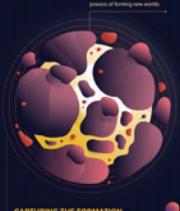
STUDYING THESE PHENOMENA MORE THOROUGHLY

• Probing black holes, billions of meters, in motion in our galaxy

CAPTURING THE FORMATION OF ROCKY PLANETS

With transforms we see know about planet formation, the ngVLA will be able to measure

- From solar origins to meander
- Into a science of place and time



PROBING THE EVENTS THAT MAKE THE UNIVERSE SHAKE

The best way of understanding merging neutron stars—the densest matter in the universe—is to understand the "what" and "why" of these events.

- Connecting the "what" with the "how" and "what's next"
- What's next? The ngVLA will be able to measure the cosmic when massive objects collide directly by reading their telltale glow
- What's next? Tracking the evolution of these surroundings



DEEPER INSIGHTS TO FIND ANSWERS TO QUESTIONS INTIMATE TO STAR FORMATION AND POTENTIALLY IMPORTANT FOR US

• Studying in detail the chemistry of dense clouds surrounding baby stars

A BETTER UNDERSTANDING OF THE PECULIAR HABITABILITY OF OTHER WORLDS

• The ngVLA will be able to reveal the amount of star-forming material a given star has to work with

• The amount of star-forming gas represented in galaxies as they age



DISCOVERING THE CONDITIONS THAT GIVE RISE TO LIFE IN OTHER STAR SYSTEMS

The interaction of biology, chemistry, and astronomy

With the ngVLA as part of our astronomical observatory ecosystem, we'll learn about these cosmic mysteries—and so much more. What will you find?



IDENTIFYING HOW MUCH STAR-FORMING FUEL EXISTS THROUGHOUT THE HISTORY OF GALAXIES

This will give us a more complete picture of galaxy evolution, when combined with

- How fast galaxies form gas into stars
- How many galaxies have already become stars



Figure: ngVLA infographics posters.



Figure: Frame capture from WebsEdge video and ngVLA web page.

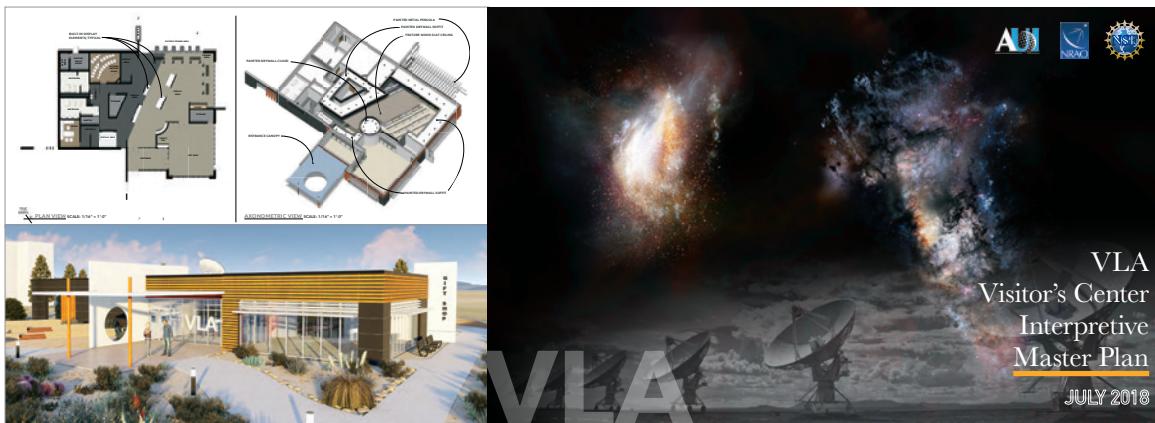
ngVLA

The artist and designer time allocated for the cancelled projects was shifted to the creation of new ngVLA animations. An initial flyover animation was created that is under revision with the new dish design. EPO also worked with WebsEdge to create a video for the spring meeting of the American Physical Society (APS): <http://ngvla.nrao.edu/video/aps-tv>. After an audit of the materials developed to date, a style guide specific to ngVLA products has been created. This guide will inform the creation of future ngVLA products.

Visitor Center Operations

NRAO operates a small Visitor Center on the site of the Karl G. Jansky Very Large Array, west of Magdalena, NM. The site has indoor and outdoor public exhibits, a small auditorium, popular gift shop, and monthly tour program. Updates were made to a subset of brochures distributed at the Visitor Center to ensure up-to-date content and a uniform presentation.

Saturday tours were expanded to include first and third Saturdays of each month, and the Open Houses each April and October continue to be popular. The VLA served 25,236 people, exceeding FY2017 attendance by almost 3000. More than 4000 adult and student groups received special tours this year. Part time tour guides were added to the staff in 2018 and summer tours are supplemented with Research Experience for Undergraduate students on weekends.



A new VLA Visitor Center interpretive plan and architect's concept design for a new visitor experience were established and the groundwork for a major fundraising campaign was laid to implement the upgrades. Until funds can be secured, EPO will continue to make incremental upgrades to improve the existing experience.

MANAGEMENT & ADMINISTRATION



Senior Management Organization

The NRAO organization in 2018 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 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 .



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 interim Assistant Director **Michael Shannon** provides program and project management support and systems engineering services to NRAO project leaders and Pls. 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 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.

MANAGEMENT & ADMINISTRATION



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.

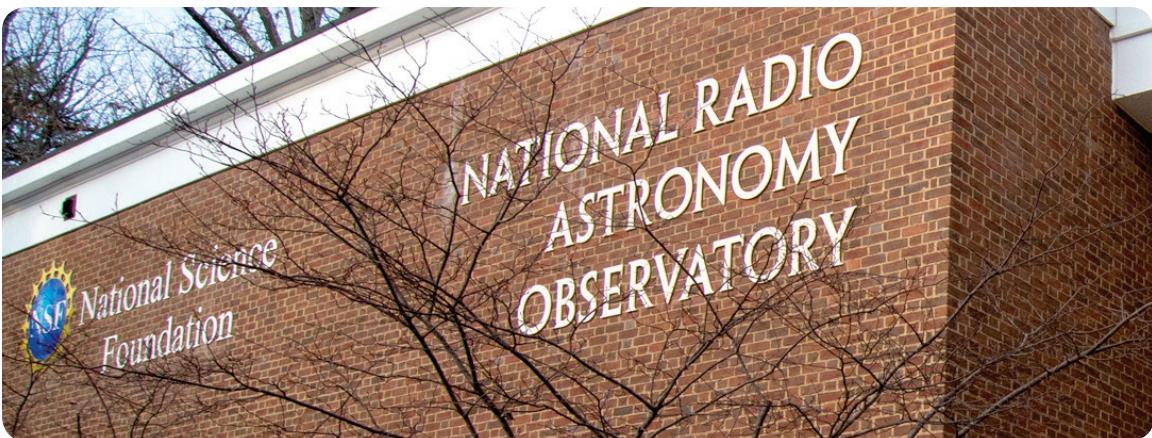


Faye Giles, Assistant Director for Human Resources, directs Observatory-wide human resources policies and programs; including compensation, benefits, recruiting, employment, employee relations, diversity, organizational development, performance management and training.

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.

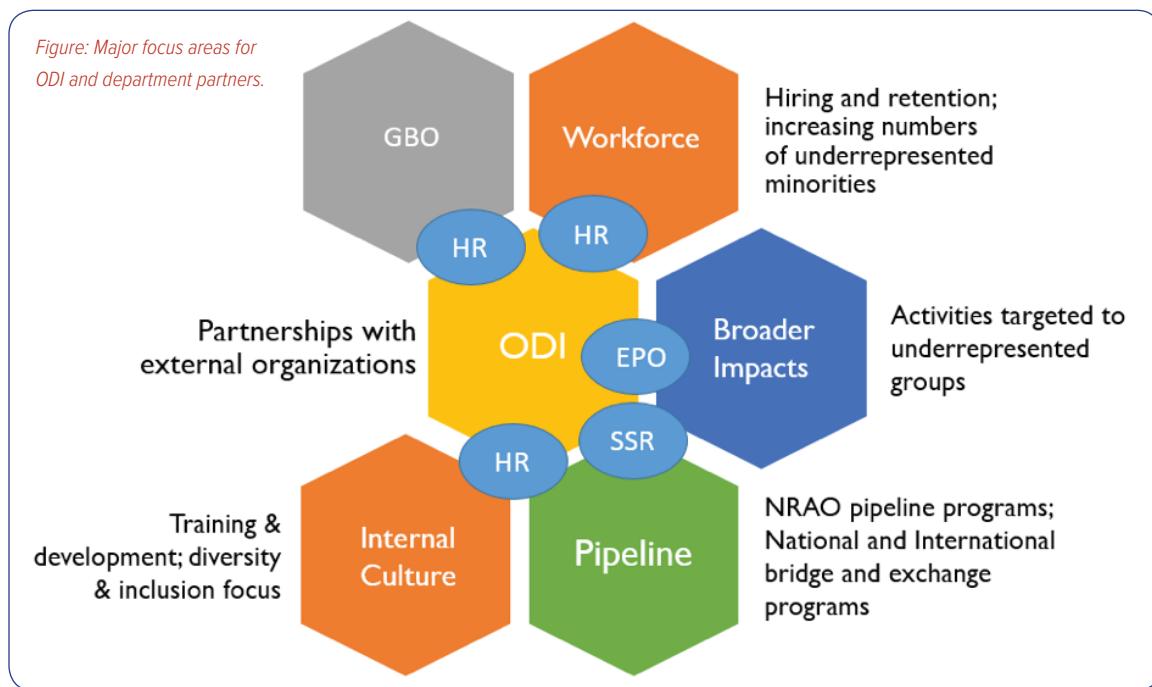


The Office of Diversity & Inclusion (ODI) led by Program Manager **Lyndele von Schill**, is attached to the Director's Office. The Science Communications Office (SciCOM) led by **Mark Adams** is also attached to the Director's Office and is responsible for communicating NRAO science, accomplishments, 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 FY2015 to support NRAO in achieving its core mission goals by increasing staff diversity and inclusion across the Observatory, developing and implementing programs to improve the recruitment, retention and success of under-represented and under-served students and staff members, and fostering a work environment that is inclusive of all individuals. In 2018, the ODI Director worked closely with Human Resources (HR), Education & Public Outreach (EPO), and Science Support & Research (SSR) to develop and maintain programs that affect the NRAO work force, broader impact efforts, new and ongoing pipeline initiatives, and the internal NRAO culture and climate.



NRAO continues to focus on education and training related to the importance of a diverse workforce and inclusive environment. In 2018, ODI and HR continued to offer online training that included 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 on a volunteer basis.

While most courses are voluntary, managers and supervisors were encouraged to include diversity training in each employee's Performance Evaluation Process goals, resulting in more employee engagement. Before serving on search committees, members are required to complete training on implicit bias.

Coaching and Mentoring	Uncovering Implicit Bias
Conflict Resolution	Team Building Across Cultures
The Power of Respectful Language	Transitioning to Respect
Diversity in Action	Unlawful Harassment Prevention
Practicing Inclusion: Diversity Awareness	The Bystander Effect

MANAGEMENT & ADMINISTRATION

In 2018, the Diversity Advocates (DA) and Employee Diversity Groups (EDGs) program was evaluated and re-designed, resulting in a new set of DAs and EDG members in Virginia, New Mexico, and Chile for FY2019 and 2020. The DA and EDG members will complete a 12-month training program to increase awareness of diversity and inclusion-related issues, and to provide skills for addressing issues that arise in the workplace.

Local and National Programs

NRAO's 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.

NRAO participation in the NSF-funded Louis Stokes Alliance for Minority Participation (LSAMP) Virginia-North Carolina Alliance resulted in internships for two students at the CDL. Because the LSAMP program has similar goals to the NAC program (though not intended to be year-long), NRAO incorporates the LSAMP students into the NAC program, resulting in a total of 14 NAC-sponsored students in FY2018–2019.

The 2018 National Astronomy Consortium (NAC) placed 12 undergraduate students, from community colleges and universities across the country, with trained mentors at NRAO and three additional partner sites: Space Telescope Science Institute, University of Wisconsin-Madison, and Princeton University. Students were recruited from partner Minority-Serving Institutions (MSIs) and Historically Black Colleges and Universities (HBCUs), and through targeted outreach to Hispanic-Serving Institutions





Above left: NAC 2018 students with Dr. Gates. **Above right:** NAC 2018 students with Dr. Razzaghi.

(HSIs). The NAC students interacted with REU students for shared activities (colloquia, site visits, lectures, etc.), and worked on original research projects with their mentors. The NAC program includes student participation in professional development workshops, weekly meetings with opportunities to present their research, and participation in diversity-related talks by invited speakers. NAC students and mentors were also offered the opportunity to complete online diversity training.

In FY2018, invited speakers included several NAC alumni, now in graduate school. A cross-site visit by the Space Telescope Science Institute NAC students to NRAO enabled the participants to interact with each other, and with the University of the Virgin Islands NINE Hub representatives.

Professional-level speakers, representing a diverse range of careers and career paths, included Dr. Andrea Razzaghi (NASA), Dr. Hakeem Oluseyi, Dr. Sylvester “Jim” Gates (Brown University), and Dr. Charles Liu (American Museum of Natural History).

Rising NAC undergraduate seniors were once again invited for a recruiting visit to Princeton and Rutgers Universities.

The NAC VI workshop was scheduled 14-16 September 2018 in Washington, DC, but was postponed due to Hurricane Florence. The workshop was rescheduled to take place at the 2019 American Astronomical Society winter meeting in Seattle.

This past year marked the sixth year of NAC programming, resulting in 55 active NAC alums. Nearly half of these alums (25) are now in graduate school, while many of the remaining alums are still undergraduates. While there have been a number of successful efforts designed to build and maintain peer-mentoring relationships across cohorts, NRAO collaborated in 2018 with three NAC graduate students (Moiya McTier, Sinclair Manning, and Chima McGruder) to develop a more formalized plan for NAC alum engagement and support: the Council of Representatives for Engagement. These representatives will design and implement plans for strengthening the peer-network and providing a mechanism for NAC students to report barriers to their success.

The Radio Astronomy and Physics – New Mexico (RAP-NM) program is a summer camp experience for rising ninth-graders from the Socorro, NM area. This program is developed and implemented by the EPO department, and is partially supported by the ODI office through the support of undergraduate student mentors from the NAC Program. This collaboration provides mentoring and education experience for NAC students, while providing role models for the RAP-NM participants.



Princeton and Rutgers Visit, 7 – 10 August 2018: [L-R Back] Alex Fortenberry, Allison Erena, Antoine Washington, Kaimi Kahihikola. [L-R Front] Cecilia Molina, Angelina Gallego, and Lina Florez.

MANAGEMENT & ADMINISTRATION

The Socorro Electronics Division Laboratory Experience for Undergraduates program was intended to provide educational experiences for women, Native American and Hispanic students, from schools beyond New Mexico Tech. Despite several years of intensive recruiting efforts, including recruitment presence at the annual Society for Advancement of Chicanos and Native Americans in Science conferences, appropriate candidates were not successfully identified. With the retirement of the Electronics Division Lead, this program has ended, and will be replaced by increased research opportunities in the NAC program.

International Partnerships

The NRAO International Exchange Program (NINE) program was established as an initiative to increase the numbers of underrepresented community members in astronomy, nationally and internationally. The NINE program addresses this need by improving opportunities for members of underrepresented communities to participate in research in radio astronomy and related fields.

The NINE program develops Hub partnerships with Historically Black Colleges and Universities and Hispanic Serving Institutions in the U.S., and with universities or observatories in countries with a radio astronomy presence. Professionals and students from the partner organizations visit the NRAO and complete a short, intense training program in the use of Very Large Array Sky Survey (VLASS) data and Raspberry Pi units to learn about astronomical image analysis. The participants also learn project management principles and develop a fully described plan for establishing NINE Hubs at their home institution where they can transfer their learned skills to students, faculty, and the community.

In 2018, the Hampton University Hub continued to offer physics and astronomy education and hands-on experience – observing with an optical telescope and Radio Jove – to middle- and high-school students from the Hampton City School system, through the H2O program. The students presented their research at the American Association for the Advancement of Science Emerging Researchers Network (ERN), the Black Engineer of the Year Award STEM, and National Society of Black Physicists meetings, with support from NRAO.



Above left: Hampton H2O students traveling to ERN meeting in D.C. Above right: H2O students at ERN meeting.

In 2018, the NINE Program lost its Program Manager prior to the summer training program and requested a secondment from the NINE South African Radio Astronomy Observatory (SARAO) Hub Lead (Anja Fourie), who provided the Project Management component of the NINE program. Brian Kent, NRAO Scientist, developed and delivered an innovative training program that focused on the use of Raspberry Pi (RPi) units as a teaching and research tool.

Two new NINE Hubs were created in FY2018: The University of the West Indies (Trinidad) and The University of the Virgin Islands (an HBCU).

Led by Antonio Hales, the ODI – Chile program provided research experiences to two students from December 2017 – March 2018. Students accepted in the ODI-Chile summer research program come from universities without research opportunities, which limit opportunities for graduate school. The research was conducted in the offices of the Joint ALMA Observatory, under supervision of NRAO/ALMA staff.



Science Communications

The Science Communications Office (SciCom) organized the NRAO presence at the winter AAS meeting, held 8 – 12 January 2018 in National Harbor, Maryland, including an NRAO Town Hall, and Observatory participation in the meeting's multi-day exhibition. NRAO also actively participated in the undergraduate orientation session, and the local public outreach events organized by the AAS and sponsored by AUI. SciCom assisted with a Special Session titled *The Very Large Array Today and Tomorrow: First Molecules to Life on Exoplanets*. SciCom organized the NRAO presence at the summer AAS meeting, 3 – 7 June 2018 in Denver, Colorado, including participation in the meeting's multi-day exhibition and local public outreach events.

SciCom organized and chaired a scientific symposium at the 15 – 19 February 2018 American Association for the Advancement of Science (AAAS) Annual Meeting in Austin, Texas, titled *The Chemistry and Physics of Nascent Planetary Systems*. This well-attended symposium described 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 presenters were Karin Öberg (Harvard), Meredith Hughes (Wesleyan), and David Wilner (Harvard–Smithsonian Center for Astrophysics). In April 2018, SciCom and the ngVLA Project Office submitted a science symposium proposal for the February 2019 AAAS Annual Meeting titled *Multi-messenger Time-domain Astronomy in the ngVLA Era*. This proposal was peer-reviewed and officially accepted by the AAAS in July 2018. The presenters for this symposium will be Alessandra Corsi (Texas Tech), Eric Murphy (NRAO), and Kunal Mooley (NRAO/Caltech).

SciCom continued to edit and publish the monthly NRAO electronic newsletter, eNews, each issue of which was distributed to 9,000+ scientists around the world. SciCom 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 SciCom to publicize key events and accomplishments. SciCom also edited and published the semi-annual CASA News. The NRAO Research Facilities brochure was updated and published in December 2018.

SciCom 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, CO, an annual gathering of 10,000+ scientists, engineers, software developers, CIOs, and IT administrators from universities, industry, and government agencies.

SciCom collaborated with the Director's Office and staff across the Observatory to prepare NRAO reports, briefings, and support materials for NSF and for the 2018 Users Committee (UC), which met in Socorro 15 – 16 May 2018. The ALMA North American Science Advisory Committee (ANASAC), a standing sub-committee of the Users Committee, met on 14 May.

SciCom 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.

MANAGEMENT & ADMINISTRATION

Spectrum Management

The ability to observe without harmful radio frequency interference (RFI) is fundamental to NRAO science. NRAO undertakes a variety of activities directed at maintaining a clean electromagnetic environment at and around its facilities, including testing of installed equipment, formulating rules regarding operation of installed and visiting equipment, and mitigating or remediating externally interfering sources.

Spectrum management is a regulatory process whereby spectrum is apportioned into bands that are allocated to applications, subject to rules intended to shield them from mutual interference. Spectrum allocations and rules are formulated at national and international levels. NRAO participates actively in national and international spectrum management to protect and improve observing conditions for all astronomers, and has done so since its inception.

Site Spectrum Management

The NM Operations Interference Protection Office coordinated spectrum usage in 2018 for the VLA site by the following means.

- Responding to requests for Special Temporary Authority submitted through the NSF from the National Telecommunications and Information Administration (NTIA). The requests are analyzed for their potential impact to radio astronomy observing by performing propagation simulations and mapping terrain profiles, calculating the expected power flux density at the array, and comparing the results to internationally recognized detrimental interference thresholds. Negotiations with the active spectrum user are conducted to limit, reduce, or eliminate the potential interference.
- Informing external spectrum users at the U.S. Space Command (GPS-L3), the Tethered Aerostat Radar System sites, and other military and commercial shared-spectrum users of NRAO and National Astronomy and Ionosphere Center planned spectrum usage each month. Jointly used spectrum may then be scheduled on a first-come-first-served basis, by priority, or by prior cooperative agreements.
- Monitoring VLA site spectrum conditions using array observations and external monitoring equipment, and reviewing the resulting spectral plots and observer reports to detect new, unknown RF emissions. Detections in spectrum allocated to radio astronomy trigger source identification and technical discussions with the responsible spectrum user. Particularly detrimental emissions in non-radio astronomy spectrum allocations lead to good-will discussions with the responsible spectrum user with the goal of interference reduction or elimination via technical means.
- Performing RF emissions tests on incoming commercial or NRAO-designed equipment and reviewing the results to determine interference potential. Equipment found to exceed the detrimental limits are either rejected, modified, shielded, or submitted for redesign.

National and International Spectrum Management

Coordination with the prospective satellite broadband wireless internet providers OneWeb and SpaceX was handed off to the NSF Electromagnetic Spectrum Management Unit at a March 2018 meeting at NSF headquarters. Iridium, the satellite telephone operator, has launched all but ten of its second-generation satellites, de-orbited many old ones and shifted to a more normal operating mode whereby the new satellites are using the same 8 MHz bandwidth as the older ones. Interaction with Iridium occurs indirectly through the activities of International Telecommunication Union-Radio communications sector (ITU-R) Working Party (WP) 4C as Iridium seeks to be allowed to provide safety of life services to maritime. Measurement of unwanted emissions from Iridium is ongoing at the Leeheim satellite monitoring station in Germany.

The Federal Communications Commission (FCC) is advocating for an early rollout of 5G wireless services even before Agenda Item 1.13 is settled at World Radio Conference (WRC) 19. The FCC recently released an order preempting local control of existing and new 5G infrastructure, and preempting the imposition of local fees beyond those associated with the most basic cost recovery for maintaining utility pole infrastructure. Many states, including West Virginia, already had their own version of this law. In West Virginia, the bill was co-sponsored by the state representative from Pocahontas County, where the Green Bank Observatory is located, and efforts were later made to try to ensure that enforcement of the state law would not compromise the National Radio Quiet Zone or the West Virginia Radio Astronomy Zoning Act.

NRAO engaged with T-Mobile regarding prospective 5G access to spectrum at 31.8–33.4 GHz. T-Mobile calculated separation distances based on ad hoc out-of-band emissions masks that were substantially more restrictive than those allowed by the FCC and enforced upon equipment manufacturers. The separation distances derived with T-Mobile masks would allow FCC-compliant devices to generate harmful interference without recourse to complaint by radio astronomy. NRAO pointed out its concerns with T-Mobile's position by noting that T-Mobile and the U.S. have insisted that the FCC emissions mask be used in ITU-R compatibility studies, in part because telecom operators insist that they have no control over the devices used on their networks.

The FCC was petitioned for early relief and special consideration by a prospective operator of High Altitude Platform Systems that are being considered at ITU-R under WRC-19 Agenda Item 1.14. These communications hubs circulating in the stratosphere at 20 km and visible for 500+ km would present profound complications to radio astronomy observing in the K and Ka bands. NRAO filed twice in opposition with the FCC, while awaiting the possible completion of much-delayed compatibility studies at the ITU-R in November 2018 under a set of guidelines formulated by the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF).

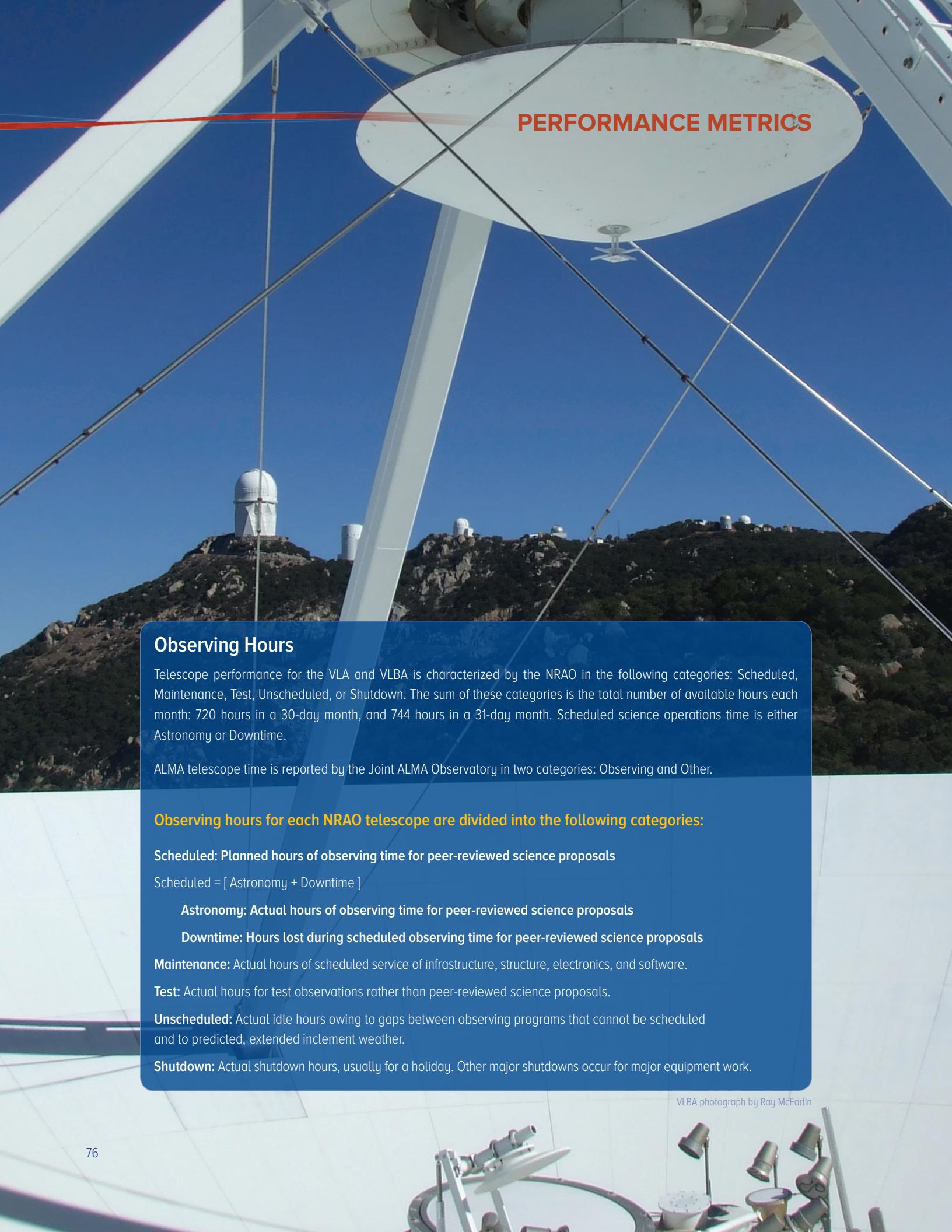
NRAO participates in monthly meetings of U.S. radio astronomy working group WP 7D, led by NSF, and whenever possible in the annual open meeting at the National Academy of Sciences Committee on Radio Frequencies (CORF).

As Chair of IUCAF, the NRAO Spectrum Manager is now responsible for organizing its budget and arranging its activities, reporting to the International Astronomical Union (IAU), Union Radio Scientifique Internationale (URSI), Committee on Space Research (COSPAR), and International Council for Science (ICSU), and formulating an agreed international position on agenda items of concern at the WRC-19. With the recent reorganization of the European Science Foundation's Committee on Radio Astronomy Frequencies (CRAF), IUCAF has become even more the main source of direct influence on behalf of radio astronomy at ITU-R.

The radio astronomy working group WP 7D recently completed work on an ITU-R Report describing the international registration of distributed telescope systems like SKA or ngVLA and another report describing compatibility studies between radio astronomy and vehicular radar. Revision of an existing omnibus report describing more than a dozen radio quiet zones worldwide is also underway. International recognition of radio quiet zones must be judged the highest priority for radio astronomy now that the skies are projected to become increasingly bright.

As the WRC-19 study cycle drew nearer to its conclusion at the 2nd Conference Preparatory Meeting in Geneva in February 2019, the focus of international activity in 2018 was on the finalization of the draft WRC-19 input text and many outstanding compatibility studies.

As part of its newly adopted Strategic Plan 2020–2030, the IAU has charged itself with the organization of an international meeting on Dark and Quiet Sky Protection involving IAU and international organizations International Commission on Illumination (CIE), United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS), United Nations Educational, Scientific and Cultural Organization (UNESCO), ITU-R, and others. NRAO will be heavily involved in this effort through its leadership of IAU's C.B4, its position on the steering group of C.B7, and on the IAU EC Working Group on Dark and Quiet Skies, and its membership in the AAS Committee on Light Pollution, Radio Interference, and Site Protection.



PERFORMANCE METRICS

Observing Hours

Telescope performance for the VLA and VLBA 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

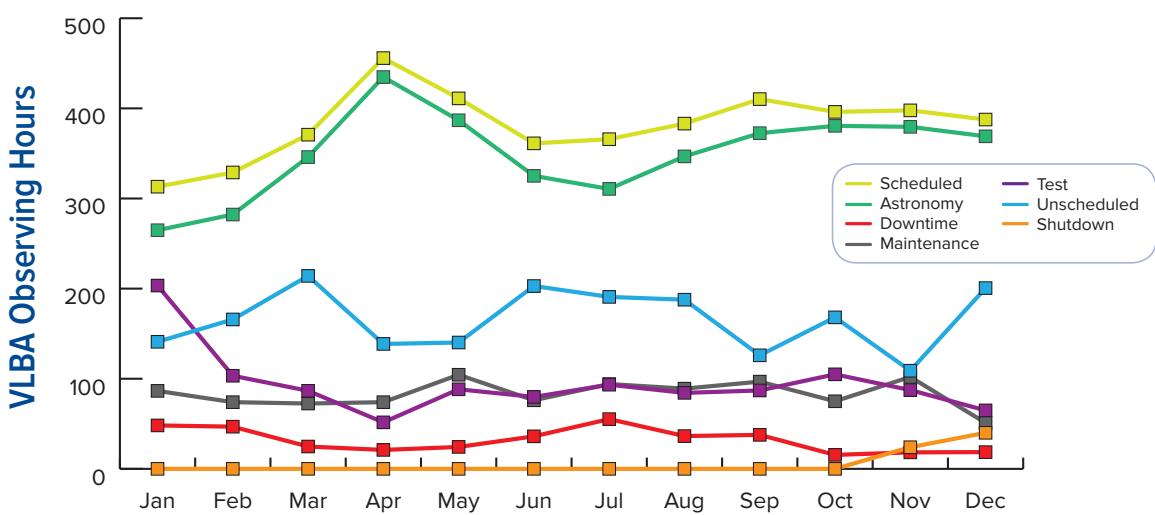
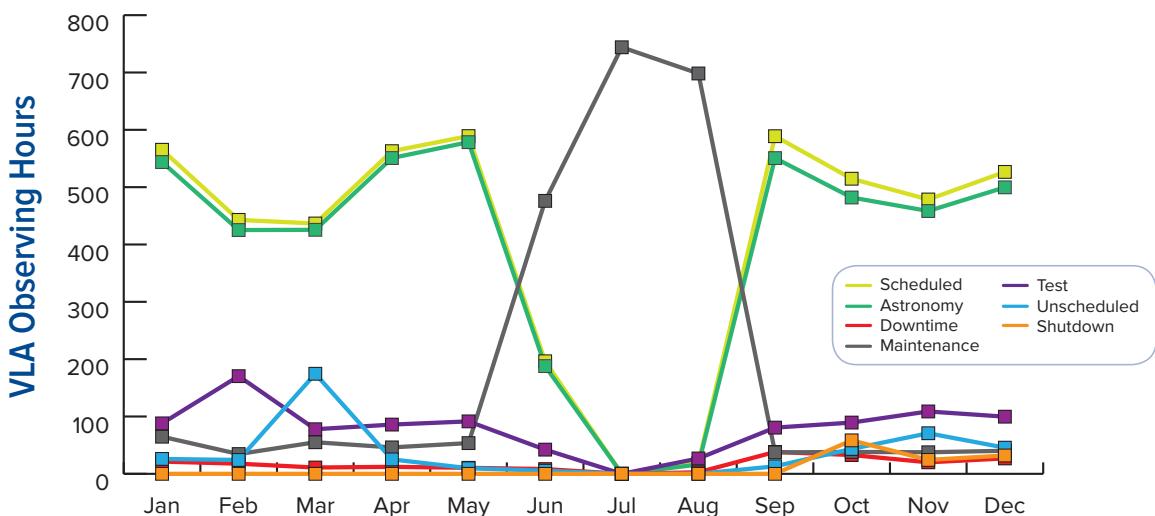
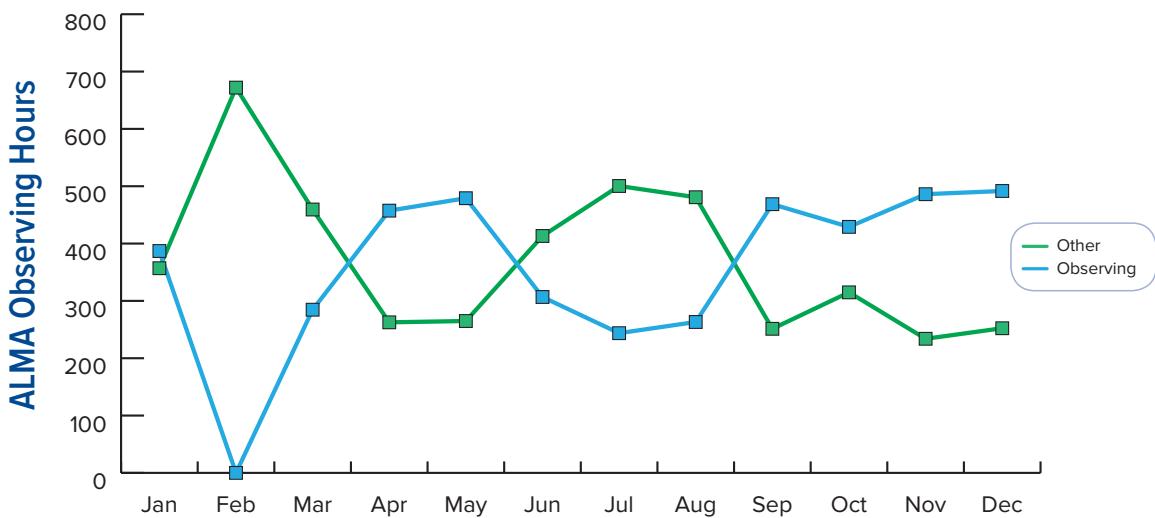
Maintenance: Actual hours of scheduled service of infrastructure, structure, electronics, and software.

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.

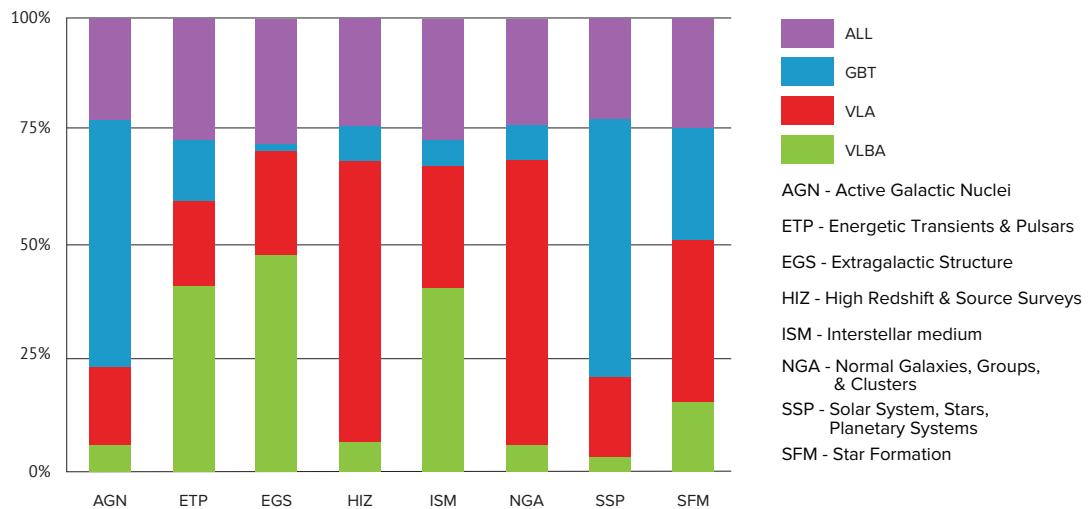
Shutdown: Actual shutdown hours, usually for a holiday. Other major shutdowns occur for major equipment work.

VLBA photograph by Ray McFarlin



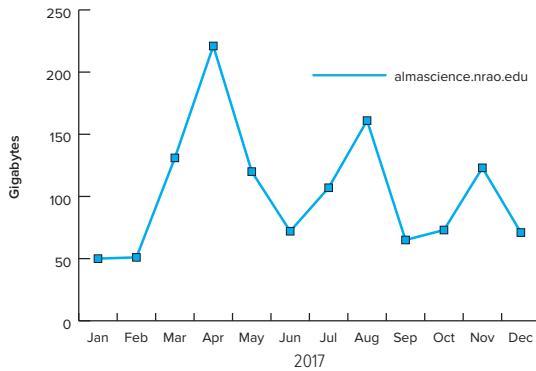
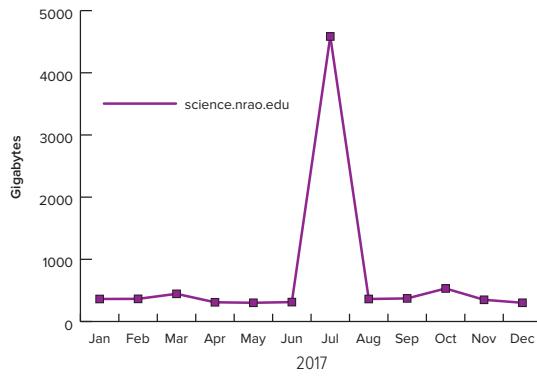
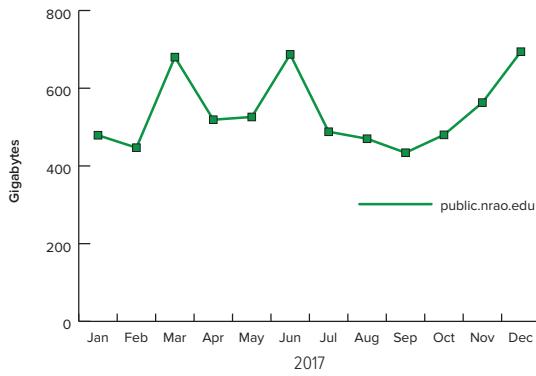
2018 PERFORMANCE METRICS

Observing Hours by Science Category



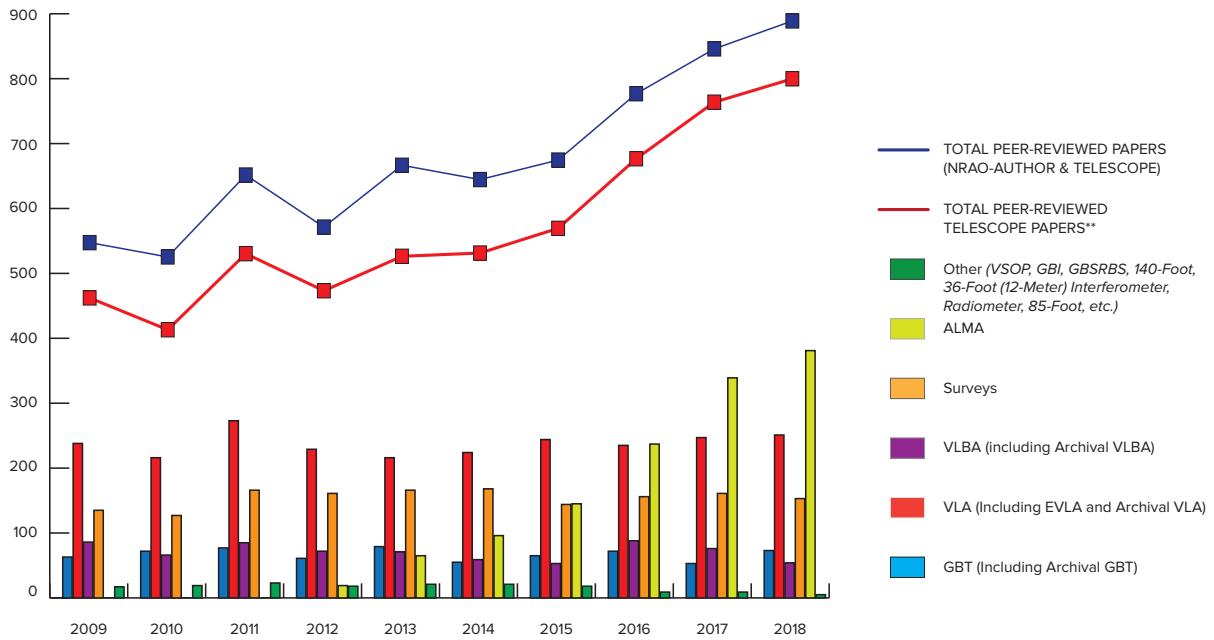
Observing hours for each of the GBT, VLA, and VLBA are tracked in the eight science categories defined in the NRAO proposal evaluation and time allocation process.

NRAO Website Volume



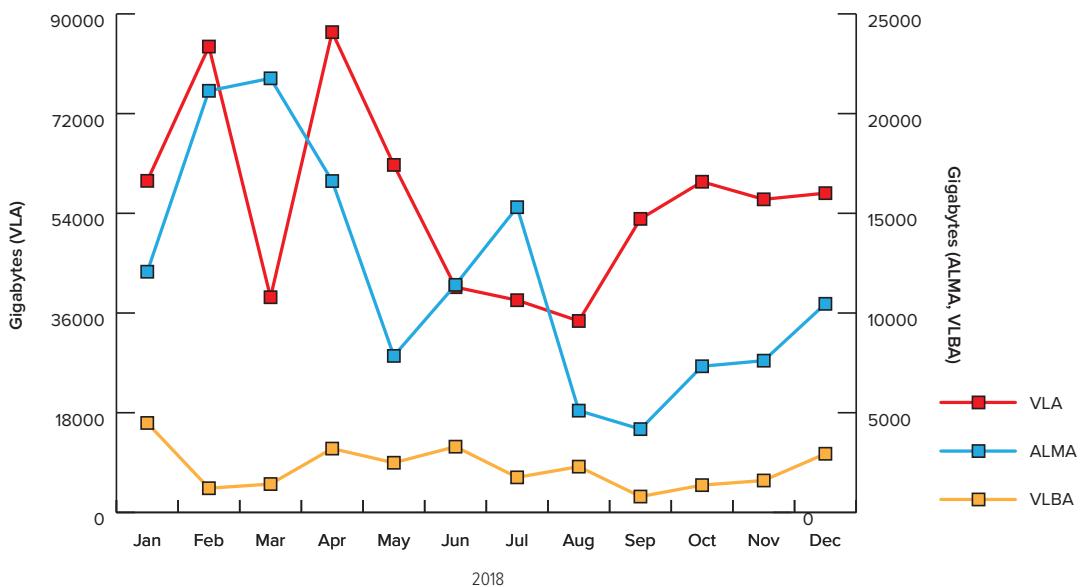
The public.nrao.edu website volume reflects activity for press releases and other online public information. The science.nrao.edu website volume reflects activity by scientists interested in submitting observing proposals or seeking other professional astronomical information about GBT, VLA, and VLBA.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

2018 NRAO REFEREED PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX A: PUBLICATIONS

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APPENDIX B: EVENTS & MILESTONES

3 January 2018

NRAO Semester 2018B Call for Proposals opens

8-12 January

231st AAS meeting
Washington, D.C.
NRAO Town Hall
NRAO Exhibit
Special Session: *The Very Large Array Today & Tomorrow: First Molecules to Life on Exoplanets*
Summer Student Presentations
Undergraduate Orientation
Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

16-18 January

Magnetic Fields or Turbulence?
National Tsing Hua University
Hsinchu, Taiwan

1 February

NRAO Semester 2018B Call for Proposals deadline

1-2 March

AUI Board of Trustees meeting
Pasadena, California

17 February

American Association for the Advancement of Science Annual Meeting
The Chemistry and Physics of Nascent Planetary Systems

21 March

ALMA Cycle 6 Call for Proposals published
Joint ALMA Observatory, Chile

19-20 March

2018 NRAO Postdoctoral Symposium
Socorro, New Mexico

27-28 March

NRAO / LBO Community Day
California Institute of Technology
Pasadena, California

19 April

ALMA Cycle 6 Call for Proposals deadline
Joint ALMA Observatory, Chile

14 May

ALMA North American Science Advisory Committee (ANASAC) meeting
Socorro, New Mexico

15-16 May

NRAO Users Committee
Socorro, New Mexico

16-23 May

Synthesis Imaging Workshop
Socorro, New Mexico

3-7 June

232nd AAS meeting
Denver, Colorado
NRAO Exhibit
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

4-5 June

NRAO / LBO Community Day
Dunlap Institute for Astronomy and Astrophysics
University of Toronto
Toronto, Canada

14-15 June

AUI Board of Trustees meeting
Charlottesville, Virginia

26-29 June

Astrophysical Frontiers in the Next Decade and Beyond
Portland, Oregon

29 June

NRAO Semester 2019A Call for Proposals opens

1 August

NRAO Semester 2019A Call for Proposals deadline

20-31 August

International Astronomical Union XXXth General Assembly
Vienna, Austria

24 August

IAU Division B: *New Results in Radio Astronomy*
Vienna, Austria

27 August

IAU Division B: *The History of Large Single Dish Projects*
Vienna, Austria

13-14 September

NRAO / LBO Community Day
Instituto Nacional de Astrofísica, Óptica y Electrónica
Puebla, Mexico

30 September

ALMA Cycle 5 science observations end
Joint ALMA Observatory, Chile



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

1 October

ALMA Cycle 6 science observations start
Joint ALMA Observatory, Chile

24-26 October

AUI Board of Trustees meeting
Washington, D.C.

30 October

Jansky Lecture
Charlottesville, Virginia

1 November

Jansky Lecture
Green Bank, West Virginia

9 November

34th New Mexico Symposium & Jansky Lecture
Socorro, New Mexico

12-15 November

SuperComputing18 (SC18) exhibition
Dallas, Texas

10-14 December

TORUS 2018: The Many Faces of AGN Obscuration
Puerto Varas, Chile

11-12 December

NSF Program Review
Charlottesville, Virginia

19 December

ALMA Cycle 7 Pre-Announcement
Joint ALMA Observatory, Chile

APPENDIX C: ADVISORY COMMITTEES

ALMA North American Science Advisory Committee (ANASAC)

Subcommittee of Users Committee

Jin Koda, (ANASAC), Stony Brook University, 2021

Giles Novak (ANASAC/ASAC), Northwestern University, 2020

Kate Su (ANASAC), University of Arizona, 2021

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

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

Stephen White (ANASAC/ASAC), Kirtland AFB, 2020
NA ASAC Vice-Chair

Dan Marrone (ANASAC/ASAC), University of Arizona, 2018

Christine Wilson (ANASAC/ASAC), McMaster University, 2020

NRAO Users Committee

2018 Users Committee Membership

Four-Year Term - Commencing January through December

Loren D. Anderson, West Virginia University, 2018

Jin Koda, (ANASAC), Stony Brook University, 2021

Kate Su (ANASAC), University of Arizona, 2021

Edo Berger, Harvard University, 2021

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

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

Ilse Cleeves, University of Virginia, 2021

Laurent Loinard, UNAM, 2021

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

Christopher De Pree (CASA), Agnes Scott College, 2021

Dan Marrone, UC Co-Chair, University of Arizona, 2018

Stephen White (ANASAC/ASAC), Kirtland AFB, 2020
NA ASAC Vice-Chair

Steven Ellingson, Virginia Tech, 2018

Giles Novak (ANASAC/ASAC), Northwestern University, 2020

Christine Wilson (ANASAC/ASAC), McMaster University, 2020

Trish Henning, University of New Mexico, 2019

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

CASA Users Committee

The fifth CASA Users Committee face-to-face meeting was held at NRAO – Socorro on 25-26 October 2018. The 2018 CASA Users Committee members are listed below, with their regional representation indicated in parentheses.

Chris DePree (North America, Chair)

Ilse van Bemmel (Europe)

Cornelia Lang (North America)

D.J. Pisano (North America, Deputy Chair)

Michael Bietenholz (North America)

Se-Heon Oh (East Asia)

Adam Avison (Europe)

Yi-Jehng Kuan (Taiwan)

Shigehisa Takakuwa (East Asia)

AUI Visiting Committee

The AUI Visiting Committee is appointed by the AUI Board of Trustees to review the management and research programs of the Observatory. The Visiting Committee meetings are held at alternating NRAO sites. The current membership of the Committee follows. The last year of each Committee members term is given in parantheses.

Rachel Akeson (Chair), IPAC/Caltech
(2020)

Paul Gueye, Michigan State University
(2022)

James Jackson, Boston University
(2020)

Luis Rodriguez, UNAM (2020)

Brian Keating, UC San Diego (2022)

Patricia McBride, Fermi National Accelerator Laboratory (2021)

Margaret Meixner, STSci (2020)

David Reitze, LIGO Laboratory (2021)

Greg Taylor, University of New Mexico
(2022)

Belinda Wilkes, Chandra X-ray Center
(2021)

Time Allocation Committee

Semester 2018B

Kristine Spekkens

Extragalactic Structure (EGS)
Royal Military College of Canada

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 Calgary/University of Capetown

Dominik Riechers

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

Wen-fai Fong

Energetic Transient and Pulsars (EPT)
University of Arizona

Semester 2019A

Kristine Spekkens

Extragalactic Structure (EGS)
Royal Military College of Canada

Mark Whittle

Active Galactic Nuclei (AGN)
University of Virginia

Russ Taylor

Normal Galaxies, Groups and Clusters (NGA)
University of Calgary/University of Capetown

Adam Tomczak

High Redshift and Source Surveys (HIZ)
University of California

Anita Richards

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

Christina Lacey

Interstellar Medium (ISM)
Hofstra University

Lee Mundy

Star Formation (SFM)
University of Maryland

Wen-fai Fong

Energetic Transient and Pulsars (EPT)
Northwestern University

APPENDIX D: FISCAL YEAR 2018 FINANCIAL SUMMARY

(all figures are \$k USD)

Functional Work Breakdown Structure Element	GBO	VLA/ngVLA	LBO/VLBA	ALMA	GB Ops	NM Ops	HQ & CV Ops	CDL	External Grants	Total
Administrative Services	\$4,346.7	\$2,066.9	\$2,204.6	\$10,632.2	(\$131.2)	\$1,792.2	(\$1,216.5)	–	–	\$19,694.8
Development Programs	–	\$5,348.8	–	\$2,888.9	–	–	\$170.8	\$2,985.6	–	\$11,394.2
Director's Office	\$850.8	–	\$498.3	\$6,316.4	\$0.0	\$3.5	\$3,965.2	–	–	\$11,634.2
Education & Public Outreach	\$284.5	–	–	\$659.0	\$72.5	–	\$729.7	–	–	\$1,745.7
Science Operations	\$495.5	\$33.4	\$8.5	\$9,718.0	–	–	\$8,505.9	\$8.4	–	\$18,769.7
Telescope Operations	\$5,725.6	\$10,192.8	\$5,140.9	\$13,822.8	\$292.3	\$70.8	\$1,041.1	\$37.7	–	\$36,324.2
External Grants	–	–	–	–	–	–	–	–	\$3,960.8	\$3,960.8
Grand Total	\$11,703.1	\$17,641.9	\$7,852.3	\$44,037.3	\$233.6	\$1,866.5	\$13,996.3	\$3,031.7	\$3,960.8	\$103,523.5

Fiscal Year 2018 = 1 October 2017 – 30 September 2018



VLA and Setting Moon
Credit: Jeff Helleman (NRAO/AUI/NSF)

APPENDIX E: ACRONYMS

Acronym Definition

AAAS	American Association for the Advancement of Science
AAS	American Astronomical Society
AATF	African American Teaching Fellows
ACA	Atacama Compact Array
AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
ANASAC	ALMA North American Science Advisory Committee
AOS	Array Operations Site
ARC	ALMA Regional Center
arcsec	arcsecond
ASIAA	Academia Sinica Institute for Astronomy and Astrophysics
ASIC	Application Specific integrated Circuit
AST	NSF Division of Astronomical Sciences
AU	Astronomical Unit
AUI	Associated Universities, Incorporated
CARMA	Combined Array for Research in Millimeter Astronomy
CARTA	Cube Analysis and Rendering Tool for Astronomy
CASA	Common Astronomy Software Applications
CDL	Central Development Laboratory
CDR	Critical Design Review
CIS	Computing Information Systems
CO-I	Co-Investigator
COSMOS	Cosmic Evolution Survey
CUP	Correlator upgrade Project
DA	Diversity Advocate
DMS	Data Management & Software Department
DOMT	Digital Orthomode Transducers
DSACore	Dynamic Scheduling Algorithm
DSP	Digital Signal Processing
EDG	Employee Diversity Group
EGS	Extragalactic Structure
EPO	Education and Public Outreach
ERN	Emerging Researchers Network
ESO	European Organisation for Astronomical Research in the Southern Hemisphere
ETP	Energetic Transients and Pulsars
FCC	Federal Communications Commission
FE	Front End
FET	Field Effect Transistor
FIRST	Faint Images of the Radio Sky at Twenty centimeters
FRB	Fast Radio Bursts
FTE	Full Time Equivalent
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
GOST	General Observing Setup Tool
GRB	Gamma Ray Burst
HBCU	Historically Black Colleges and Universities
HBT	Heterojunction Bipolar Transistors
HERA	Hydrogen Epoch of Reinonization Array
HPC	High Performance Computing
HR	Human Resources
HSA	High Sensitivity Array
HST	Hubble Space Telescope
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
ISM	Interstellar Medium
IT	Information Technology
ITU-R	International Telecommunication Union – Radiocommunication
IUCAF	Inter-Union Committee on the Allocation of Frequencies

JAO	Joint ALMA Observatory
JPL	Jet Propulsion Laboratory
KASI	Korean Astronomy and Space Science Institute
KBO	Kuiper Belt Object
kHz	kiloHertz
Kpc	kiloparsec
KSG	Key Science Goals
LBA	Long Baseline Array
LBO	Long Baseline Observatory
LNA	Low Noise Amplifier
LNF	Low Noise Factory
LO	Local Oscillator
LRU	Line Replaceable Unit
LSAMP	Louis Stoke Alliance for Minority Participation
LSST	Large Synoptic Survey Telescope
LWA	Long Wavelength Array
M+C	Monitor and Control
MHz	Megahertz
MIT	Massachusetts Institute of Technology
MMIC	Monolithic Millimeter-wave Integrated Circuit
MoU	Memorandum of Understanding
MPIfR	Max Planck Institut für Radioastronomie
MPifa	Max Planck Institut für Astronomie
MREFC	Major Research Equipment and Facility Construction
MSI	Minority Serving Institution
Myr	Megayear
μJy	microJansky
NA	North American
NAASC	North American ALMA Science Center
NAC	National Astronomy Consortium
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
NESS	Network for Exploration and Space Sciences
NGA	Normal Galaxies, Groups, and Clusters
NGC	New General Catalog
ngVLA	Next Generation Very Large Array
NINE	National and International Non-Traditional Exchange
NINS	National Institutes of Natural Sciences (Japan)
NM	New Mexico
NMT	New Mexico Institute of Mining and Technology
NRAO	National Radio Astronomy Observatory
NRCC	National Research Council - Canada
NRL	Naval Research Laboratory
NRQZ	National Radio Quiet Zone
NSF	National Science Foundation
NSBP	National Society of Black Physicists
OCA	Office of Chilean Affairs
ODI	Office of Diversity and Inclusion
OMT	OrthoMode Transducer
OPT	Observation Preparation Tool
OS	Operating System
OSF	Operations Support Facility
PAF	Phased Array Feed
PAPER	Precision Array for Probing the Epoch of Reionization
pc.	parsec
PHT	Proposal Handling Tool
PI	Principal Investigator
PIO	Public Information Officer
PM	Program Management
PST	Proposal Submission Tool
QA	Quality Assurance

APPENDIX E: ACRONYMS

RAP-NM	Radio Astronomy and Physics in New Mexico
REU	Research Experiences for Undergraduates
RF	Radio Frequency
RFI	Radio-Frequency Interference
RMS	Radio-Millimeter-Submillimeter
RSRO	Resident Shared Risk Observing
RTAI	Realtime Application Interference
RTOS	Real Time Operating System
SBA	Short Baseline Array
SAC	Science Advisory Council
SADC	Serial Analog to Digital Converter
SciCOM	Science Communications Office
SCO	Santiago Central Office
SIS	Superconductor–Insulator–Superconductor
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
TKIP	Traveling-wave Kinetic Inductance Parametric
TTA	Telescope Time Allocation
UVA	University of Virginia
UVML	University of Virginia Microfabrication Laboratory
VA	Virginia
VLA	Very Large Array
VLASS	Very Large Array Sky Survey
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
WFO	Work for Others



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NRAO Headquarters & North American ALMA Science Center

National Radio Astronomy Observatory
520 Edgemont Road
Charlottesville, Virginia U.S.A 22903-2475
+1-434-296-0211

NRAO - Central Development Laboratory

National Radio Astronomy Observatory
1180 Boxwood Estate Road
Charlottesville, Virginia U.S.A 22903-4608
+1-434-296-0358

NRAO - Pete V. Domenici Science Operations Center

National Radio Astronomy Observatory
P. O. Box 0
Socorro, New Mexico U.S.A 87801-0387
+1-575-835-7000

NRAO/AUI - Chile

NRAO/AUI
Av. Nueva Costanera 4091
Suite 502
Vitacura, Santiago Chile
+56-2-2210-9600



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