# 2019 ANNUAL REPORT

NRAO

NATIONAL RADIO
ASTRONOMY OBSERVATORY

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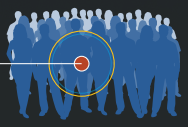

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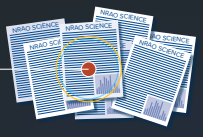


**COVER:** *Rendering of ngVLA. Credit: NRAO/AUI/NSF, S. Dagnello*

**LEFT:** *Sunrise at the Very Large Array. Credit: NRAO/AUI/NSF, J. Hellerman*

*ALMA Antenna. Credit: Pablo Carillo, ALMA*

# DIRECTOR'S REPORT

TONY BEASLEY
*NRAO Director*

In 2019, the National Radio Astronomy Observatory (NRAO) instruments, hardware, software, and people contributed to a wide range of outstanding science outcomes. The imaging of the supermassive black hole at the center of the galaxy M87 by the Event Horizon Telescope has been characterized by many as the Science Highlight of 2019, or even the science highlight of the century. This remarkable result was achieved via years of effort by many collaborators around the world, and has triggered renewed interest in black hole research. The Atacama Large Millimeter/submillimeter Array (ALMA) was vital to this research: without the ultra-sensitive phased ALMA, this compelling science would not have been possible.

The first epoch of the Very Large Array Sky Survey (VLASS) was completed in 2019, and images from the entire sky visible from central New Mexico are online and triggering new proposals and interests. Observing for the second epoch of VLASS will begin in mid-2020.

Additional funding for design and development of a next generation Very Large Array (ngVLA) project enabled completion of a Reference Design. Three antenna conceptual design studies were awarded in late 2019, and significant effort was invested in presenting the ngVLA to the Astro2020 Decadal Survey committees and process.

The NRAO made excellent progress in 2019 on a range of strategic initiatives that are improving the Observatory's scientific capabilities and the community's ease-of-use. The Science Ready Data Products (SRDP) initiative is well underway, and beginning to deliver new capabilities and insights to the ALMA and VLA research communities. It will soon fundamentally change the way radio astronomy is done. At the Central Development Lab (CDL), six new patents were awarded in 2019, and new technologies, such as superconducting Traveling Wave Kinetic Inductance Parametric Amplifiers (TKIP), are being developed for benefit of astronomers worldwide.

We strongly support the growth of a diverse and inclusive NRAO research community via our Jansky Fellowships, the Reber Fellows, student programs (undergraduate and graduate), Student Observing Support funding, the National Astronomy Consortium, and much more. With cross-Observatory support, the Office of Diversity & Inclusion is implementing programs and policies that are improving the recruitment, retention, and success of under-represented and under-served students in our field. These programs and policies are also fostering a work environment for our increasingly diverse staff that is inclusive of all individuals. While there remains much to do, the NRAO has taken these challenges head-on and is a leader in our community.

With the strong support of the National Science Foundation and Associated Universities, Inc., the NRAO staff are operating, maintaining, and continuously improving the world's most capable observatories for the astronomy community. The year 2019 was remarkable; the future looks promising. We invite you to join us.

**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.*

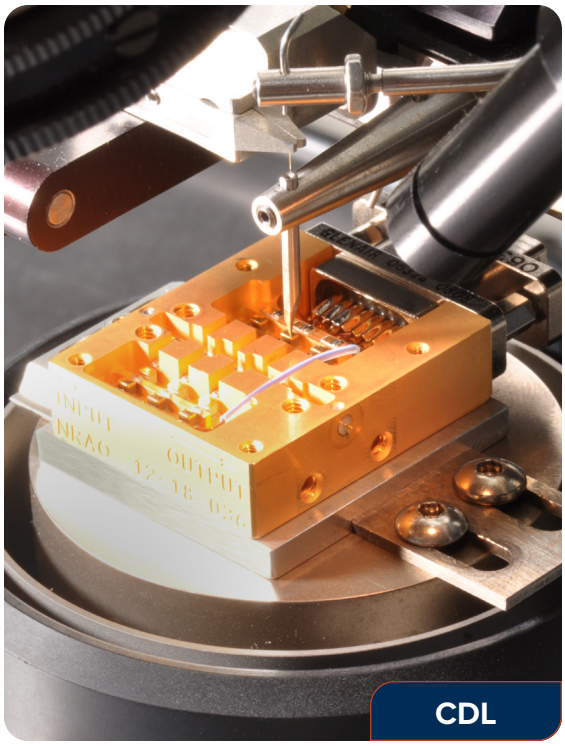

Credit: ALMA (ESO/NAOJ/NRAO); A. Marinkovic


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 2019, 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


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 2019 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.

## Imaging a Supermassive Black Hole

The direct imaging of a supermassive black hole (SMBH) event horizon at the heart of the galaxy Messier 87 by the Event Horizon Telescope (EHT) was an extraordinary scientific achievement, the culmination of years of effort by an international team, in collaboration with NRAO staff, to perform submillimeter Very Long Baseline Interferometry (VLBI) observations at the ultra-high angular resolution of 20 microarcseconds.

ALMA was vital to this research: without the ultra-sensitive phased ALMA, these observations would have been impossible. The ALMA phasing project was funded inpart through the ALMA development program.

A defining feature of the images of radio emission at the heart of galaxy M87 is an irregular but clear bright ring, whose size and shape agree closely with the expected lensed photon orbit of a 6.5 billion solar mass black hole. Soon after Einstein introduced general relativity, theorists derived the full analytic form of the photon orbit, and first simulated its lensed appearance in the 1970s. By the 2000s, it was possible to sketch the "shadow" formed in the image when synchrotron emission from an optically thin accretion flow is lensed in the black hole's gravity. During this time, observational evidence began to build for the existence of black holes at the centers of active galaxies, and in our own Milky Way. In particular, a steady progression in radio astronomy enabled VLBI observations at ever-shorter wavelengths, targeting SMBHs with the largest apparent event horizons: M87, and Sgr A* in the Galactic Center. The compact sizes of these two sources were confirmed by studies at 1.3mm, first exploiting baselines from Hawai'i to the mainland U.S., then with increased resolution on baselines to Spain and Chile.

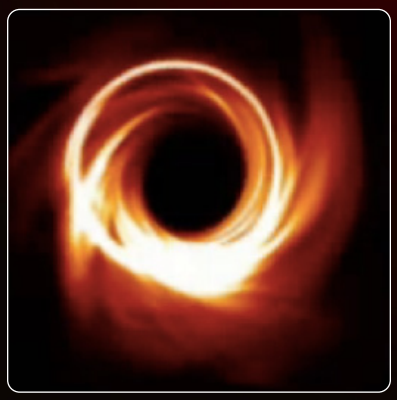
Over the past decade, the EHT extended these first measurements of size to mount the more ambitious campaign of imaging the shadow itself. In April 2017, the EHT observed M87 on four days using an array of eight radio telescopes at six geographic locations: Arizona (USA), Chile, Hawaii (USA), Mexico, the South Pole, and Spain. Years of preparation and fortuitous planet-wide good weather yielded a multi-petabyte dataset. The results presented here, from observations through images to interpretation, issue from a team of instrument, algorithm, software, modeling, and theoretical experts, following a tremendous effort by a group of scientists that span all career stages, from undergraduates to senior members of the field.

The final images emerged after a rigorous evaluation of traditional imaging algorithms and new techniques tailored to the EHT instrument – alongside many months of testing the imaging algorithms through the analysis of synthetic data sets.

The resultant image of the shadow confines the mass of M87 to within its photon orbit, providing the strongest case for the existence of SMBHs. These EHT observations are consistent with Doppler brightening of relativistically moving plasma close to the black hole lensed around the photon orbit. They strengthen the fundamental connection between active galactic nuclei and central engines powered by accreting black holes through an entirely new approach.

More than 200 scientists from 59 institutes in 20 countries and regions have devoted years to the effort, all unified by a common scientific vision. This historic result provides perhaps the ultimate verification of strong-field general relativity and signals the development of a new field of research in astronomy.

**Publications:**
***Focus on the First Event Horizon Telescope Results*** **(I-VI)**
**Astrophysical Journal Letters, 875, L1-L6 (10 April 2019)**
**Event Horizon Telescope Collaboration: Akiyama, Kazunori (NRAO, Haystack Observatory, National Astronomical Observatory of Japan, Harvard University) et al.,** ***First M87 Event Horizon Telescope Results.***



[Above] *EHT 230 GHz image of the M87 black hole event horizon.* [Left] *Model for the General Relativistic shadow caused by the severe space-time bending around the Schwarzschild radius, seen as a bright ring with a dark center, indicating the radius of the orbits of the last photons able to escape the extreme gravitational field of the 6 x $10^9$ $M_\odot$ black hole (EHT Collaboration: Akiyama, Kazunori et al., 2019).*

## Precision Black Hole Masses

The authors present high resolution (0.1 arcsec ~15pc) ALMA imaging of the CO 2-1 emission of the dusty molecular disk surrounding the supermassive black hole (SMBH) in the massive elliptical galaxy, NGC 3258 (d ~31 Mpc), probing well within the gravitational sphere of influence of the SMBH. These data reveal a quasi-Keplerian central increase in projected rotation speed rising from 280 km/sec at the disk's outer edge to >400 km/sec near the disk center. The authors construct dynamical models for the rotating disk and fit beam-smeared model CO line profiles directly to the ALMA data cube. These models incorporate flat and tilted-ring disks that provide a better fit of the mildly warped structure in NGC 3258, demonstrating that the exceptional angular resolution of the ALMA data makes it possible to infer the host galaxy's mass profile within r = 150 pc solely from the ALMA CO kinematics, without relying on optical or near-infrared imaging data to determine the stellar mass profile. The model therefore circumvents any uncertainty in the BH mass that would result from the substantial dust extinction in the galaxy's central region. The best model fit yields $M_{BH}$ = 2.249 x $10^9$ $M_\odot$, with a statistical model-fitting uncertainty of just 0.18%, and systematic uncertainties of 0.62% from various aspects of the model construction and 12% from uncertainty in the distance to NGC 3258. This observation demonstrates the full potential of ALMA for carrying out highly precise measurements of black holes masses in early-type galaxies containing circumnuclear gas disks.

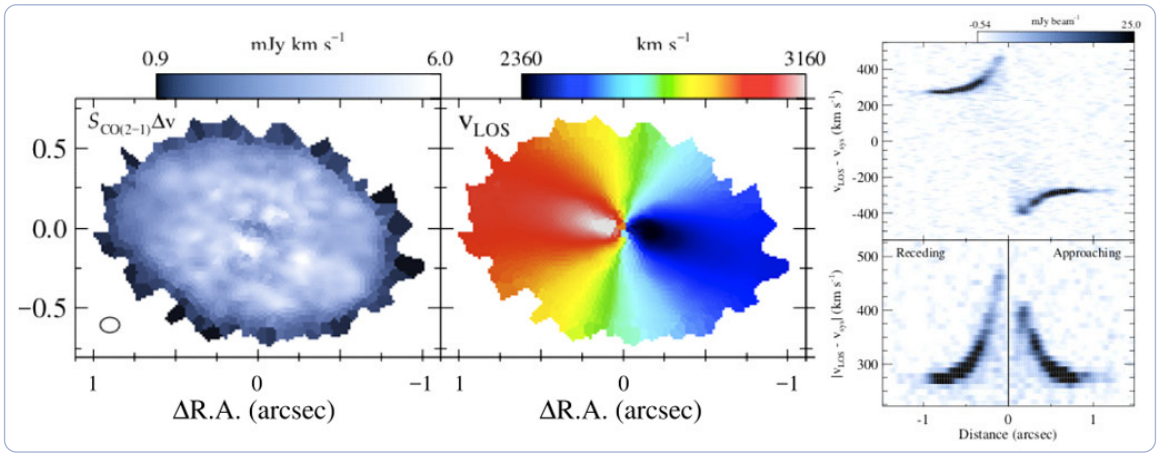
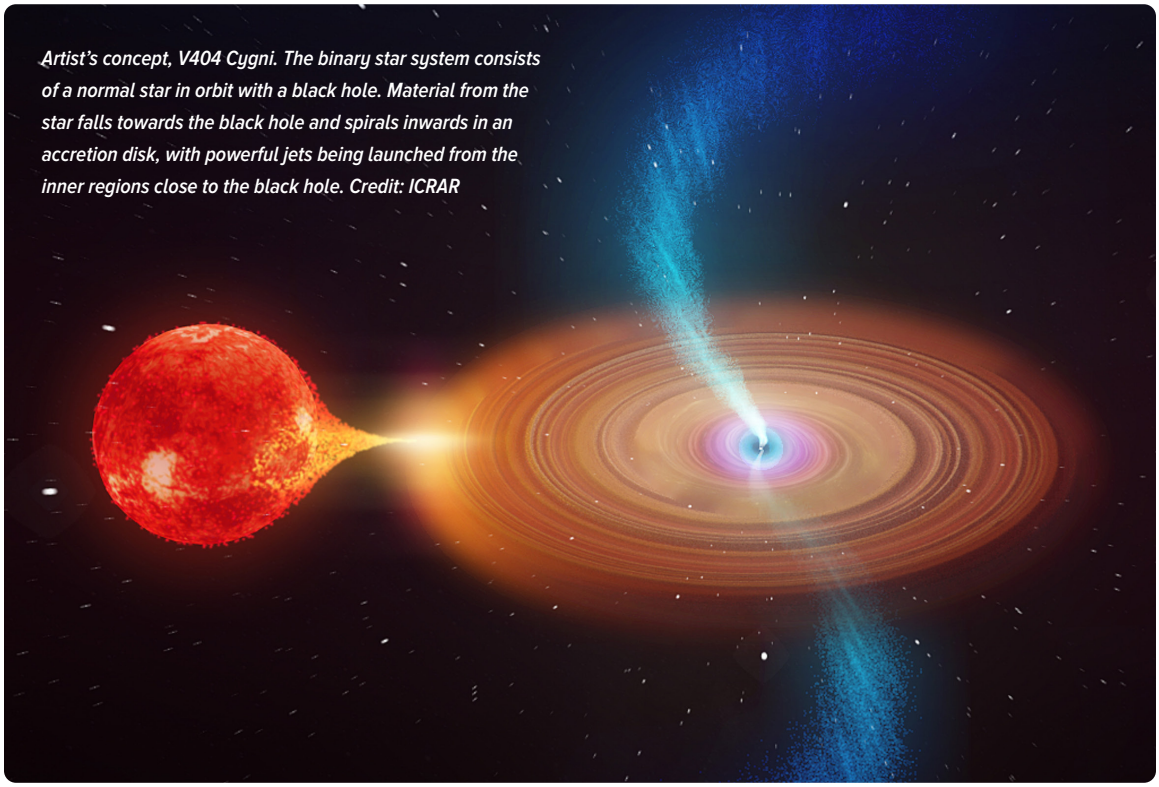



*Figure:* **[Left]** *CO 2-1 moment maps.* **[Right]** *CO 2-1 spectrum and PV diagram for NGC 3258. (Boizelle et al. 2019)*

**Publication: Benjamin D. Boizelle (Texas A&M, University of California, Irvine), et al., *A Precision Measurement of the Mass of the Black Hole in NGC 3258 from High-resolution ALMA Observations of Its Circumnuclear Disk,* Astrophysical Journal, 881, 10 (13 August 2019).**

## A Rapidly Changing Jet Orientation

Powerful relativistic jets are one of the primary ways in which accreting black holes provide kinetic feedback to their surroundings. Jets launched from or redirected by the accretion flow that powers them are expected to be affected by the dynamics of the flow, which for accreting stellar-mass black holes has shown evidence for precession due to frame-dragging effects that occur when the black hole spin axis is misaligned with the orbital plane of its companion star. Recent theoretical simulations have suggested that the jets can exert an additional torque on the accretion flow, although the interplay between the dynamics of the accretion flow and the launching of the jets is not yet understood. In this contribution, Miller-Jones et al. report a rapidly changing jet orientation — on a time scale of minutes to hours — in the black hole X-ray binary V404 Cygni, detected with the Very Long Baseline Array during the peak of its 2015 outburst. The authors demonstrate that this changing jet orientation can be modelled as the Lense-Thirring precession of a vertically extended slim disk that arises from the super-Eddington accretion rate. These findings suggest that the dynamics of the precessing inner accretion disk could play a role in either directly launching or redirecting the jets within the inner few hundred gravitational radii. Similar dynamics should be expected in any strongly accreting black hole whose spin is misaligned with the inflowing gas, both affecting the observational characteristics of the jets and distributing the black hole feedback more uniformly over the surrounding environment.



*Artist's concept, V404 Cygni. The binary star system consists of a normal star in orbit with a black hole. Material from the star falls towards the black hole and spirals inwards in an accretion disk, with powerful jets being launched from the inner regions close to the black hole. Credit: ICRAR*

**Publication: James C.A. Miller-Jones (International Centre for Radio Astronomy Research – Curtin University) et al., *A Rapidly Changing Jet Orientation in the Stellar-mass Black-hole System* V404 Cygni, Nature, 569, 374 (29 April 2019).**

## Measuring the Hubble Constant Via Superluminal Motion

The Hubble constant ($H_0$) measures the current expansion rate of the Universe, and plays a fundamental role in cosmology. Enormous effort has been dedicated over the past decades to measure $H_0$. Notably, Planck cosmic microwave background data and the local Cepheid-supernovae distance ladder measurements determine $H_0$ with a precision of ~1% and ~2% respectively. A $3\sigma$ level of discrepancy exists between the two measurements, for reasons that have yet to be understood.

Gravitational wave (GW) sources accompanied by electromagnetic (EM) counterparts offer an independent, "standard siren" measurement of $H_0$, as demonstrated following the discovery of the neutron star merger, GW170817. This measurement does not assume a cosmological model and is independent of a cosmic distance ladder. The first joint analysis of the GW signal from GW170817 and its EM localization led to a measurement of $H_0 = 74^{+16}_{-8}$ km/sec/Mpc.

In this analysis, the degeneracy in the GW signal between the source distance and the observing angle dominated the $H_0$ measurement uncertainty. Recently, Mooley et al. (Nature **561**, 355, (2018)) obtained tight constraints on the observing angle using high angular resolution imaging of the radio counterpart of GW170817. Hotokezaka et al. report an improved measurement $H_0 = 70.3^{+5.3}_{-5.0}$ km/sec/Mpc by using these new radio observations, combined with the previous GW and EM data. The authors estimate that just 15 more GW170817-like events, having radio images and light curve data, will potentially resolve the tension between the cosmic microwave background and Cepheid-supernova measurements, as compared to 50–100 GW events without such data.

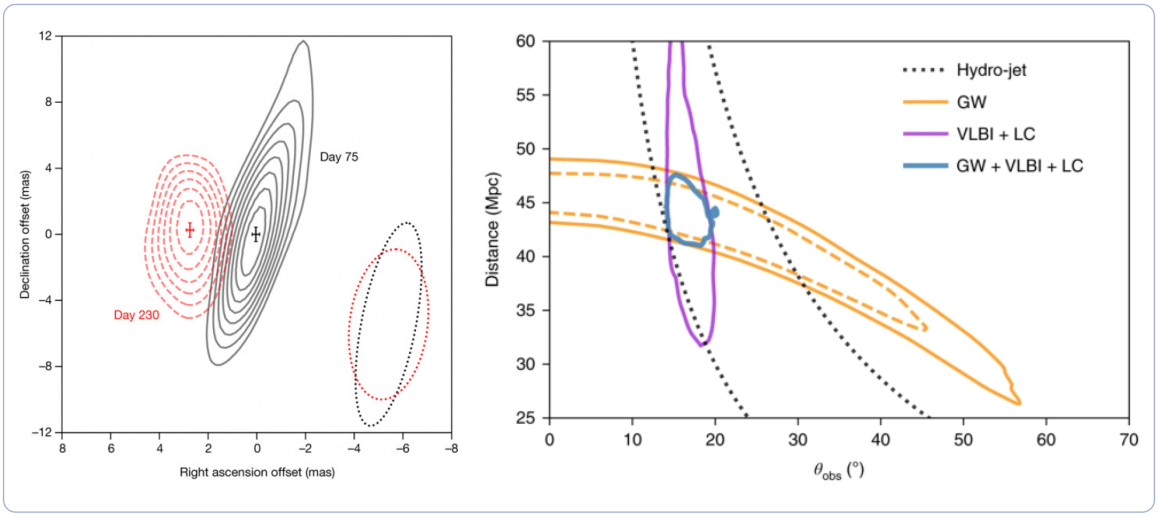



*Figure:* **[Left]** *Proper motion of the VLBI components of GW170817 at 5 GHz over 155 days.* **[Right]** *Distance to the source versus rotation plane for the merger, from which the Hubble constant can be derived (K. Hotokezaka et al. 2019).*

**Publication: Hotokezaka, Kenta (Princeton University) et al., *A Hubble Constant Measurement from Superluminal Motion of the Jet in GW170817*, Nature Astronomy, 3, 940 (8 July 2019).**

## Star Formation in Luminous and Ultra-luminous Galaxies

Linden et al. present the first results of a high-resolution Very Large Array imaging survey of luminous and ultra-luminous infrared galaxies (U/LIRGs) in the Great Observatories All-sky LIRG Survey (GOALS). From a full sample of 68 galaxies, the authors selected 25 luminous infrared galaxies that show resolved extended emission at sufficient sensitivity to image individual regions of star formation activity beyond the nucleus. Ranging from 10 pc to 1 kpc, the resolution was adequate to isolate numerous massive star forming regions across the galaxies, including those in tidal tails and filaments.

With wideband radio continuum observations that sampled frequencies from 3–33 GHz, the authors made extinction-free measurements of the luminosities and spectral indices of 48 individual star-forming regions having deprojected galactocentric radii that lie outside the 13.2 μm core of the galaxy. The median 33 GHz thermal fraction and 3–33 GHz spectral index measured for these extranuclear regions is 65% ± 11% and −0.51 ± 0.13, respectively. These values are consistent with measurements made on matched spatial scales in normal star-forming galaxies, and suggest that these regions are more heavily dominated by thermal free-free emission relative to the centers of local U/LIRGs.

The authors also find that the median star formation rate derived for these regions is ~1 $M_{\odot}$/year, and when placed on the sub-galactic star-forming main sequence of galaxies, they are offset from their host galaxies' globally averaged specific star formation rates. The authors conclude that while nuclear starburst activity drives LIRGs above the star-forming main sequence of galaxies, extranuclear star formation still proceeds in a more extreme fashion relative to what is seen in local spiral galaxies.

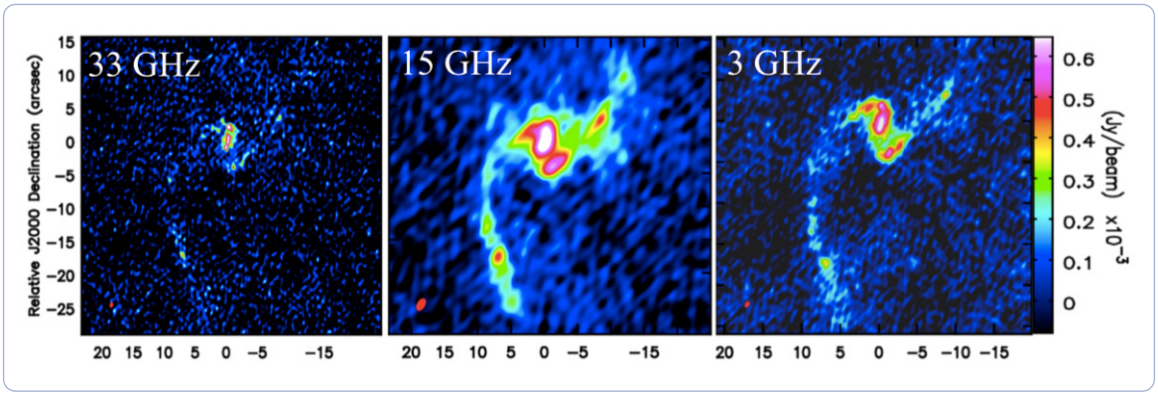



*Figure: Multifrequency imaging of a typical galaxy in the GOALS VLA survey, NGC 3110 at a distance of 70 Mpc (Linden et al. 2019).*

**Publication: S.T. Linden (Univ of Virginia) et al., *A Very Large Array Survey of Luminous Extranuclear Star-forming Regions in Luminous Infrared Galaxies in GOALS,* Astrophysical Journal, 881, 70 (13 August 2019).**

## A High-resolution, 3D Neutral Hydrogen Survey

The COSMOS H I Large Extragalactic Survey (CHILES) Very Large Array (VLA) deep field is the first high-resolution, three-dimensional survey of neutral hydrogen (HI) 21cm emission over a substantial cosmic volume. In this initial contribution, Hess et al. present a study of 16 neutral hydrogen (HI)-detected galaxies found in 178 hours of Very Large Array observations from Epoch 1 of the CHILES. They focus on two redshift ranges between $0.108 \leq z \leq 0.127$ and $0.162 \leq z \leq 0.183$ which are among the worst affected by radio frequency interference (RFI). While this represents only 10% of the total frequency coverage and 18% of the total expected time on source compared to what will be the full CHILES survey, they demonstrate that their data reduction pipeline recovers high-quality data even in regions severely impacted by RFI. They also report on in-depth testing of an automated spectral line source finder to produce HI total intensity maps which are presented side-by-side with significance maps to evaluate the reliability of the morphology recovered by the source finder. The team recommends that this become a common-place manner of presenting data from upcoming HI surveys of resolved objects. They use the COSMOS 20k group catalogue and extract the filamentary structure using a topological algorithm to evaluate the H I morphology in the context of both local and large-scale environments and discuss the shortcomings of both methods. Many of the detections show disturbed H I morphologies suggesting they have undergone a recent interaction which is not evident from deep optical imaging alone. The sample showcases the broad range of ways in which galaxies interact with their environment. This is a first look at the population of galaxies and their local and large-scale environments observed in H I by CHILES at redshifts beyond the $z = 0.1$ Universe. These VLA observations provide crucial insight into the physics of the gaseous evolution of the neutral atomic gas in galaxies, and guidance for future deeper surveys with next generation radio arrays.

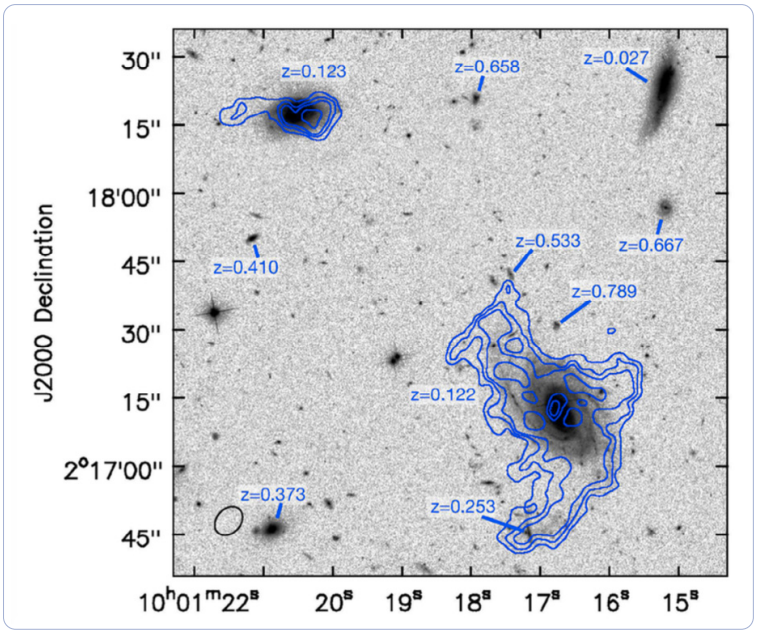
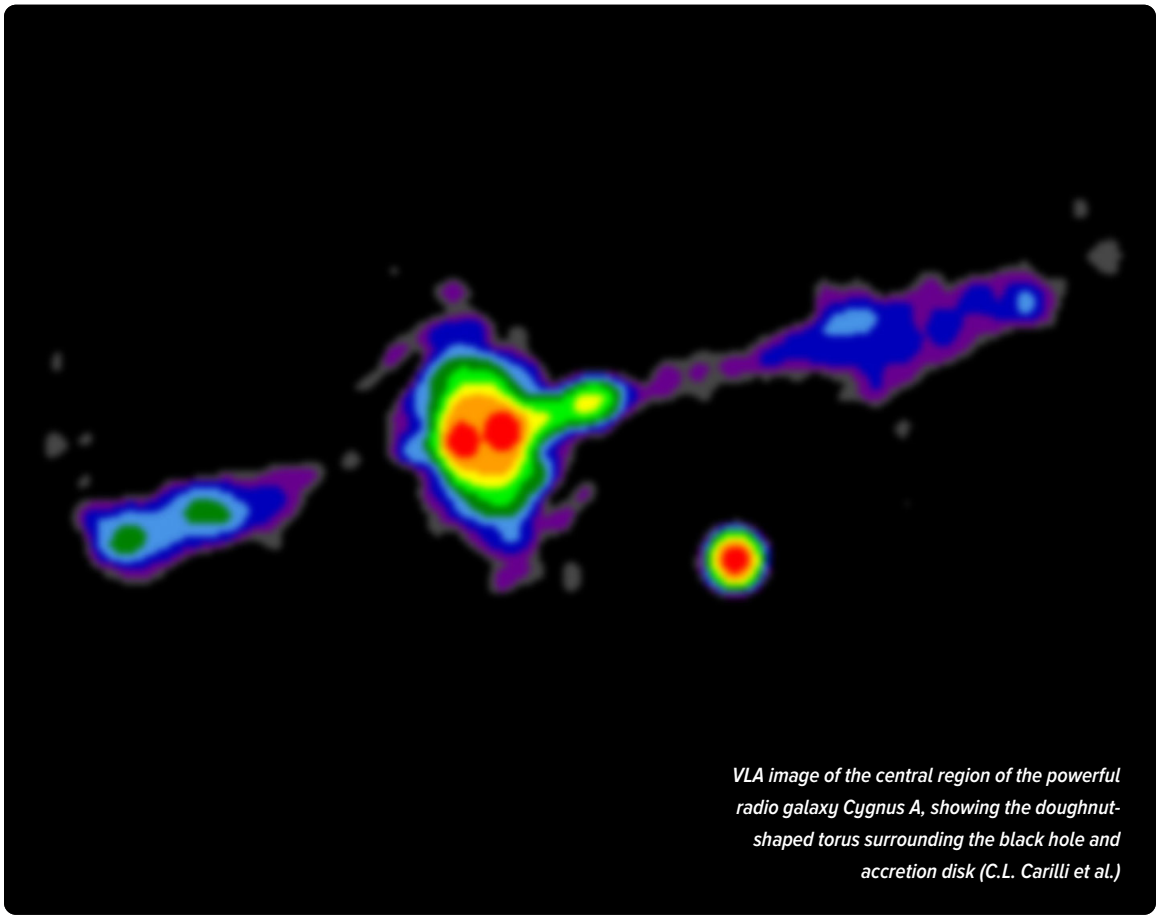



*Figure: CHILES VLA image of an HI group at z = 0.12 (Hess et al., 2018).*

**Publication: Kelley M. Hess (Netherlands Institute for Radio Astronomy) et al., *CHILES: HI Morphology and Galaxy Environment at z=0.12 and z=0.17,* Monthly Notices of the Royal Astronomical Society, 484, 2234 (20 December 2018).**

## Probing the Torus of an Active Galactic Nucleus

An active galactic nucleus (AGN) corresponds to the process of prodigious energy production by gas in-fall onto a supermassive black hole. In this work, Carilli et al. present the first direct imaging of what may be the thick torus in the AGN of the archetype powerful radio galaxy Cygnus A, using the Very Large Array at 18–48 GHz, with a resolution down to 45 milli-arcseconds. Such a torus has long been a key component of AGN models, but direct imaging on the relevant physical scales in sources of extreme (quasar-like) luminosities, remains scarce. An elongated structure, perpendicular to the radio jets and centered on the core, is well resolved, with a full length of 0.48 arcsec (528 pc), and a full width of 0.26 arcsec (286 pc). The radio emission spectrum is consistent with optically thin free-free emission. The authors present a model of a flaring torus, with a half-opening angle for the poloidal region of 62°. The radio jets are oriented along the poles. The observations require a clumpy gas distribution, with the free-free emission dominated by clumps with densities ≥ 4000 $cm^{-3}$.



*VLA image of the central region of the powerful radio galaxy Cygnus A, showing the doughnut-shaped torus surrounding the black hole and accretion disk (C.L. Carilli et al.)*

**Publication: C.L. Carilli (National Radio Astronomy Observatory) et al., *Imaging the AGN Torus in Cygni A,* Astrophysical Journal Letters, 874, L32 (5 April 2019).**

## A Cannonball Pulsar

English et al. conducted imaging with the Very Large Array and performed a Fermi timing analysis of the 115 millisecond γ-ray and radio pulsar PSR J0002+6216, which is at a distance of ~6,500 light-years, and was discovered in 2017 by the Einstein@Home citizen-science project. Their research demonstrates that the pulsar lies at the apex of a narrowly collimated, cometary-like, seven arcminute tail of nonthermal radio emission, which they identify as a bow-shock pulsar wind nebula. The tail of the nebula points back toward the geometric center of the supernova remnant CTB 1 (G116.9+0.2) 28 arcminutes away, at a position angle $\theta_{\mu}$ = 113°. They measured a proper motion with 2.9$\sigma$ significance from their Fermi timing analysis giving μ = 115 ± 33 milliarcseconds/year and $\theta_{\mu}$ = 121° ± 13°, corresponding to a large transverse pulsar velocity of 1100 km/sec at a distance of 2 kpc. This proper motion is of the right magnitude and direction to support the claim that PSR J0002+6216 was born from the same supernova that produced CTB 1. This research explores the implications of this for pulsar birth periods, asymmetric supernova explosions, and mechanisms for pulsar natal kick velocities.

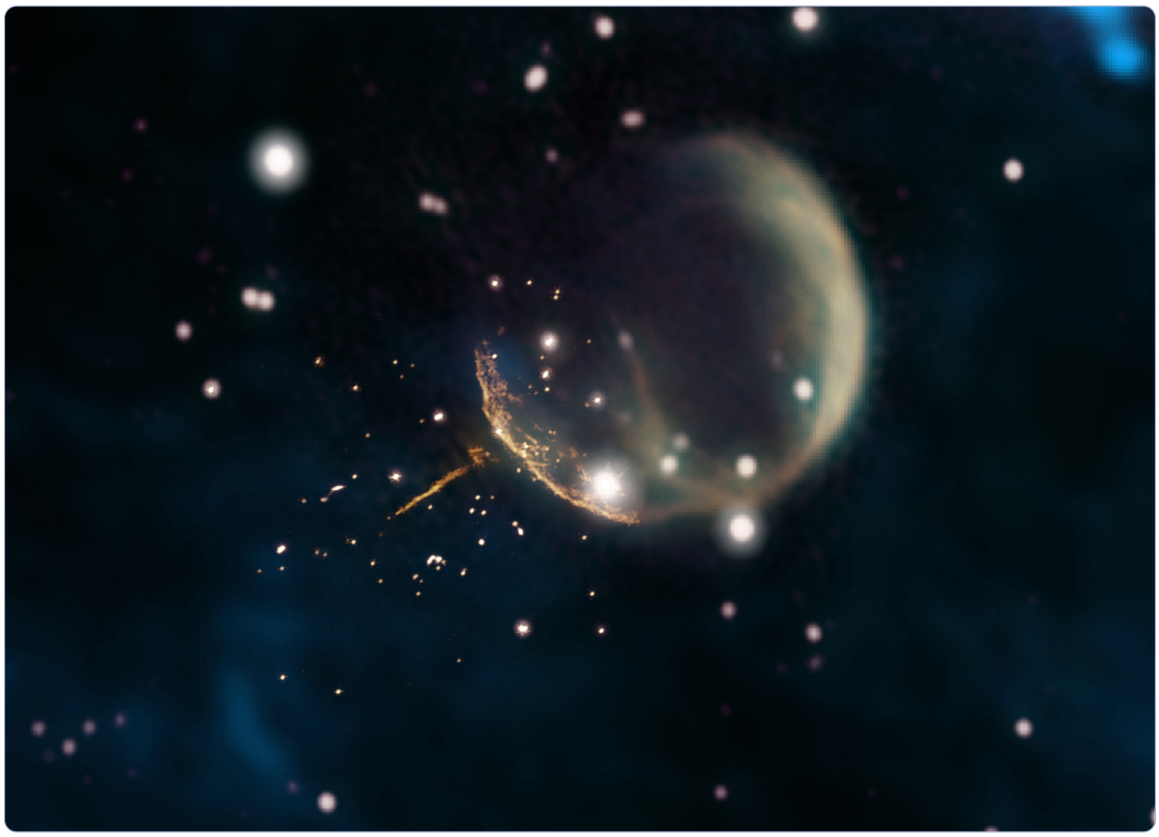


*Figure: Jayanne English, University of Manitoba; F. Schinzel et al.; NRAO/AUI/NSF; DRAO/Canadian Galactic Plane Survey; and NASA/IRAS.*

**Publication: F. K. Schinzel (NRAO) et al., *The Tail of PSR J0002+6216 and the Supernova Remnant CTB 1,* Astrophysical Journal Letters, 876, L17 (3 May 2019).**

## Circumplanetary Disk Detection

The combination of high-resolution ALMA dust imaging and Very Large Telescope (VLT) imaging of the ionized gas in a protoplanetary system, PDS 70, has shown evidence for accretion onto planets themselves, for the first time. PDS 70 is a planetary system forming around a 0.8 $M_{\odot}$ T Tauri star at a distance of 113 pc.

In this work, Isella et al. describe the discovery of a spatially unresolved source of submillimeter continuum emission ($\lambda$ = 855 μm) associated with a young planet, PDS 70c, recently detected in H$\alpha$ emission around the 5 Myr old T Tauri star, PDS 70. The authors interpret the emission as originating from a dusty circumplanetary disk with a dust mass between 2 x $10^{-3}$ $M_{\oplus}$ and 4.2 x $10^{-3}$ $M_{\oplus}$. Assuming a standard gas-to-dust ratio of 100, the ratio between the total mass of the circumplanetary disk and the mass of the central planet would be between $10^{-4}$ and $10^{-5}$. The authors also report the discovery of another compact continuum source 0.074 ± 0.013 arcsec southwest of a second known planet in this system, PDS 70b, that was previously detected in near-infrared images. The authors speculate that the latter source might trace dust orbiting in proximity of the planet, but more sensitive observations are required to unveil its nature.

VLT imaging of H$\alpha$ emission has revealed two forming planets, present in a gap in the dust disk, at distances of 23 and 35 AU from the star, with masses of 4 and 12 $M_J$. ALMA 350 GHz images down to 0.05 arcsecond resolution show dust emission from the planets themselves, indicating circumplanetary disks associated with the forming planets. These mini-dust disks will eventually coalesce to form moons and dust rings, similar to those seen around the giant planets in the Solar System.

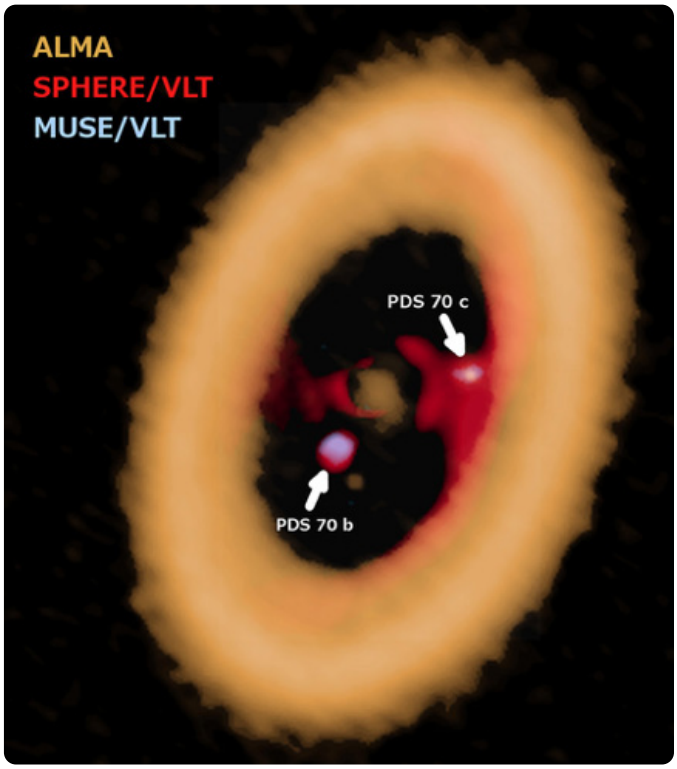


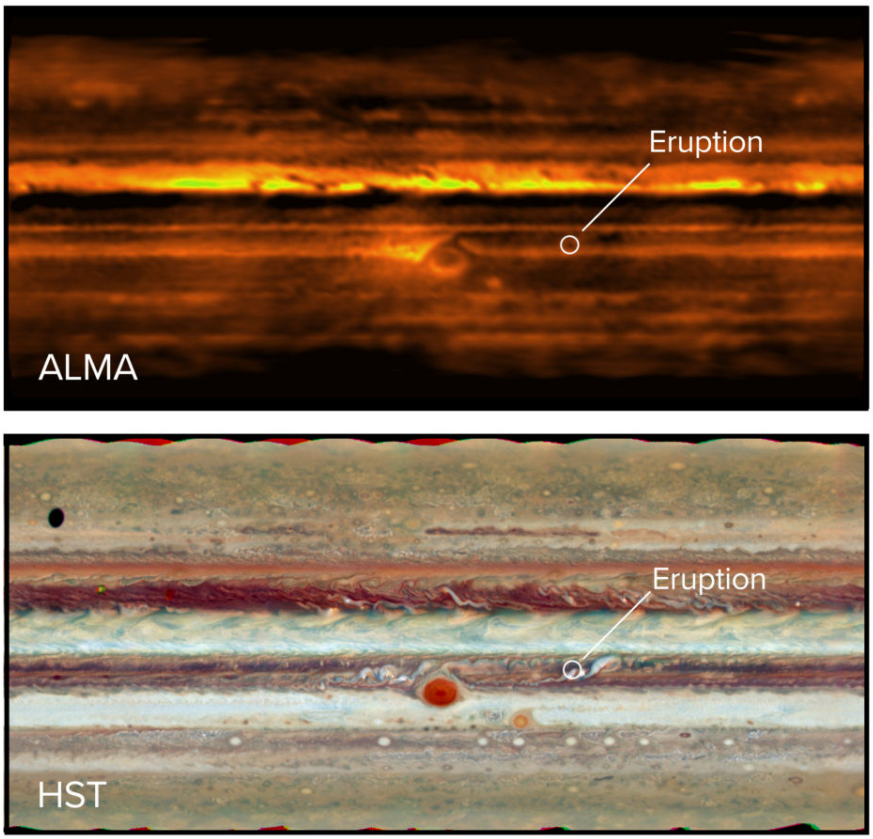

*Figure: ALMA 350 GHz and VLT images of the protoplanetary disk, PDS 70 (Isella et al.)*

**Publication: Andrea Isella (Rice University) et al., *Continuum Submillimeter Emission Associated with Candidate Protoplanets,* Astrophysical Journal Letters, 879, L25 (10 July 2019).**

## The Solar System at Millimeter Wavelengths: Jupiter

Imke det Pater et al. obtained the first maps of Jupiter at 1–3 mm wavelength with ALMA in early January 2017, just days after an energetic eruption in the southern hemisphere was reported by the amateur community, and ~2–3 months after the detection of similarly energetic eruptions in the northern hemisphere. Their ALMA observations probe below the ammonia cloud deck and show that the erupting plumes in the South Equatorial Belt bring up ammonia gas from the deep atmosphere. While models of plume eruptions that are triggered at the water condensation level explain data taken at uv–visible and mid-infrared wavelengths, these ALMA observations provide a crucial, hitherto missing, link in the moist convection theory by showing that ammonia gas from the deep atmosphere is indeed brought up in these plumes. Contemporaneous Hubble Space Telescope data show that the plumes reach altitudes as high as the tropopause. The authors suggest that the northern hemisphere plumes also rise up well above the ammonia cloud deck and that descending air may dry the neighboring belts even more than in quiescent times.

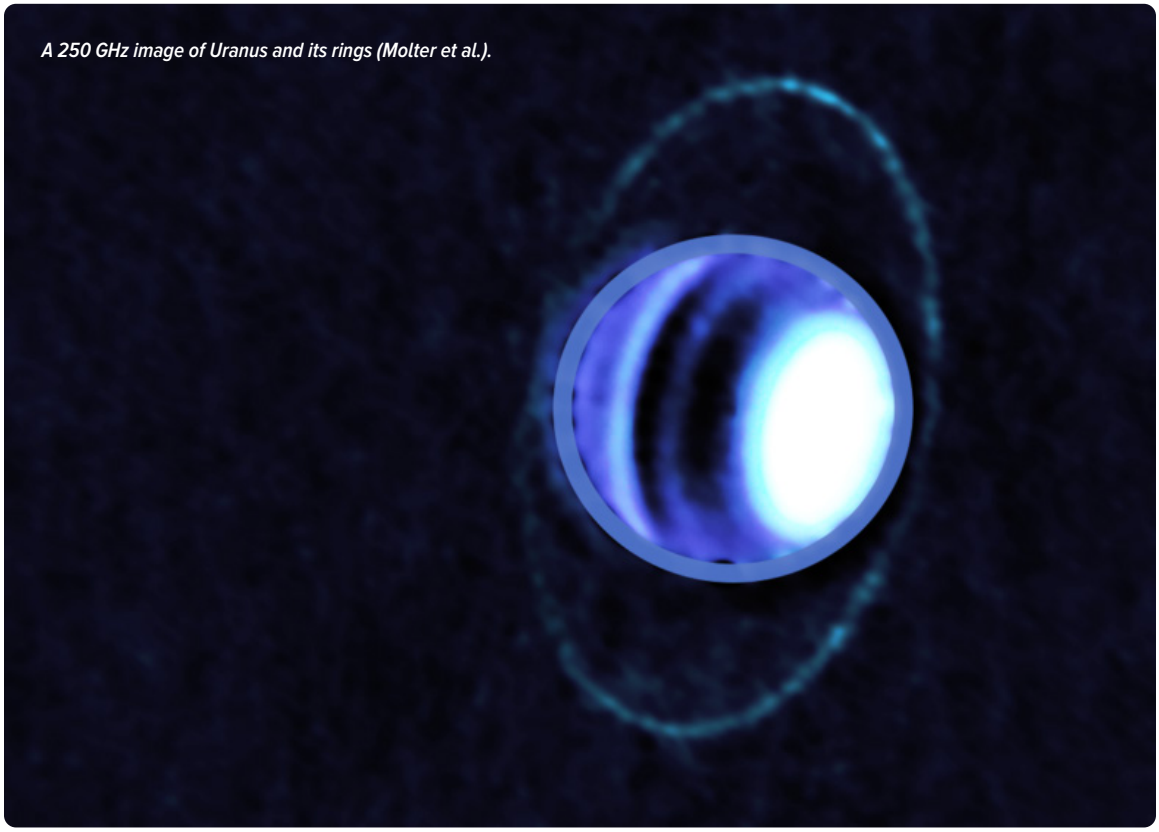
*Figure: Ammonia in the Jovian atmosphere (de Pater et al.).*




**Publication: Imke de Pater (University of California, Berkeley) et al., *First ALMA Millimeter-wavelength Maps of Jupiter with a Multiwavelength Study of Convection,* Astronomical Journal, 158, 139 (October 2019).**

## The Solar System at Millimeter Wavelengths: Uranus

The narrow main rings of Uranus are composed of almost exclusively centimeter- to meter-sized particles, with a very small or nonexistent dust component; however, the filling factor, composition, thickness, mass, and detailed particle size distribution of these rings remain poorly constrained. Using millimeter (1.3–3.1 mm) imaging with ALMA and mid-infrared (18.7 μm) imaging from the Very Large Telescope, Molter et al. observed the thermal component of the Uranian ring system for the first time. The ε ring is detected strongly and can be seen by eye in the images; the other main rings are visible in a radial (azimuthally averaged) profile at millimeter wavelengths. A simple thermal model similar to the Near-Earth Asteroid Thermal Model is applied to the ε ring to determine a ring particle temperature of 77.3 ± 1.8 K. The observed temperature is higher than expected for fast-rotating ring particles viewed at our observing geometry, meaning that the data favor a model in which the thermal inertia of the ring particles is low and/or their rotation rate is slow. The ε ring displays a factor of 2–3 brightness difference between periapsis and apoapsis, with 49.1% ± 2.2% of sightlines through the ring striking a particle. These observations are consistent with optical and near-infrared reflected light observations, confirming the hypothesis that micron-sized dust is not present in the ring system.



*A 250 GHz image of Uranus and its rings (Molter et al.).*

**Publication: Edward M. Molter (University of California, Berkeley) et al., *Thermal Emission from the Uranian Ring System,* Astronomical Journal, 158, 47 (July 2019).**

# NORTH AMERICAN ALMA OPERATIONS

Photo by: Pablo Carillo, ALMA

North American ALMA Operations (NA ALMA Ops) is the NRAO department that ensures that the North American scientific community has the tools, information, support, and access to make optimal scientific use of ALMA. This NRAO department also provides scientific, technical, and business support to Observatory operations in Chile in concert with the Joint ALMA Observatory (JAO) staff and international partners, and supports a long-term ALMA development program for technical enhancement.

**The NA ALMA Ops department includes four divisions:**

- North American ALMA Science Center (NAASC);
- Offsite Technical Maintenance and Support, including Construction Warranty support;
- NA ALMA Development Program; and
- NRAO/AUI Office of Chilean Affairs (OCA).

**In 2019, NA ALMA Ops focused on the following high-level initiatives:**

- Support JAO Operations and NA community use of ALMA. Continue the Observatory's outstanding scientific productivity;
- Deliver fully calibrated data and representative images of ALMA standard observing modes to Principal Investigators within 30 days of the final successful execution on the array and facilitate the ALMA workflow development;
- Support the NRAO Science Ready Data Products strategic initiative. Deliver true science-ready products while continuing to meet ALMA core deliverables;
- Expedite NA community science publications. Support NA PIs in getting data to publication, ensure that they are competitive with their regional peers;
- Enhance staff relations and the work environment in Chile, build toward the next collective bargaining agreement. Complete the multicancha, and continue to build the Diversity and Inclusion Outreach program in Chile; and
- Support the ALMA 2030 Development Roadmap in NA.

## North American ALMA Science Center

The North American ALMA Science Center (NAASC) is located at 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 2019 as the North American community's interface to the ALMA Observatory for expert advice and assistance, including proposal preparation and submission, data reduction and processing, 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 contributes support for Chile operations.

## Cycle 6 Science Operations

ALMA Cycle 6 science operations finished on schedule on 30 September 2019: 92% of Grade A+B projects were fully completed, and many not completed had received more than half the requested time.

NAASC staff provided oversight in Cycle 6 science operations of all the approved NA ALMA Principal Investigator (PI) programs to ensure PIs submitted, reviewed, and approved their projects for scheduling, and, if needed, to provide communication between PIs and the JAO. Throughout 2019, NAASC staff acted as Contact Scientists for the 250+ approved Cycle 6 observing programs (including Director's Discretionary Time) from North America. In addition, the NAASC coordinated with the JAO and other ARCs on scheduling the Astronomer on Duty shifts to Chile, with NAASC scientists covering more than 14 shifts over the year.

Six Cycle 6 filler programs were approved on the Atacama Compact Array (ACA). These programs were designed to fill a gap in the ACA observing schedule in June-July 2019. The programs were selected based on input from scientists at the JAO and the ALMA Regional Centers. The proposed programs were reviewed by JAO Department of Science Operations staff with final approval by the ALMA Director.

## Cycle 7 Call for Proposals & Science Operations

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 7 Call for Proposals opened 19 March 2019, with a submission deadline of 15:00 UT on 17 April 2019. ALMA observing proposals were solicited for scientific observations to be scheduled from October 2019 -September 2020. The Call for Proposals announced that Cycle 7 would allocate 4300 hours of 12-m Array time and 3000 hours of ACA time.

**ALMA technical capabilities available for the first time in Cycle 7 included:**

- Band 7 observations in configurations C43-9 and C43-10;
- Band 7 solar observations 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 became 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 deg of the science target. The data rate limitation from previous cycles was significantly relaxed so that PIs could, e.g., place high spectral resolution windows in long baseline configurations that were previously hampered due to high data rates.

The JAO conducted a Cycle 7 Supplemental Call for proposals with a deadline on 1 October 2019 that enabled proposers to request the ACA in stand-alone mode. Following the Main Call by five months, the Supplemental Call maximized the ACA scientific output by allowing more timely science to be proposed. Proposals accepted in the Cycle 7 Supplemental Call received priority Grade C and have lower priority than ACA proposals accepted in the Cycle 7 Main Call. A total of 249 proposals were submitted. A total of 8199 hours were requested, of which 3069 hours (37%) were accepted from 99 proposals.

For the first time, proposals submitted in the Supplemental Call were peer-reviewed using a distributed system in which each proposal team selects a designated reviewer to participate in the review, which was completed in December 2019 when PI notification letters were sent.

Cycle 7 ALMA science operations were initiated, on schedule, on 1 October 2019. The first Cycle 7 science data were delivered to a PI just 12 hours after the data were acquired with ALMA.

## Cycle 8 Call for Proposals

A pre-announcement for the ALMA Cycle 8 Call for Proposals was published to the ALMA Science Portal on 19 December 2019. The Call was initially released 19 March 2020, with a proposal submission deadline of 15:00 Universal Time on 17 April 2020.


The ALMA partnership organized the Fourth ALMA Science Conference in Cagliari (Sardinia, Italy) on 14–18 October 2019. A capacity crowd of 235 scientists from around the world attended. The full breadth of ALMA science was discussed, from the Solar System to the high-redshift Universe. Special emphasis was placed on results from the first rounds of ALMA Large Programs, ALMA's high resolution and high frequency capabilities, the new Solar and Very Long Baseline Interferometry modes, as well as the synergy between ALMA and other observatories. As in previous editions of the conference series, the scientific priorities for the implementation of the ALMA Development Roadmap were also discussed.

### ALMA Ambassadors

The 2019 ALMA Ambassadors program was at the core of NAASC efforts to reach out to potential observing proposal Principal Investigators (PIs) across the community. The 2019 ALMA Ambassadors received intensive training at NRAO headquarters in February 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 2019 Ambassador then organized and hosted a local ALMA proposal preparation workshop in March or April 2019 at their home institution in advance of the Cycle 7 ALMA proposal deadline on 17 April.

The 2019 ALMA Ambassadors at NRAO Headquarters, February 2019 [Left to Right]: David Rebolledo (JAO), Veronica Allen (NASA Goddard), Angus Mok (Toledo), Dyas Utomo (OSU), Kristina Nyland (NRL), Justin Spilker (UT-Austin), Liton Majumdar (NASA JPL), George Privon (UFL), Toby Brown (McMaster), Cassie Reuter (Illinois Urbana-Champaign), Megan Ansdell (UC-Berkeley), Erin Cox (Northwestern), Jon Ramsey (UVA guest), Allison Noble (MIT), Tannaz Farrahi (UVA guest), Jorge Zavala (UT-Austin), and Maria Jesus Jimenez Donaire (CfA).

## Community Support

Hosting or sponsoring scientific meetings and workshops is an integral part of the NAASC strategic initiative for knowledge transfer and ALMA results dissemination. In 2019, the NAASC was a host and/or a major contributor to many scientific and topical meetings, such as the International Symposium on Molecular Spectroscopy, in Champaign, Illinois, 17–21 June 2019.


*Figure: International Symposium on Molecular Spectroscopy, 17-21 June 2019. Champaign, Illinois*

The NAASC provides overall management of ALMA Helpdesk activities including routine ticket reviews, enforcement of ticket service level agreements, and formulation of new Knowledgebase articles based on user questions. In FY2019, NAASC staff, led primarily by the data analysts, answered 500+ Helpdesk tickets submitted to ALMA Helpdesk Departments, including the Proposal Submission Emergency Departments for the Cycle 7 main and supplemental calls.

Face-to-face (f2f) support continued through 2019 with 40+ visitors to the NAASC and 30+ scientific staff from around the world remote accessing the NAASC cluster for data processing.

ALMA calibration and imaging pipeline testing and development continued in 2019 for the deployment of the Cycle 7 ALMA pipeline, and was aligned with the broader NRAO Science Ready Data Products (SRDP) initiative. The NAASC successfully delivered the heuristics for the Cycle 7 ALMA calibration and imaging pipeline and continued working on the development priorities to improve Quality Assessment (QA) scores, accelerate data review and quality assurance, and improve selected calibration and imaging heuristics.

The CASA Testing Lead role stayed within the NAASC in 2019 and testing and validation continued with the focus on: (a) improvements to imaging, parallelization, and performance; (b) continued improvements to documentation; and (c) CASA activities determined by new ALMA and SRDP capabilities.

A main objective of the Data Processing Workflow group is to deliver fully calibrated data and representative images of ALMA standard observing modes to PIs within 30 days of the date of last successful execution on the array (45 days for non-standard modes). Over the course of 2019, the NAASC successfully delivered data to NA PIs at an average pace of 35 days for all observing modes (standard or non-standard) for Cycle 6 datasets. The Integrated Science Operations Team (iSOpT) presented to the ALMA Board a proposal for a raw data delivery pilot program that enabled a random subset of PIs to download the raw data

products from the ALMA Archive immediately after the data have undergone preliminary QA at the ALMA site. Through the initial response, 25% of PIs that were afforded this option took advantage of the raw data delivery. In addition, the NAASC continued to deliver raw data to triggered and time critical observing programs throughout Cycle 6. The ALMA project conducted an external review of the development, priority setting, and implementation of the ALMA Archive. NAASC staff were heavily involved in this effort generating documentation and preparing presentations in preparation for this review.

## ALMA Development

ALMA Development-funded upgrades typically progress through three development phases of increasing technological readiness:

- Conceptual study,
- Prototype/pre-production, and
- Production and implementation.

ALMA Development projects generally follow successful studies and take a concept from the prototype phase through production and implementation. Typical development award types are:

- Project: A large-scale (>$1M USD), multi-year initiative involving relatively mature technology which may lead to full implementation in the ALMA Observatory.

- Strategic Study: A mid-scale (≤$0.4M USD), two-year investigation of an emerging technology of specific, strategic interest which may lead to a Development Project.

- General Study: a small-scale (≤$0.2M USD), one-year investigation of an emerging technology which may lead to a Development Project.

A Call for Proposals released in 2019 funded eight general studies for Cycle 7 to commence in FY2020.

## Ongoing Development Projects

Fiber Optic Project – JAO (Cycle 1): The fiber optic link between the Operations Support Facility (OSF), Array Operations Site (AOS), and Santiago is fully functional and operating via a temporary permit. The project remained open in 2019 as the final operating permit was processed by the Chilean Ministry of National Assets (Ministerio de Bienes Nationales).

Expansion of the Central Local Oscillator Article to Five Subarrays – NRAO (Cycle 2): This project procured and tested all the required modules and equipment. The complete chain was installed, tested, and commissioned at the AOS. The system was integrated into the software control system. The project is held open pending adjudication of the final test results and acceptance of the final report by ALMA.

Design and Testing of a Prototype Band 2 Cartridge – NRAO (Cycle 2): A Band-2 Prototype Cartridge Preliminary Design Review conducted 30–31 May 2017 resulted in clearance to proceed to detailed design phase to design, build, and test a prototype Band 2 (67–90 GHz) cartridge. A Cycle 5 proposal for a Band 2+ project was well-rated and mature, but did not proceed. The Band 2 prototype cartridge project completed planned work but has otherwise been on hold. The team has agreed to assist the EU Band 2+3 team with cartridge and Low Noise Amplifier testing in 2020.

Band 3 CCA Magnet and Heater Installation for Deflux Operations – NRC-HIA (Cycle 2): This project is modifying the Band 3 Cold Cartridge Assembly to add a heater element to reduce observed azimuth-dependent total power variations. The heater solution was successfully tested at the National Research Council of Canada-Herzberg Institute of Astrophysics (NRC-HIA) and underwent verification testing by the JAO. Various delays have been caused by test results validation and an inability to reproduce the original total power variations. The design has been finalized and NRC-HIA is building the initial heater kits for delivery in early 2020. Integration into each Band 3 CCA will continue over three years.

A Significant Upgrade to the ALMA 64-Antenna Correlator – NRAO (Cycle 5): This project was to provide a modest upgrade of the ALMA Baseline Correlator electronics to increase spectral resolution and processed bandwidth. Due to insurmountable technical challenges and key personnel retirements, this project has been cancelled.

ALMA Phasing System Phase 2 (APP2) – MIT Haystack (Cycle 5): This project features initiatives to improve VLBI capabilities and performance for ALMA. Major components include enabling spectral line VLBI, extending the frequency range of phasing to Bands 1–7, improving the calibration mechanism to allow observations of weaker sources, the introduction of a single-dish VLBI mode, and a pulsar mode. On-sky testing has been conducted during multiple ALMA VLBI campaigns in coordination with other observatories. Most capabilities are on track to be offered during Cycle 8 operations, though extending VLBI to other receiver bands (specifically Band 7) is expected to be delayed to Cycle 9 or later.

## Ongoing Development Studies

Three ALMA Development Studies completed in 2019, and a fourth continued. The completed Studies were:

- Full-Mueller Mosaic Imaging with ALMA – NRAO (Cycle 5)
- Neuroscope: Neural Machine Intelligence Tools for Discovery and Interpretation in Complex ALMA Data – Rice University (Cycle 5)
- Quantum-Limited Very-Wideband RF and IF Amplifiers – NRAO (Cycle 5).

Wideband Low-Noise Balanced IF Amplifiers for Band 6 – NRAO (Cycle 5): This study investigates multiple designs for development of an improved Intermediate Frequency (IF) amplifier. Although these amplifiers have future applications to Bands 3–10, this development is anticipated to lead to a prototype that can be integrated into an upgraded Band 6 cartridge. Originally focused on a 4–12 GHz balanced amplifier, the study was extended by a year to investigate higher bandwidths and the possibility of using a low-noise isolator in lieu of the balanced concept.

## Construction Warranty

The ALMA Warranty Policy governs the claims resolution against NA ALMA Construction Project deliverables. Latent design and/or workmanship defects in two deliverables were resolved in 2019.

The NA ALMA Construction Project delivered 25 antennas to the JAO. The primary reflecting surface of these antennas all exhibit, in varying degree, deviation from the required rms surface accuracy of 25μ over the full operating temperature range. The NRAO negotiated a tolling agreement with the supplier (Vertex Antennentechnik GmbH) and thereby suspended the supplier warranty period while NRAO and Vertex collaborated on determining the root cause and developing a corrective action(s) plan. Vertex acknowledged and accepted responsibility for the associated costs.

A design review by NRAO and Vertex with JAO in fall 2018 determined a new wall heater system design to be satisfactory for eliminating the root cause of the excessive thermal dependence of the antenna primary surface. The final production design consists of six heater mats with associated cabling and controller hardware, and a software upgrade that implements the heater control feedback loop. Installation was initiated by Vertex 4 February 2019 and continued through completion of the antenna software upgrade on 30 June 2019. Corrective action on the remaining NA antennas commenced and was completed.

The NA ALMA Construction Project was responsible for the delivery of four Front End Handling Vehicles (FEHVs) to the JAO. Each vehicle transports and manipulates an antenna Front End. Because of anomalies and non-conformances identified during earlier inspections, new vehicle chassis for the four FEHV Units were fabricated. Final delivery of the four FEHVs occurred in late 2019.

## Office of Chilean Affairs

The NRAO Office in Santiago (SCO) supports the legal and business affairs of AUI/NRAO in Chile for ALMA operations. It provides the services that require a local presence in Chile that cannot be effectively discharged from North America. The Office of Chilean Affairs (OCA) oversees compliance with Chilean law in all spheres of Observatory operations, with a focus on human resources activities, including the implementation of collective contracts. The OCA is responsible for fiscal functions, contracts and procurement, local property management, export/import activities, and travel support. OCA also monitors safety, environmental, and regulatory issues in coordination with the NRAO safety manager and the ALMA Environmental Working Group.

After an analysis of OCA office alternatives in Vitacura, Santiago, an improved location was secured that is closer to the JAO Santiago Central Office and represents better value. The estimated relocation date is late 2020. This larger space will relieve office congestion, support EPO activities, and support visitors and International Staff Members doing science outside the JAO.

**Labor Relations:** In preparation for the 2020 ALMA collective bargaining, OCA contributed to the analysis and discussion of the JAO staffing budget, leading to the agreement of a reasonable envelope by the Human Resource Advisory Group and Heads of Administration Advisory Group. The office also led a stakeholders mapping exercise as part of its public affairs strategy. Engagement with key stakeholders identified in that exercise will take place in 2020, with support from a public relations firm. OCA also supported the JAO in designing its first climate survey, which was carried out in July-August. A second union was constituted in September, with 31 employees from SCO, OSF, and OCA. The stated objective of Union No2 is to ensure continuation of benefits. Monthly meetings continued with the original union and meetings with Union No2 were added.

**EPO and Diversity and Inclusion (D&I):** The OCA EPO officer and legal representative act as liaisons with the local communities and the JAO to increase recognition of ALMA, AUI, and NRAO in Chile.

OCA supported the Sister Cities and Observatories New Mexico cohort visit to San Pedro in March, the Astronomy in Chile Education Ambassadors Program (ACEAP) in July–August, the Fifth Astronomy EPO Summit organized by Comisión Nacional de Investigación Científica y Tecnológica (CONICYT) in Temuco in September, and organized outreach activities in Antofagasta. A 20 July event at the American Corner in Universidad Católica del Norte underscored U.S.-Chile scientific collaboration.

OCA was a leader in 2019 in the Promovamos Vocaciones Científicas (ProVoca) campaign to promote STEM vocations among underrepresented minorities. Given their low participation and retention in these careers in Chile, the campaign began with a focus on girls and female role models. Nine videos were produced and released on social media. A major communications effort was launched resulting in unprecedented coverage in traditional print media, television, and radio. The initiative was

unveiled on CNN Chile and featured in 100+ publications, and OCA launched a substantial social media presence. Institutional relations were strengthened with universities, government agencies, museums, and nonprofit organizations, making AUI/NRAO known for its commitment to diversity and inclusion. ProVoca also had a positive staff impact, recognizing and raising the visibility of ALMA female role models. OCA organized a ProVoca activity in Visviri – the northernmost town in the Andean highlands – involving the Aymara indigenous community during the winter solstice.

*Figure: Ninety adults and children from Visviri, the northernmost town in Chile, attended a Provoca event on 20 June 2019. Visiting astronomers and Aymara representatives shared the celebration of the Aymara New Year.*

OCA also organized Hour of Code sessions (November, June) and two talks on Impostor Syndrome, targeting underserved students in Santiago. Presentations were given on inclusive astronomy at Universidad Bernardo O'Higgins and on communicating science to Universidad de Chile's graduate students. In collaboration with the JAO, OCA hosted a meet up of Women Who Code, opening recruitment opportunities.

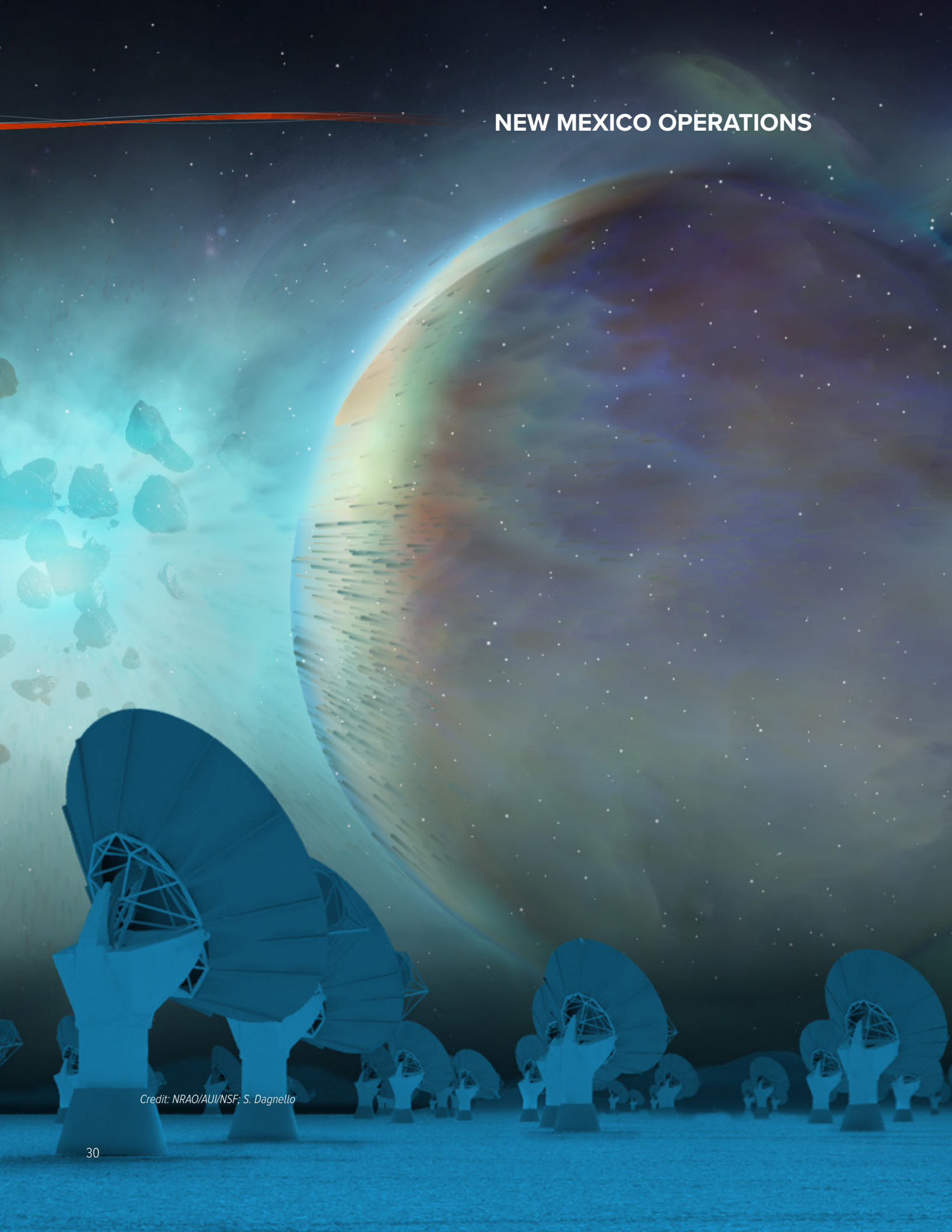
**Multicancha:** Construction of an indoor sports facility (multicancha) at the OSF has been hampered by poor contractor schedule and quality performance. Construction completion has shifted from 30 November 2019 to 15 February 2020. To ease cash flow problems and mitigate risks of the contractor leaving, an addendum was signed in September providing four bonus payments subject to milestone completions. The first addendum milestone (concrete repairs) was completed in mid-September 2019.

**Chajnantor Plateau Power:** Working closely with CONICYT´s Parque Astronómico Atacama, AUI launched conceptual engineering and environmental studies in 2019 to assess options for electrical power provision to current and future observatories on the Chajnantor plateau.

Photo: ALMA (ESO/NAOJ/NRAO), A. Marinkovic/X-Cam

Photo: ESO/José Francisco Salgado (josefrancisco.org)

# NEW MEXICO OPERATIONS



*Credit: NRAO/AUI/NSF; S. Dagnello*

Two of NRAO's telescope facilities—the Karl G. Jansky Very Large Array (VLA) and the Very Long Baseline Array (VLBA)—are maintained and operated from New Mexico in the southwest United States. These instruments provide state-of-the-art centimeter-wavelength capabilities to the astronomy community. In 2019, NRAO commissioned new observing modes for these instruments, matched to the latest scientific requirements. The following sections describe the operational, maintenance, and development activities associated with each instrument, noting that many activities are carried out by the same personnel with activities closely coordinated across both instruments.

## Karl G. Jansky Very Large Array (VLA)

The VLA comprises twenty-seven 25-meter diameter antennas in a Y-shaped configuration on the Plains of San Agustin in west-central New Mexico. In 2019, NRAO continued to offer a suite of robust and scientifically powerful observational capabilities designed and tailored to address the community's scientific needs. The availability of these capabilities is made possible through the activities described below.

### VLA Sky Survey

The VLA Sky Survey (VLASS) began observing its first epoch in September 2017, completing the first half of the sky in February 2018 (VLASS1.1). Quick Look images for VLASS1.1 were completed in Fiscal Year (FY) 2018, and it was expected that higher quality, Single Epoch (SE) continuum images would be completed in FY2019. However, technical issues with the VLASS1.1 data discovered late in FY2018 associated with the pointing of antennas with old-style Antenna Control Units delayed the start of SE imaging. New algorithms were developed to fix the data during imaging, and incorporated into CASA and the VLASS imaging pipeline in FY2019. The SE imaging pipeline was undergoing validation at the end of FY2019, with a new projected start date for SE imaging in FY2020. Polarization cube imaging will follow SE continuum imaging. In spite of the delay in SE images delivery, NRAO hosted a VLA Sky Survey Special Session at the American Astronomical Society January 2019 meeting that was well-attended and well-received, but cancelled plans for a later VLA Sky Survey science meeting, pending SE images delivery. Observing for the second half of the sky for the first epoch (VLASS1.2) took place in the B and BnA configurations, as scheduled, and the Quick Look imaging for VLASS1.2 was completed.

In addition to the well-defined set of basic data products from the survey that NRAO will deliver, the five-year Canadian Initiative for Radio Astronomy Data Analysis (CIRADA) project is working on creating, archiving, and serving enhanced VLASS data products. The scope of NRAO interaction with CIRADA was defined and finalized in 2019.

Effective 1 October, VLASS development and operations were integrated with the Science Ready Data Products initiative in the NRAO Science Support and Research (SSR) department.

### realfast

The field of Fast Radio Burst (FRB) detection is rapidly developing. New discoveries, including localizations – from VLA, Australian Square Kilometre Array Pathfinder, and Canadian Hydrogen Intensity Mapping Experiment – have begun to narrow down the possible progenitors of these enigmatic events. The sparse number of accurate (~0.1 arcsec) localizations is still hampering our ability to further narrow the progenitor possibilities. The goal of the realfast development project is to design and implement a commensal fast transient system for the VLA, and to investigate various options available for searching for these events: assessing the number of antennas, bandwidth, processing needed, algorithms to be used, etc.

A proposal to support development of such a system was submitted to the NSF Advanced Technologies and Instrumentation (ATI) program for funds in FY2017–FY2019, and this proposal was accepted for funding. In FY2019, the realfast system was made operational for limited operational modes (standard continuum, low frequency). A one-year, no-cost extension was requested by the project, and granted by the NSF, and will be used to complete realfast commissioning for all operational modes.

## Science Operations

NRAO continued to offer three types of observing programs to VLA users in the Calls for Proposals issued in 2019: General Observing (GO), Shared Risk Observing (SRO), and Resident Shared Risk Observing (RSRO). In the Call for Proposals for the 2019B observing semester, two capabilities were promoted from SRO to GO: frequency averaging and phase-binned pulsar observing. In the Call for Proposals for the 2020A observing semester, observing with 32 subbands per baseband was promoted from SRO to GO, and three capabilities were promoted from RSRO to SRO: Y1 observing in support of VLBA, coherent-dedispersion pulsar observing, and P-band polarization observing. RSRO programs supported in 2019 included coherent-dedispersion pulsar, fast-dump, P-band polarization, and 4-band observations.

A large fraction of the scientific support is invested in maintaining receiver, antenna, and array performance and ensuring that the NRAO user community has access to quality instrumentation and updated information to effectively use the VLA. Key operational tasks carried out by the scientific staff in support of these functions are summarized below.

**Support Calls for Proposals:** Capabilities to be offered in the 2019B and 2020A semesters were defined, and user documentation for all capabilities for the relevant Call for Proposals updated. Scientific testing of user tools needed to prepare proposals, e.g., the Proposal Submission Tool, was undertaken, and technical reviews for proposals and evaluation of proposals for RSRO contributions were performed.

**Documentation:** Technical documentation detailing hardware and software functionality for staff and users was written, as well as operational procedures and documentation for the operations staff. The VLA Observational Status Summary was updated before the 2019B and 2020A Call for Proposals, along with the Guide to Observing with the VLA on the NRAO web site.

**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 After 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 & 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 characterized and help mitigate RFI contamination in observing bands.

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

**Calibration Data:** Detailed data was collected with the array for a range of calibration purposes, including flux density scale calibrator models, and polarization and bandpass calibration.

## Site Maintenance and Renewal

**Antennas:** VLA antennas were routinely cycled through the Antenna Assembly Building for checkout and overhaul. Five antennas were cycled through the assembly building in FY2019, and the azimuth bearing in antenna #21 was replaced.

The two transporters used to move the antennas during reconfigurations underwent maintenance and repair. Maintenance on the 40-year-old transporters included servicing the motors, checking the generators that maintain critical power to the antenna during a move, lubricating moving parts, assessing the health of the 24-wheel axles and wheels, and maintaining electrical and hydraulic systems. Fatigue cracks were found on the transporter truck rotation collars, of which there are four per transporter. An improved rotation collar was designed. Two of these collars were fabricated and installed on one transporter.

**Track:** Careful inspection of the VLA railroad tracks continued, checking for problems that could compromise transporter safety. These inspections also guarded against problems that could jeopardize the safety of the maintenance rail vehicles used by technicians to service the antennas.

A total of 5,098 cross-ties were replaced. Five track intersections were scheduled to be replaced, and this goal was also completed. The railroad crossing over U.S. Highway 60 was replaced with modern concrete crossing planks.

**Site Infrastructure:** The VLA site buildings, utility systems, and grounds undergo routine annual inspection and preventive maintenance. The site transformers underwent yearly preventive maintenance procedures. Other regular activities included: road grading, roof repairs, heating and cooling systems maintenance, fire brigade and emergency medical response team training, and much more.

Large scale improvements and equipment purchases for the VLA site were carried out as part of overall improvements in VLA infrastructure: the installation of a new fire pump controller and backup power generator, replacement of a control building HVAC compressor, replacement of doors and windows around the site, and the purchase of a new Computer Numerical Control knee mill.

## Technical Upgrades and Enhancements

**Solar Capable Receivers:** The final six receivers were upgraded to solar observing capabilities and installed. This campaign has provided all antennas with solar observing capabilities in L, X, and Ku-bands, while 12 antennas have either S or C-band receivers capable of solar observing (six of each receiver).

**VLA ACU Replacement:** The electronics to repair the existing VLA Antenna Control Units (ACUs) are no longer available. Without replacement parts, antennas with failed ACUs would no longer participate in observations, posing a serious operational risk. All legacy VLA ACUs must be replaced with newer technology units to increase the operational lifetime of the VLA antennas, as well as eliminating problems with the legacy design and greatly improving antenna pointing and tracking capabilities. The first new ACU was installed in FY2013 and the 11th through 13th new ACU units were installed in 2019.

**Upgraded Servo SCR Cards:** Silicon Controlled Rectifiers (SCR) provide high current to the antenna drive motors. These NRAO-developed all-digital versions of an obsolete analog design improve the performance and operational lifetime of the servo system. Three sets of upgraded SCRs were installed in 2019.

**Variable Frequency Drive Development:** A digital printed circuit board was designed and built to control four variable speed refrigerators. As part of the overall system development, it is an interface to an analog PCB which filters the digital signals and provides power to the refrigerators used on a receiver.

## Observing Capability Enhancements

The VLA continued to provide new capabilities to the user community to optimize and enhance the science with the array. This strategy has proven effective in keeping users engaged, and it is a critical factor in keeping VLA scientific productivity high.

Scientific staff and RSRO effort were directed to the following observing capability enhancements in FY2019.

**Frequency Averaging for Continuum Observations:** Scientific staff tested and commissioned the frequency averaging software after it was implemented, and its observing status was promoted to GO.

**Pulsar Observations:** After the software for phase-binned pulsar observations was implemented, scientific staff proceeded with testing and commissioning, and this pulsar observing style was promoted to GO. Similarly, coherent-dedispersion pulsar observations were commissioned and promoted to SRO status.

**Weather Prediction in the Observation Scheduling Tool:** Scientific staff provided an example software implementation of retrieving weather prediction values from the National Weather Service computer server to the software developers in the DMS department. Wind speed is particularly important as it is used to determine what project to observe next. After integration into the Observation Scheduling Tool, scientific staff tested the implementation, and it was put into the production system in 2019.

**RFI Exclusion:** The Wideband Interferometric Digital Architecture Correlator (WIDAR) software includes the ability to blank data based on power level. This is potentially useful for excluding data badly affected by RFI. This software was tested by scientific staff, and shown to be quite effective in some circumstances.

## Next Generation Very Large Array


The NRAO further engaged the science and technical community in 2019 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. The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, as well as unprecedented broadband 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 the cosmic baryon cycle down to parsec-scales out to the Virgo cluster, making a cosmic census of the molecular gas which fuels star formation back to first light and cosmic reionization, and novel techniques for exploring temporal phenomena from milliseconds to years in this new era of multi-messenger astrophysics. The ngVLA will be optimized for observations at 1.2–116 GHz, between ALMA at submillimeter wavelengths and the future Phase I Square Kilometre Array (SKA-1) at decimeter and longer wavelengths.

The ngVLA project has developed the science requirements, system requirements, system architecture, and supporting system design that form the foundation for conceptual development and a proposal to the NSF AST Directorate for Major Research Equipment and Facilities Construction candidacy.

The NRAO facilitated the submission of ngVLA science white papers to the Astro2020 Decadal Survey in January 2019 and submitted an ngVLA facilities white paper in July. The ngVLA Science Book was distributed in early 2019. The three-document set comprising the ngVLA Reference Design Concept was completed in August. A risk-adjusted, fully costed, and documented estimate for the reference design was also completed. The NRAO continued a series of open science and technology meetings, organized by science working groups and science and technical advisory councils, involving hundreds of U.S. and international scientists. These included well-attended, international science meetings on Theoretical Advances Guided by RMS Arrays in Seattle in January 2019 and Radio/Millimeter Astrophysical Frontiers in the Next Decade in Charlottesville in July. A special ngVLA technical session on the reference design was held at the January International Union of Radio Science (URSI) meeting in Boulder, Colorado.

### Science Goals

The compelling science case and reference design for the ngVLA were developed via a collaboration between NRAO and the international astronomy community, led by the ngVLA Science Advisory Council. More than 80 broad and compelling science cases were developed at 1.2–116 GHz. Each of the derived key scientific goals (KSGs) for a future radio/millimeter telescope must: (1) address an important question in astrophysics that has broad scientific and societal implications; (2) require the capabilities of a ngVLA; (3) exhibit synergies with existing or planned facilities in the 2025+ time frame. The resulting five highest-priority ngVLA KSGs were determined to be:

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;

4. Using Galactic Center pulsars to make a fundamental test of gravity; and

5. Understanding the formation and evolution of stellar and supermassive blackholes.

## Technical Concept

The ngVLA technical concept is a synthesis radio telescope operating at centimeter wavelengths that consists of 244 reflectors of 18m diameter, and 19 reflectors of 6m diameter, connected by optical fiber to a signal processing center. Implementation and logistics divide the array into three subsets:

- A Main Array (MA) of 214 reflector antennas each 18m diameter, operating in a phased or interferometric mode, distributed to sample scales from 10s of meters to 1000km. A dense core and spiral arms provide high surface brightness sensitivity, while outer stations increase resolution.

- A Short Baseline Array (SBA) of 19 reflector antennas of 6m aperture will be sensitive to a portion of the larger angular scales poorly sampled by the MA.

- A Long Baseline Array (LBA) of 30 reflector antennas each of 18m diameter located in 10 clusters will provide continental-scale baselines (BMAX = 8860 km) and sub-milliarcsecond resolution.

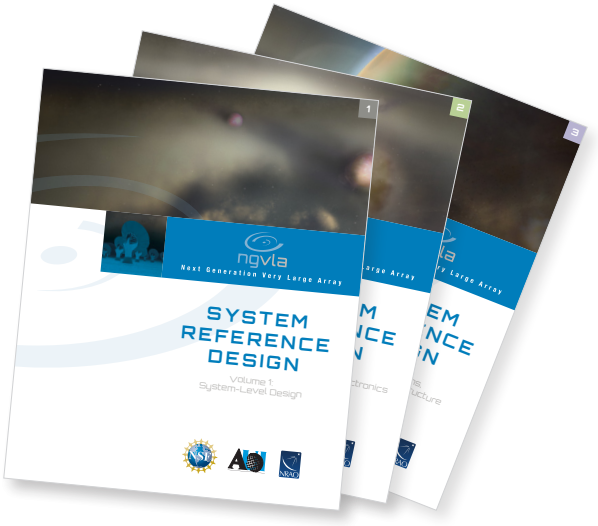
The ngVLA will have ~10x the sensitivity of the VLA and ALMA, continental-scale baselines providing sub-milliarcsecond-resolution, and a dense core on kilometer-scales for high surface brightness sensitivity. The facility will be operated as a proposal-driven instrument. The key deliverable for ngVLA users will be images and image cubes generated using calibration and imaging pipelines. Pipeline products, raw visibilities, and calibration tables will be archived.

## Astro2020 Preparations

In 2019, the ngVLA project in collaboration with the broad astronomy community, prepared and developed a sound, strongly supported submission to the Astro2020 Decadal Survey, including community white paper submissions, a reference design concept, technical trade studies and initial prototype development, and active participation in Astro2020-sponsored events including NRAO/ngVLA-led science and technical meetings.

## ngVLA Reference Design

In 2019, the ngVLA project released the three volumes of the System Reference Design technical compendium, a low technical-risk, costed concept that supports the key science goals, and forms the technical and cost basis of the ngVLA Astro2020 Decadal Survey proposal. The compendium includes 56 technical documents crafted by 54+ engineers and scientists. While led by NRAO, the author list includes the U.S. and international radio community. Many more contributed to the science case and science requirements definition, or through critical review. This technical compendium describes the end-to-end ngVLA system and is a snapshot of the facility concept technical development as of August 2019. The reference design is available on the ngVLA website.




## Community Studies

The ngVLA project strategically supported and funded three community studies in 2019 that targeted key research areas: proto-planetary disk imaging; simulations of high-redshift atomic and molecular gas; and advanced imaging techniques for sparsely sampled arrays.

## Project Outreach

In 2019, discussions were held with potential domestic and international partners to determine their ability to undertake ngVLA work packages. An inaugural international development meeting was held in Socorro in May to discuss potential partnerships and the possible distribution of ngVLA work packages. The meeting was attended by representatives from Canada, Japan, Mexico, and Taiwan.

The first ngVLA international workshop was hosted by the National Astronomical Observatory of Japan in Mitaka in September. The workshop included programmatic, scientific, and technical project overviews, but focused on Japanese scientific interests in an ngVLA-like instrument. A joint ngVLA-SKA meeting on a Future Large Radio Telescope Alliance was held in Reykjavik, Iceland in June to investigate a possible scientific alliance between SKA and ngVLA.

The ngVLA project organized a special session on the ngVLA reference design and technical development at the URSI National Radio Science Meeting in Boulder, Colorado in 2019. This provided an opportunity to demonstrate the maturity of the ngVLA project and community participation in the design process.

The special session consisted of invited talks on the reference design development and technical development activities leading up to the system conceptual design review. Half of the talks were from community collaborators, demonstrating broad participation.

A Special Session at the January 2019 AAS titled *Theoretical Advances Guided by Radio-Millimeter-Submillimeter Arrays* highlighted theoretical breakthroughs enabled by the VLA and ALMA, summarized planned VLA and ALMA improvements, discussed theoretical leaps that are likely to follow, and underscored VLA and ALMA relevance to the science themes motivating observatories that could be commissioned in the next decade. The Session included invited talks covering astrophysical jets, planet formation, astrochemistry, galaxy formation, multi-messenger astrophysics, and a poster session.

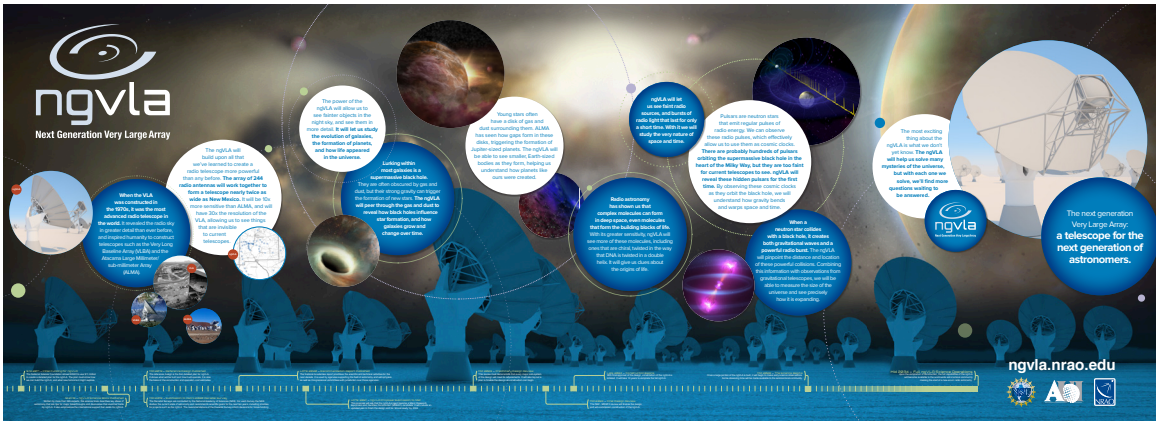



*Figure: ngVLA display at the VLA Visitor Center*

## Technical Development Projects

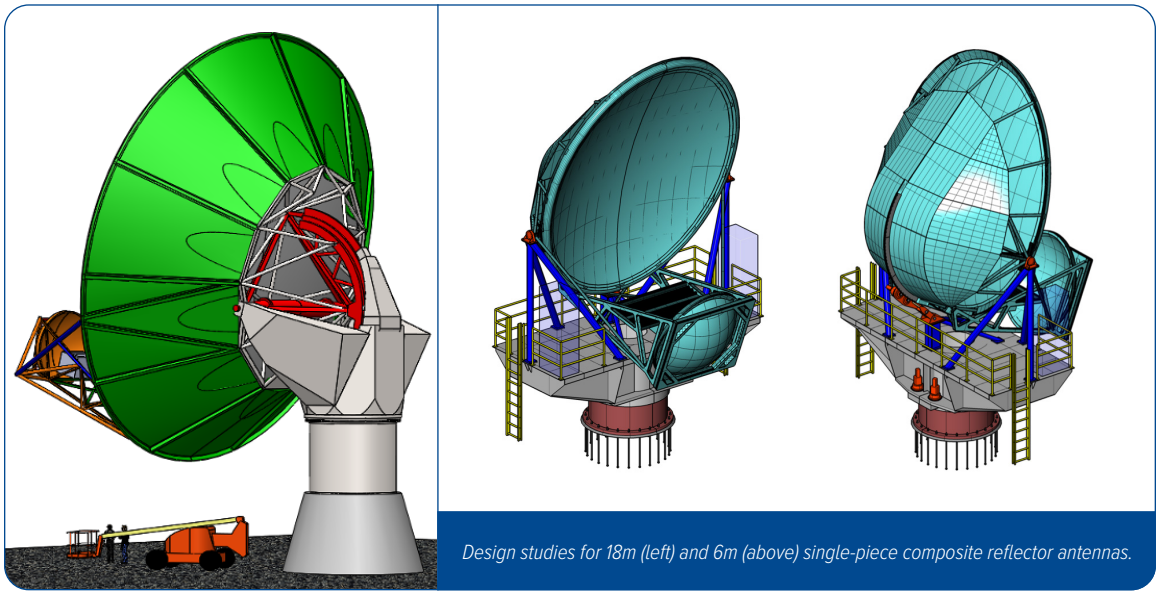
**Antenna Design:** Two antenna mechanical design studies were completed in 2019: a more traditional multi-piece aluminum reflector designed by General Dynamics Mission Systems (GDMS), as well as 18m and 6m single-piece composite reflector antennas designed by the National Research Council of Canada–Herzberg Astronomy and Astrophysics (NRC-HAA). The preliminary design reviews of the GDMS and NRC-HAA antenna concepts were completed, and the results of the studies were included in the ngVLA reference design package. Given the favorable results, technically and financially, NRAO released a request for proposal (RfP) for additional antenna mechanical design concepts. The Antenna Final Design and Prototype Request for Proposal is scheduled to be released in 2020.

**Correlator Study:** A new correlator-beamformer architecture and development plan was developed at the NRAO Central Development Laboratory in 2019.

The ngVLA project continued to conduct research and development of key enabling technologies. These focused development projects, many started in FY2018, enable NRAO to ensure that the resulting design is within budget and low technical risk. While a portion of this research and development is being conducted within the Observatory, the NRAO is also engaging the broader technical community with subcontracts for development studies and supporting intellectual property development at commercial firms and higher education institutions.

The areas selected for study were based on a risk assessment. System elements with high cost variance or technical uncertainty have been prioritized for development. Completing these studies will allow the project to assert, with confidence, that the technical risk and cost of the concepts proposed at the eventual conceptual design review are understood.

**Composite Antenna Structure:** In early 2019, NRAO and NRC-HAA completed the design review for an 18m and a 6m single-piece composite reflector antenna design study. Based on the composite reflector design results, NRAO pivoted to featuring this design as the submitted reference design concept with the traditional antenna design as supporting documentation. NRAO identified areas of the composite design that would benefit from further refinement.



*Design studies for 18m (left) and 6m (above) single-piece composite reflector antennas.*

National Research Council Canada

**Wide Angle Feed Design:** Two wide-angle axially corrugated feedhorn designs for ngVLA Band 6 (70-116 GHz) were machined, and the input match and radiation patterns were measured. One feed was directly scaled from the reference design. The other was scaled from a SKA Band 2 feed, re-analyzed, and built by ElectroMagnetic Software and Systems (EMSS) under contract. Measured results show good agreement with simulated patterns and return loss. A tolerance analysis of the EMSS-designed feed verified the volume production feasibility using conventional machining, retiring a key technical risk.

A lengthy study by EMSS quantified the degradation in sensitivity and sidelobe levels of the combined feed and antenna optics, assuming several off-axis feed locations in all three planes. The study included detailed modeling of antenna temperature using ngVLA shaped optics. The study analyzed the RF performance degradation of the antenna, using General Reflector Antenna Software Package models of the optics deformed by gravity, temperature change, and wind loading.

**Wide Band Feed Design:** To improve performance in the low frequency bands, three separate design studies were funded, the first by EMSS, the second by Commonwealth Scientific and Industrial Research Organization (CSIRO), and the third by Lyrebird Antenna Research (LAR, through CSIRO). Each study explored alternatives to the current wideband feed design. Band 2 frequencies were assumed, as it has the widest fractional bandwidth requirement, and would also be easier to prototype and test.

EMSS opted to use the all-metal quad-ridged feed design, but developed a computationally efficient optimization algorithm with parameterized analytic profiles for the horn and ridges, rather than just a numerical approach. Their design achieved a notable improvement in overall sensitivity, with a reduction in low-frequency spillover. The most useful result was their ability to better quantify some of the performance trades in an all-metal quad-ridged design.

LAR opted to pursue an alternative and novel all-metal wideband feed concept, the "bullet feed." It proved to be bandwidth-limited to slightly more than an octave, and had the drawback of complexity and higher loss in the coaxial launcher section. These factors rule it out as a viable alternative.

CSIRO explored dielectric-loaded feed designs with ~3.5:1 bandwidth. Their approach was a simplified, re-optimized version of an earlier 6:1 bandwidth ridged feed horn used on the Parkes antenna. The analysis results were impressive: aperture efficiency was almost as high and flat as the axially corrugated feed, excellent input match, much lower cross-polarization, lower spillover noise, and minimal added loss/noise from the dielectric. This design performance is very attractive.

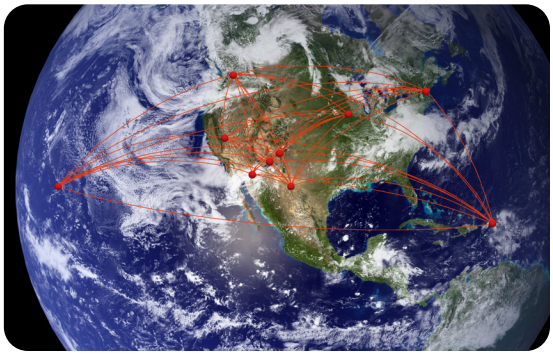
**Integrated Receiver Development:** The ngVLA antenna electronics employ a novel integrated receiver concept developed at CDL, with miniaturized downconversion, sampling, and data transmission in a lightweight, compact package mounted with the receiver dewar at the antenna secondary focus. The package offers cost, performance, and reliability advantages when compared to conventional modular designs. The concept employs Monolithic Microwave Integrated Circuit (MMIC) downconverters and other warm electronics coupled to an ASIC sampler and optical data transmission module.

The CDL has demonstrated the feasibility of this concept with discrete parts, but the technical risks are not fully retired, nor will the performance gains be proven, until the design is implemented on a silicon chip suitable for mass manufacture. The project pursued such a silicon solution in FY2018, and the ASIC chips were received in FY2019. The chips are expected to be characterized in 2020.

**WVR Development Platform:** The ALMA Water Vapor Radiometer (WVR) operating at 183 GHz allows ALMA to observe phase calibrators much less frequently, improving observing efficiency. The lower elevation VLA site will not, however, allow the operation of 183 GHz WVRs for the ngVLA, and the use of WVRs at suitable lower frequencies has not been adequately tested. In 2019, investigations were undertaken to improve understanding of 22 GHz WVR phase solutions and their limits by testing prototypes during VLA observations. A good correlation between WVR values and phase on all baselines was found. These tests will continue in 2020.

**Time and Frequency Distribution:** In 2019, the ngVLA time and frequency distribution was further refined and a deeper investigation of the requirements, interfaces, and associated risks was begun. Several areas identified for additional study included: the feasibility of long-distance fiber synchronization (>300 km), requirements and technique for synchronization at continental distance scales, and key requirements for power, stability, and integration time and frequency distribution equipment. A collaboration continued with NRC-HAA on a high-risk, high-reward incoherent clocking technique for Local Oscillator distribution. Additional collaboration was initiated with the NAOJ, as well as with industrial partners. These collaborations are envisaged as key continuing elements in optimizing the ngVLA time and frequency design, and/or lowering the cost and risk of the design.

## Very Long Baseline Array (VLBA)



The VLBA comprises ten 25-meter diameter antennas at locations ranging from Hawaii to the U.S. Virgin Islands. NRAO continued to work to increase VLBA capabilities, particularly bandwidth. The VLBA was part of the Long Baseline Observatory (LBO) through FY2018. In early FY2019, the LBO was dissolved, and the VLBA was reintegrated into NRAO.

### Science Operations

NRAO continued to offer three types of observing programs to VLBA users: General Observing (GO), Shared Risk Observing (SRO) and Resident Shared Risk Observing (RSRO). For the 2019B observing semester, 4 Gbps recording was offered as SRO (VLBA stations only), and observing with the GMVA including phased-ALMA (Cycle 7) was offered as GO. For Semester 2020A observing, 4 Gbps recording was promoted from SRO to GO, and baseband data copy and Y1 observing with a single VLA antenna were promoted from RSRO to SRO. In addition, in Semester 2020A, an option for service observing was offered, where NRAO staff provide help setting up observations, with data calibration after observing, and with imaging.

Operational tasks carried out by the scientific staff to support maintaining VLBA receiver, antenna, and array performance and ensuring that the user community had access to quality instrumentation and information are summarized below.

**Support Calls for Proposals:** Capabilities to be offered in Semesters 2019B and 2020A were defined, and user documentation for the Calls for Proposals updated. User tools required to prepare proposals, such as the Proposal Submission Tool, were carefully tested. Technical reviews were provided for proposals and evaluation of proposals for RSRO contributions.

**Documentation:** Technical documentation detailing hardware and software functionality for staff and users was written, as well as operational procedures and documentation for the operations staff. The VLBA Observational Status Summary was updated prior to each Call for Proposals.

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

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

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

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

**Global Millimeter VLBI and the High Sensitivity Array:** The VLBA occasionally observed in parallel with other observatories, as requested by users whose scientific goals require the inclusion of baselines to large aperture and/or distant facilities. Scheduling and correlation of these observations required coordination, a significantly more complex process than VLBA-only observations.

## Development

**Ongoing Development:** In late FY2017, a project was started to replace the VLBA Mark5C data recorders with more modern and maintainable Mark6 units. In 2019, the Mark6 units were deployed to all sites and the transition from Mark5C completed. Following commissioning, the 4 Gbps data rate mode was made available to astronomers under the SRO program for Semester 2019A, doubling the available bandwidth.

**New Development:** Funding for initial work on a new VLBA digital back end architecture was identified to address the end-of-life of the current VLBA digital back end system while also progressing technical capabilities of the antenna electronics. The new architecture will be more sustainable while also increasing the bandwidth it is capable of processing, increasing band pass stability, improving tuning flexibility, and providing a platform for future upgrades or use by new partners. NRAO engineering staff began development of the software and firmware architecture and code in 2019 while also performing some early end-to-end data processing demonstrations on lab hardware.

## Major Antenna & Site Maintenance

Two VLBA stations were scheduled for major maintenance visits in 2019. The participating maintenance staff consist of engineers, technicians, and VLBA site techs – Tiger Teams – that travel for multi-week visits to perform key preventive maintenance actions and corrective repairs on antennas and site infrastructure. The first 2019 campaign, for the Los Alamos (LA) VLBA station, had to be deferred. The second major 2019 maintenance visit, to Maunakea (MK), was carried out.

The Los Alamos (LA) campaign was postponed to 2020 because MK required an unexpected second visit for critical repairs after severe weather in February. Thus, the MK site was visited twice: the first addressed weather repairs and operational wear; the second dealt with regular major maintenance and the negative impact to the telescope caused by several weeks when MK could not be accessed due to protestor activity.

Maintenance staff resources were also challenged by multiple unscheduled visits to the St. Croix (SC) VLBA site to support contracted repair work to address damage caused by hurricanes Maria and Irma. Funded via a Cooperative Support Agreement for Hurricane repair (CSA-H), this work addressed the installation of a new site generator, antenna rust abatement and metalwork repair, antenna painting, and infrastructure improvements to the site fiber, road, and fencing. In the spring, a Tiger Team traveled ahead of the contracted work to decommission and prepare the antenna for rust abatement and painting. A similar team returned in the summer to recommission the antenna and return it to service.

## Technical Upgrades & Enhancements

**VLBA Site Weather Station Upgrade:** A replacement weather station system, consisting of multiple sensor packages, mounting hardware, and interface hardware, was successfully designed, integrated, and tested in the laboratory. With this milestone met, a field unit will be prepared, accepted, and delivered for use at a VLBA site in FY2020.

**Synthesizer Replacement Phase III:** Leveraging an existing design, staff built the first L404B dual synthesizer module and commissioned it on the Pie Town (PT) VLBA antenna. This synthesizer provides advanced tuning capabilities and will replace the existing synthesizers at each VLBA site via a multi-year rollout.

**Installation of Antenna E-rack:** As part of a strategic development plan for VLBA antenna electronics, a new electronics rack is being installed in each antenna. The first rack was mechanically hung and outfitted before being used for L404B commissioning in 2019.

# SCIENCE SUPPORT & RESEARCH

*Credit: NRAO/AUI/NSF; S. Dagnello*

The NRAO Science Support and Research (SSR) department coordinates and manages the efforts to support scientific users of NRAO facilities, seeks to broaden the Observatory's impact through education and visitor programs for scientists, and supports and oversees the research and scientific productivity of the scientific staff.

Telescope Time Allocation (TTA) manages the process and tools by which users prepare and submit proposals for use of the VLA, the VLBA, and the GBT. TTA also manages the proposal evaluation and time allocation process. Science Ready Data Products (SRDP) is a new initiative that is facilitating the use of NRAO telescopes by a growing scientific community that extends beyond the radio astronomy domain experts. Scientific User Support (SUS) provides the scientific community with the support necessary to execute successful scientific programs with NRAO facilities.

SSR supports and oversees the research activities of the NRAO scientific staff, related performance reviews, professional development activities, the Jansky Fellowship postdoctoral program, undergraduate and graduate student programs, and other scientific activities, such as the Jansky Lectureship, scientific meetings, colloquia, and seminars. SSR also manages Observatory-wide reference services, including the NRAO Library, the Historical Archives, and Statistics and Metrics.

## Jansky Fellows

The NRAO Jansky Fellowship program provides outstanding opportunities for research in astronomy. Jansky Fellows formulate and carry out investigations either independently or in collaboration with others within the wide framework of interests of the Observatory. The program is open each fall to candidates with interest in radio astronomy techniques, instrumentation, computation, and theory. Multi-wavelength projects leading to a synergy with NRAO instruments are encouraged. Three new Jansky Fellows joined NRAO in 2019.

Craig Anderson was a Bolton Fellow at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. Anderson has extensive experience working as a member of the core commissioning team for the Australian Square Kilometre Array Pathfinder (ASKAP), with direct responsibility for ASKAP's polarimetric capabilities. He brings a background in radiometric polarimetry to the new science capabilities afforded by the VLA Sky Survey and the VLA. He is hosted at NRAO Socorro.

Luis Henry Quiroga-Nuñez received his Ph.D. at Leiden Observatory and the Joint Institute for VLBI European Research Infrastructure Consortium, working with Huib van Langevelde and Anthony Brown. Quiroga-Nuñez has extensive experience with astrometric interferometric measurements using maser sources as tracers of the structure of our Galaxy. He brings his expertise in radiometric astrometry as a split Jansky Fellow at NRAO Socorro and the University of New Mexico working on the Bulge Asymmetries and Dynamical Evolution, Bar and Spiral Structure Legacy, and Gaia projects.

Dary Ruiz-Rodriguez was a postdoctoral and Gruber fellow at the Rochester Institute of Technology, working with Joel Kastner. Ruiz-Rodriguez has broad expertise in the panchromatic study of young binary stars and the structure and evolution of circumstellar disks. Her research utilizes the power of multispectral observations at infrared, millimeter, and x-ray wavelengths to characterize protoplanetary disks, providing the connections between planet formation and the ever-growing exoplanet population in our Galaxy. She expects to continue her study of the star and planet formation process using a variety of instruments, including ALMA and the VLA, as a Jansky Fellow at NRAO Charlottesville.

During 2019, NRAO supported the following Jansky Fellows:

| | |
|---|---|
| • Kazunori Akiyama | MIT-Haystack |
| • Nolan Denman | NRAO CDL-Charlottesville |
| • Laura Fissel | NRAO Charlottesville |
| • Adam Ginsburg | NRAO Socorro |
| • Lisa Locke | NRAO CDL-Charlottesville |
| • Ryan Loomis | NRAO Charlottesville |
| • Kunal Mooley | NRAO Socorro |
| • Brian Svoboda | NRAO Socorro |
| • Jackie Villadsen | NRAO Charlottesville |

At the conclusion of their Jansky Fellowships, Laura Fissel, Adam Ginsburg, and Jackie Villadsen moved to faculty positions at Queen's University, the University of Florida, and Saint Mary's University, respectively. Lisa Locke moved to a position with the Jet Propulsion Lab Deep Space Network.

## Telescope Time Allocation: Semester 2019B

A total of 124 new VLA proposals were received by the 1 February 2019 submission deadline for Semester 2019B, including one large and 16 time-critical, triggered proposals. The oversubscription rate by proposal number was 2.5, and the proposal pressure (hours requested over hours available) was 2.1, similar to recent semesters. A single configuration (D array) was available in the 2019B semester. A total of 27 new VLBA proposals were submitted, including two large proposals and one triggered proposal. The oversubscription rate was 2.1, and the proposal pressure was 2.3, both similar to recent semesters.

There was significant demand for the time made available on space-based observatories through inter-observatory agreements, and 14 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 nine Science Review Panels (SRPs) and for technical feasibility by NRAO staff. These reviews were completed in February-March 2019 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 24–25 April in Green Bank, West Virginia. The TAC – comprising the nine SRP chairs – was charged with recommending a science program for Semester 2019B to the Observatory Director. The recommended program was reviewed and approved on 8 May.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 16 May 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 and the VLBA 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.

The Student Observing Support program continues to be available for NRAO observing programs. Principal Investigators of highly-ranked VLA and VLBA proposals are encouraged to apply for support.

## Telescope Time Allocation: Semester 2020A

A total of 193 new VLA proposals were received by the 1 August submission deadline, including three large and 28 time-critical, triggered proposals. The oversubscription rate by proposal number was 1.9 and the proposal pressure (hours requested over hours available) was 2.0, similar to recent semesters. A total of 33 new VLBA proposals were submitted. The oversubscription rate was 1.8 and the proposal pressure was 2.3, similar to recent semesters.

There was significant demand for the time made available on space observatories through inter-observatory agreements, and 17 proposals requesting time on the Hubble Space Telescope, Swift, or XMM-Newton (together with AUI/NRAO telescope time) were submitted.

The proposals were reviewed for scientific merit by nine Science Review Panels (SRPs) and for technical feasibility by NRAO staff. These reviews were completed in August – September 2019 and then considered by the Time Allocation Committee (TAC) at a face-to-face meeting on 24-25 October in Charlottesville, Virginia. The TAC – comprising the nine SRP chairs – was charged with recommending a science program for Semester 2020A to the Observatory Director. The recommended program was reviewed and approved 7 November.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 13 November and a TAC report containing information for proposers and observers, including statistics and telescope pressure plots, was released the same day. The approved VLA and VLBA science programs were 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.

The Student Observing Support program continues to be available for NRAO observing programs. Principal Investigators of highly ranked VLA and VLBA proposals are encouraged apply for support.

## eXtra-Large Proposals (X Proposals)

NRAO, the Long Baseline Observatory, and the Green Bank Observatory jointly issued a call for submissions of Expressions of Interest (EoI) in eXtra-Large Proposals (X-Proposals) with a deadline of 31 August 2018. A total of 27 EoIs were received, demonstrating high interest in the scientific potential of such large programs on all three instruments, and covering a wide range of astronomy. Extra-Large proposals were defined as those requesting 1000+ hours of telescope time and / or extending over four or more observing semesters..

NRAO analyzed the 27 EoIs from the community for X-proposals. Based on the community response, NRAO and GBO issued a special call for X-proposals on 2 July. The deadline for X-proposal submission was 1 August, the same as for regular and large proposals in Semester 2020A.

These X-Proposals were given preliminary technical review by the NRAO scientific staff and scientific reviews by the Science Review Panels, as part of the 2020A semester process. The full scientific, technical, and operations review, and the final decision for the disposition of X-Proposals, will take place in 2020. The earliest that successful eXtra-Large projects could be scheduled is the start of Semester 2020B, in August 2020. The opportunity to submit X-Proposals will likely not be repeated for at least three years.

## Science Ready Data Products

The Science Ready Data Products (SRDP) program is designed to increase the scientific impact of NRAO's interferometers by delivering science-quality products to the user community. The primary objective for 2019 was execution of a period of pilot operations to deliver capabilities to the community and gain experience in the challenges of daily operations. SRDP continued to work closely with DMS on the design, implementation, and validation of capabilities. Significant technical debt within the NRAO Archive was addressed, preparing for accelerated capability development in subsequent waves.

The Operations Plan was developed in 2019 leading to a successful review. Pilot operations began in mid-June, providing science quality calibration for the VLA and download of calibrated data directly from the Archive. User-driven imaging of ALMA data was delayed to a mid-pilot release in early 2020. Due to this delay, and to provide uninterrupted service to the community, NRAO extended the Pilot into 2020.

The SRDP program grew in 2019 with the addition of two other Observatory initiatives. The project to replace the Telescope Time Allocation tool suite has been placed under SRDP management. Based on the concept defined by the TTA team, a detailed system description and architectural concept are currently under development. Additionally, operations of the VLA Sky Survey was reorganized as a joint deliverable of SRDP and New Mexico Operations with SRDP responsible for overall project delivery.

## Robert L. Brown Award

The 2018 Robert L. Brown Outstanding Doctoral Dissertation Award was awarded to Dr. Erin Cox for her dissertation entitled *Probing Planetary Disks: from Birth to Protoplanets*. Her thesis was selected for its clear objectives and thoughtful observational approach. Her insights and conclusions make original and significant contributions to our understanding of the early protostellar cloud collapse process from which the planets are forming. The extensive set of new observations and her interpretation provide realistic glimpses into the density and magnetic structures, kinematics, and available energy budgets on resolution scales of a few tens of AU that will guide future magnetohydrodynamic simulations of the conditions under which planets of various masses and orbital radii are likely to form in nascent protostellar cloud complexes. The award was presented during a ceremony held at NRAO on 21 March.

*Dr. Erin Cox*

Erin received her Ph.D. in 2018 in Astronomy from the University of Illinois and her B.S. in Astronomy and Physics from the University of Arizona in 2012. After finishing her Ph.D., Dr. Cox took a Postdoctoral Associate position at the Northwestern University Center for Interdisciplinary Exploration and Research in Astrophysics, where she is continuing her studies of star and planet formation focusing on how magnetic fields influence the earliest stages of protostellar collapse and how this affects disk formation.

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

## Jansky Lectureship Awarded to Professor Anneila Sargent

AUI and NRAO awarded the 2019 Karl G. Jansky Lectureship to Professor Anneila Sargent, Ira S. Bowen Professor of Astronomy, Emeritus, at the California Institute of Technology (Caltech). The Jansky Lectureship is an honor established by the trustees of AUI to recognize outstanding contributions to the advancement of radio astronomy.

Professor Sargent was honored for her pioneering, and continuing, studies of young stars and the dusty disks that surround them, disks from which planets form. In addition, she has been a leader in the astronomical community, serving on important boards and committees and in offices for scientific organizations, while also helping shape the careers of younger astronomers and standing out as an inspiring role model for female scientists.

A member of the U.S. National Science Board and a Fellow of the American Academy of Arts and Sciences, Professor Sargent is a past president of the American Astronomical Society. She chaired the NASA Space Science Advisory Committee and the U.S. National Research Council Board of Physics and Astronomy, and served on the U.K. Science and Technology Facilities Council.

A native of Scotland, Professor Sargent earned her B.Sc. at the University of Edinburgh and her Ph.D. from Caltech, where she has spent her career. She was Caltech's Vice President for Student Affairs from 2007 to 2015.

Professor Sargent has led in the development of important radio observatories, serving as director of Caltech's Owens Valley Radio Observatory, and as founding director of the Combined Array for Millimeter-wave Astronomy, the U.S. precursor to the international Atacama Large Millimeter/submillimeter Array (ALMA). She served on the ALMA board for a decade and chaired it twice.

As Jansky Lecturer, Sargent gave public lectures at NRAO facilities in Charlottesville, Virginia, and Socorro, New Mexico.

## From the Archives

Installing the traveling feed system on the 300-foot Telescope in Green Bank in September 1969. An article in *The Observer* for November 1969, written by Troy Henderson and Ken Cottrell states: "Following the discovery of pulsars, in mid-1968 a visiting research group from Harvard made the proposal for a second traveling feed system, specifically for pulsar research. A joint arrangement for design and construction was worked out, and fabrication began at the NRAO shops on 1 November 1968. The feed assembly consists of a set of rails and a feed carriage which is driven along the rails at various rates. The rails are 51 feet long allowing for 46 feet of carriage travel between limits."

# DATA MANAGEMENT AND SOFTWARE

The Data Management and Software (DMS) department made key contributions to the NRAO throughout 2019. DMS deliveries have been vital for the Science Ready Data Products (SRDP) capabilities. DMS delivered components for the Very Large Array Sky Survey (VLASS) workflow, including image retrieval from the new archive and implementation of the pipeline heuristics for the remaining VLASS basic data products. New observing capabilities were implemented and supported for ALMA, VLA, and the VLBA. A stable computing platform for internal and external users was maintained and expanded. DMS contributed to the overall ngVLA project, including important portions of the Decadal Survey package.

## Scientific Information Services

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

**Computing Operations:** These site-centric groups directly support the day-to-day telescope operations and reliable data delivery to the archive and the community. The team ensures that telescope capability development projects are appropriately staffed, with resources assigned based on commitments and timelines defined within the Program Management Department (PMD) and at the relevant site.

Projects and milestones for these resources are tracked under the appropriate telescope support sections. Attention is given to support for infrastructure needed by the CASA pipeline development for use by the Joint ALMA Observatory (JAO) and ALMA Regional Centers, as well as the VLA and observer support. The successful delivery of a Red Hat Enterprise Linux (RHEL) 7 OS image for all new system installations was a focus. The adoption of Ansible has improved the deployment of key web servers, and rigorous Configuration Control now supports OS and package deployment used by DMS, SRDP, and JAO for coordination of development, testing, and release cycles.

The NAASC, in conjunction with JAO, upgraded the virtual servers for Oracle Virtual Machines (VM) to better support the database containing the metadata for ALMA archive data stored in the Next Generation Archive System (NGAS). To keep up with archive growth and consolidate aging storage, the sites migrated NGAS to higher density storage and completed the evaluation of long-term storage solutions, in-house and cloud-based. As a result, 2.2 PBytes of persistent storage was installed in Charlottesville, and 500 TBytes in New Mexico. Several refresh projects for the VLA core infrastructure were initiated in 2019, including the purchase of the new Correlator Back End cluster and core network replacement for the VLA.

**Science Computing Group (SCG):** This group provides technology-driven scientific computing support, and is tasked with delivering the next generation of data processing solutions, working in close cooperation with the DMS software division, telescope operations, and external cyberinfrastructure partners. This group is also responsible for hardware and software performance profiling and evaluations, as well as assisting with critical escalations from Operations in the event of systematic performance issues with the production infrastructure. SCG worked closely with NM Ops and Software to ensure efficient data processing of VLASS products and for SRDP Wave 1 Operational readiness. The SCG optimized the Moab cluster scheduler to allow for multiple concurrent tasks on a single system in support of batch and interactive resource requests. This group worked closely with the CASA software developers to improve performance with particular focus on memory utilization and the evaluation of non-volatile memory sub-systems. A collaboration was initiated with the University of Wisconsin Center for High Throughput Computing (CHTC) to facilitate external processing capacity for VLASS. Particular relevance is seen in adopting the HTCondor workload management system which has been used to advantage enabling high throughput, distributed computing for key science projects such as the Large Hadron Collider and multiple Grid based services. This joint venture will continue in 2020.

**Wide-Area Networking:** This science data-driven group is responsible for provisioning the long-haul, high-bandwidth, connectivity needed to uplink the telescopes and then deliver reliable throughput in support of Principal Investigator and general data access. Operational support for commodity circuits will be handed off to Communication Services in CIS once a network service has been accepted into production. The main initiative for this team was the installation of fiber optic infrastructure to an additional three VLBA sites in 2019 and the upgrade of system area networks.

## ALMA System Software

The ALMA software group spent ~50% of its time fixing bugs, addressing all high-impact bugs at high priority. All subsystems groups continued to address software maintenance issues, such as transitioning to C++11, updating Java, tracking new versions of the ALMA Common Software (ACS) and third-party libraries, and overall code refactoring to make further changes simpler. The online ALMA software group also addressed the highest priority items from the Cycle 7-8+ ObsMode planning process.

**ALMA Control Subsystem–Optimizing Observing:** Operational array efficiency can be improved by scheduling observations based on atmospheric conditions. The control subsystem group developed a component that takes water vapor radiometer data and telescope calibration results and produces products to optimize telescope scheduling. These products include highest recommended observing frequency based on phase stability, optimum phase calibration cycle time, and estimated spectral window average sky brightness variability. The first version of the observing conditions software was delivered in 2018 as part of the Cycle 6 software. The algorithms and implementation continued to be refined in 2019 as a result of on-sky testing and use in day-to-day operations and were included in the Cycle 7 software.

**ALMA Control Subsystem–Supporting Development Projects:** Numerous ALMA projects are underway, including the second-generation ALMA Phasing Project (APP2), the ACA Spectrometer, and the Hardware-in-the-Loop Simulator (HiLS). These projects, which will provide new features and functionality to the ALMA telescope, need support from the control subsystem group. The APP2 project was supported during 2019 for Cycle 6 missions.

**ALMA Baseline Correlator Subsystem–Correlator Upgrade Project:** Funding for the Correlator Upgrade Project (CUP) was approved in FY2018, successfully passing a Preliminary Design Review, but was cancelled in 2019. However, other related and supporting projects continued and are anticipated to deliver useful capabilities in later years. During 2019, support was provided for a fifth quadrant hardware implementation at the Central Development Lab. This will be eventually used by the HiLS at the ALMA Operations Support Facility in northern Chile, which will be crucial integration activities. Options were considered to facilitate higher data rates through the network to ultimately allow higher data-rate observing.

**ALMA Baseline Correlator Subsystem–4x4 Correlator Modes:** The implementation of 4x4-bit correlator modes was delivered in 2019 to increase quantization efficiency for a subset of the Cycle 7 correlator modes. An increase from 88% to 93% will be observed after the 3-bit digitizer quantization for those specific correlator modes. These changes are limited to the online software, i.e., the Correlator and Telescope Calibration subsystems and various observing tools, as there are no firmware changes expected.

**ALMA Scheduling Subsystem–Improving Observing Efficiency:** The focus of the Scheduling software group for 2019 was the dynamic scheduling algorithm (DSACore) optimization. This effort continued throughout the year as the Observatory constantly modified its capabilities, resulting in continually evolving constraints for the DSACore. The result of the optimizations of DSACore were improvements to the observing efficiency.

**ALMA Scheduling Subsystem–Technology Improvements:** The infrastructure in the scheduling subsystem has improved significantly over the past few years to solve performance issues. Until 2019, it was still based on to-be-deprecated or unsupported

*Photo: ESO/José Francisco Salgado (josefrancisco.org)*

technologies, which would become a software maintenance problem in the future years. Over 2019, the outdated technology was largely updated with alternative solutions or modern versions, mainly for Python and Java-based software.

Changes to the technology included changes at local-design level of the software. The technology improvements allowed for improvements in the software packaging, leading to improvements to the current simulation framework. The eventual result will be accelerating the algorithm optimization tasks towards better forecasting for the mid-term scheduling, including Observatory and ALMA Proposal Review Committee activities.

## Science Data Model

The Science Data Model (SDM), the metadata that describes a given observation, is shared between three major stakeholders: ALMA, the VLA, and CASA. The data model is maintained by the software group at NRAO. The SDM code base was improved to support CASA 6.0, Java 11 compatibility, and improvements to the build system. In addition, stakeholders have requested improvements to the data model itself which were implemented in 2019.

## VLA System Software

The responsibilities of this group involve 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 PI observing for Semesters 2018B and 2019A were made. In addition, software was incrementally made available for commissioning new 2019A and 2019B capabilities. This group also supported VLBA System Software.

**New or augmented VLA capabilities in 2019 included:**

- Supporting transition of Frequency Averaging to GO.
- Supporting the transitioning of YUPPI-mode pulsar observing to SRO.
- Supporting wind prediction in the OST.
- Supporting Conditional SBs in OST/OPT.
- Supporting testing RFI excision in the VLA correlator.

Transitioning the YUPPI-mode pulsar observing required OPT development. Support was provided as required for major VLA projects including realfast (fast transient detection), VLASS, and ngVLA.

## VLBA System Development

VLBA commissioning and observing support followed the same deployment cycles as the VLA. Support was provided for the Mark6 deployment and Resident Shared Risk Observing (RSRO). The VLBA Versa Model Eurocard (VME) hardware was mostly (8 of 10 stations) replaced in 2019 with a general computer based NoVME solution. Support for the NoVME transition continued in 2019 and will continue into 2020.

## Software Development

**Common Astronomy Software Applications (CASA)**

Development of the Common Astronomy Software Applications (CASA) package, the NRAO post-processing software, continues to emphasize support for the VLA and ALMA, unlocking the scientific potential of these world-leading telescopes. During 2019, NRAO continued to add capabilities and support the evolving understanding of the requirements of these forefront telescopes.

CASA version 5.5 was released to the community, providing initial support for ALMA Cycle 7, functionality needed by the Cycle 7 pipeline, and improvements for VLASS. Focus was continued on maintenance and removal of older functionality superseded by newer task implementations. There was also a renewed emphasis placed on verification testing; CASA 5.5 was the first release with documented specifications/requirements mapped directly to automated verification tests.

CASA 6 will be a major upgrade to the CASA environment, providing a modularized industry-standard representation of CASA that is Python 3.6 compliant. The change is motivated by a need to move to the new Python version, since Python 2.7 support will end in 2020, and by a need to make CASA more useful to a wider audience. CASA 6.0 has the same science content as version 5.5, and was released in beta in 2019 followed by a full release, including a monolithic version for the pipeline. Aligned 5.x and 6.x versions of CASA with the same science content will be released in 2020 and maintained for one year to allow time for users to test and migrate to the new version.

CASA 5.6 included improvements to the ALMA and VLA pipelines for Cycle 7 and for VLASS. This includes relative frequency-dependent interpolation when applying bandpass tables, small scale bias parameter control for the multi-scale multi-frequency synthesis deconvolver, auto-multithresholding on polarization data, and atmospheric and sky temperature curves in the *plotms* task.

In all releases, DMS continued to address stability and robustness issues, as well as technical debt in the calibration and imaging subsystems. The system engineering processes were reviewed and adjusted through a continuous improvement approach.

Input from the CASA Users Committee will continue to help guide CASA development choices. This feedback will be incorporated in development plans as time and resources allow. The committee has stressed the importance of reliable, well-documented code and the capture of user feedback for decision making.

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

Work on the Cube Analysis and Rendering Tool for Astronomy (CARTA) visualization software continued through the collaboration with ASIAA CASA Development Center and the South African Institute for Data Intensive Astronomy improving the user interface and expanding capabilities.

Additional collaborations are extending CASA use and capabilities. The Australia Telescope Compact Array and the Giant Metrewave Radio Telescope support CASA for reduction of their data products. This includes making a staff member available via the NRAO helpdesk to answer questions specific to these telescopes. The Joint Institute for VLBI in Europe (JIVE) added tasks to enable CASA for VLBI data.

NRAO concluded an initiative with the Square Kilometre Array (SKA) to jointly investigate the definition of a next iteration of the CASA Measurement Set Version 3 (MSV3). This was a first step in updating the underpinnings of CASA, in particular the casacore package, parts of which are 25 years old. This is important pathfinder work in the general refurbishment of CASA to ensure that it remains capable of filling VLA and ALMA needs, and can evolve for the ngVLA. In 2019, MSV3 delivered the logical schema for the new format as well as a test report showing how the casacore table data system performance could meet the needs of expected future I/O demands.

Building on the MSV3 results, work continued on CASA revitalization, initially with analysis and refactoring of casacore and its interfaces. Two trade studies were conducted. The first explored modern developments in software engineering with respect to high-performance scalable computing and data analysis, leading to the selection of a candidate programming paradigm and languages. The second focused on identifying which off-the-shelf frameworks were available to satisfy the selected paradigm. An external consultant was engaged in cooperation with PMD and a plan was developed for long-term CASA scalability.

The CASA pipeline continued to evolve to support ALMA, VLA operations, and VLASS. A major release was delivered coinciding with ALMA Cycle 6. This included parallel processing capabilities, processing of limited heterogeneous arrays, and initial ephemeris capabilities. A subsequent pipeline update provided Cycle 7 capabilities. Work proceeded on VLASS single epoch calibration and imaging, with initial SE processing started in 2019 and requirements and development work continuing on more difficult cases into 2020.

CASA and the pipeline began to work with SRDP as an additional stakeholder. SRDP continues to develop requirements that will help drive future development.

## Science Support & Archive

**New Archive:** Work on the new archive continued in 2019, driven by SRDP requirements. New capabilities were deployed as part of SRDP, but the transition of some of the old archive's existing capabilities was delayed. These will be integrated into the new archive and become the default in 2020.

**Observing Support:** The OPT, PST, and PHT were updated to support VLA observing, with the PST updated for the Semester 2019B and 2020A Calls for Proposals, the OPT updated for Semester 2019A and 2019B observing, and the PHT updated for the Semester 2019B and 2020A TAC process.

**PST Upgrade:** The NRAO Users Committee has recommended that the PST be prioritized over the OPT for significant upgrades. DMS and SSR determined the requirements for the new tool software. Based on those requirements, conceptual architecture development for a revised TTA toolset began.

**YUPPI-mode Pulsar Observing:** The software changes for observers to configure VLA phased array pulsar processing (YUPPI) using the standard OPT interfaces were delivered for Shared Risk Observing.

**Science Ready Data Products (SRDP):** The SRDP project received substantial coordinated effort across DMS. For the first development wave, much of the effort was centered on the Archive and Workflow Manager with additional deliverables provided by CASA. Archive deliverables included the ability to restore data sets for ALMA and VLA, to store, search, and retrieve images for these telescopes, and to allow PIs to change a small number of parameters for image reprocessing using a graphical interface. An improved software deployment process for SRDP, including a dedicated testing environment, was also developed.

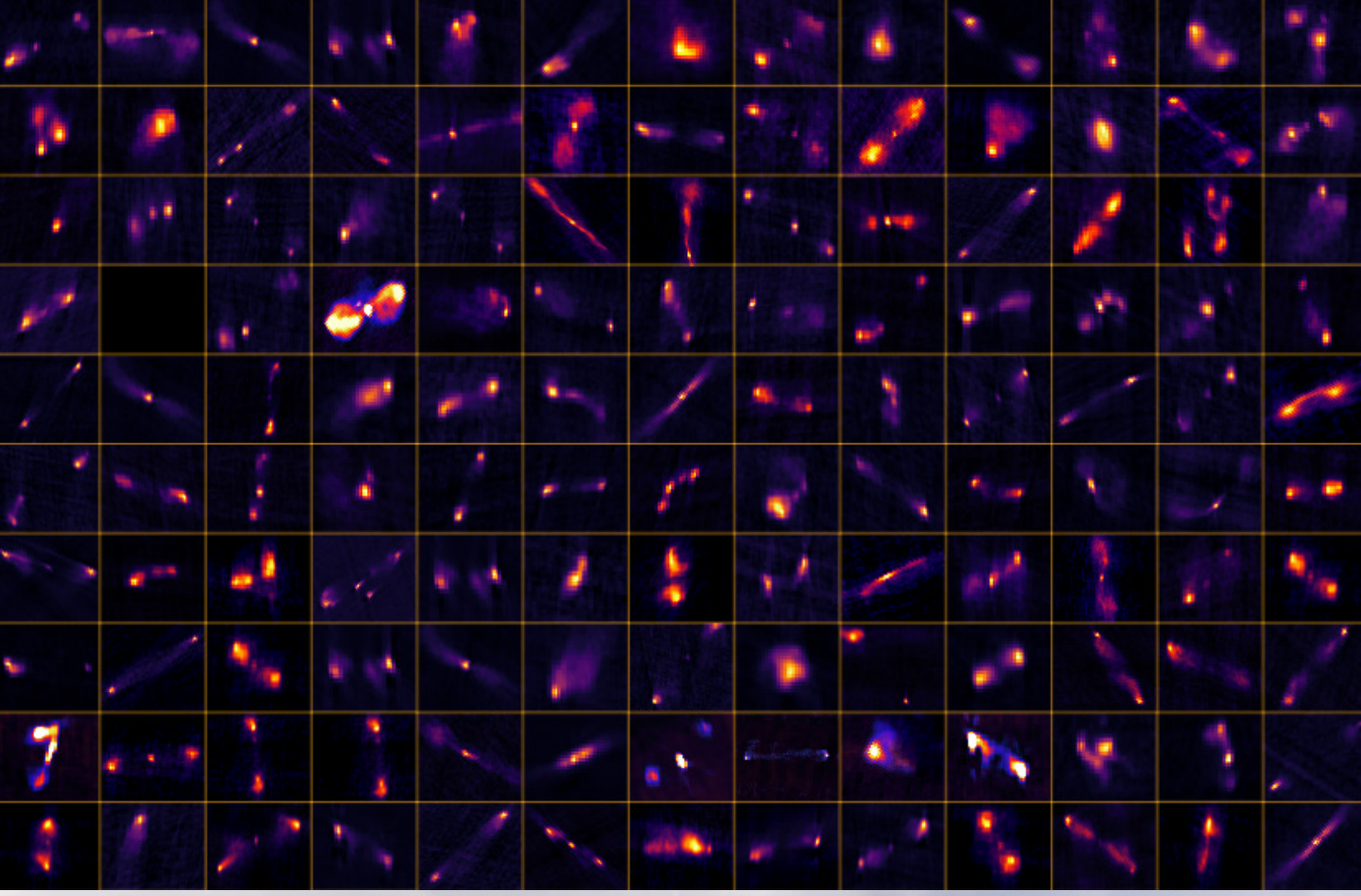
## Algorithm Research & Development

**Algorithm for Joint Single Dish-Interferometric Imaging:** An optimal wide-band algorithm was defined to combine single dish and interferometric data for accurate image reconstruction and spectral index mapping at all measured scales. Inputs from outside the Algorithm Research and Development Group were evaluated to arrive at an optimal CASA implementation. A memo and sample implementation were delivered in 2019. Additional effort will be required to integrate the algorithm in CASA.

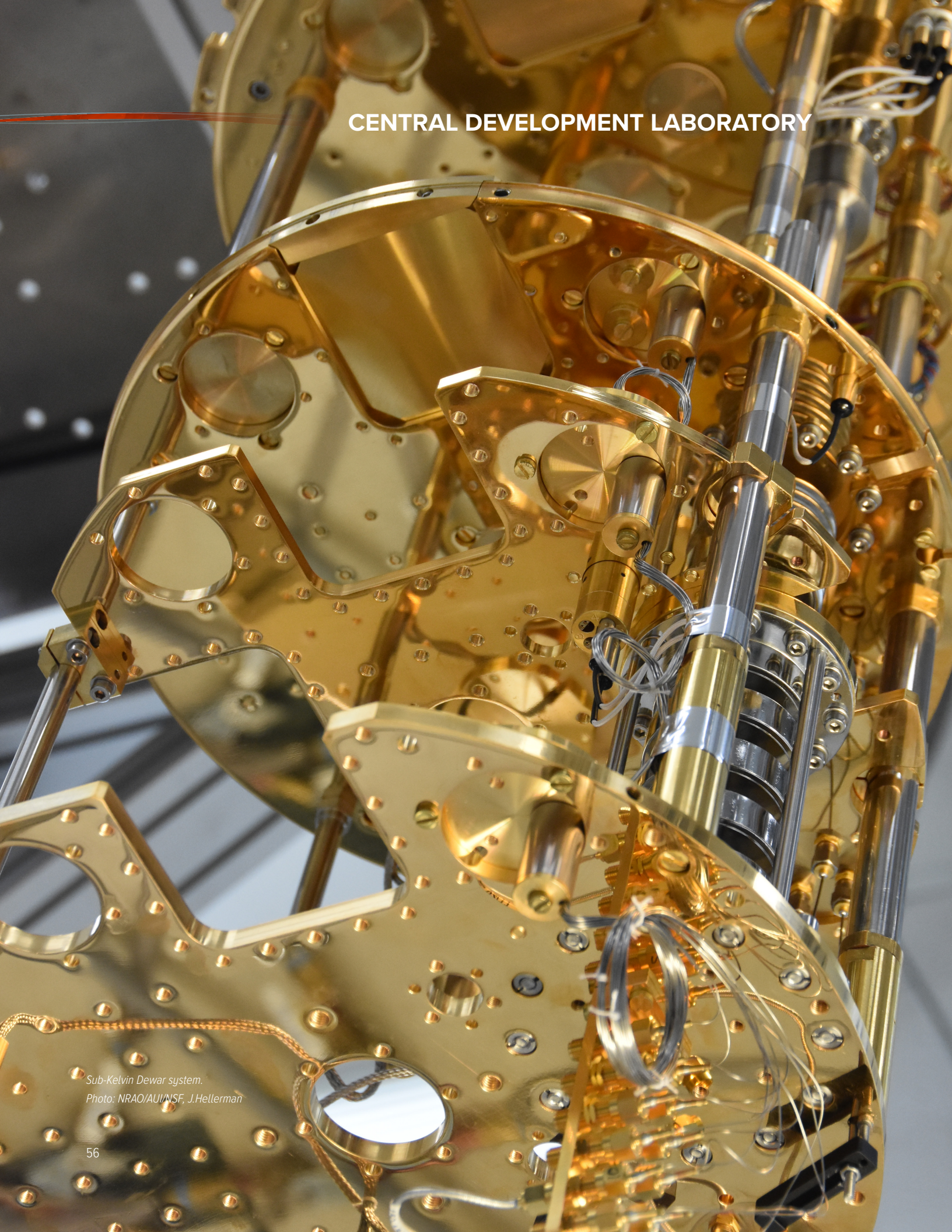
**Wide-Field Full-Mueller Imaging Algorithm:** This R&D task will commission the Full-Mueller imaging algorithm to enable wide-field, wide-band full-Stokes imaging with VLA and ALMA. This work requires code implementation, scientific verification with simulated and real data, and documentation (software design, scientific test results). The priority for this task was lowered in favor of AW-Project algorithm commissioning work required for VLASS. The infrastructure code for this task has been implemented. Work for scientific verification with simulated and real data and delivery of the associated memo is still in progress. Completion is anticipated in 2020.

**AW-Project Algorithm:** This task characterized and commissioned the AW-Project algorithm for wide-field, wide-band imaging, first for the VLA. This work was a precursor for the Full-Mueller imaging work above. The evaluation was concluded and was followed by implementation in CASA 5.6 in 2019.

**Heterogeneous antenna pointing correction in AW-Project:** Due to a critical VLASS need, the existing framework used for mosaic imaging was extended to include corrections for antenna pointing errors. The implementation is integrated with the AW-Projection framework in CASA and delivered for the user via the *tclean* task. It can be tuned via user parameters for the full range of use cases, from treating the array as homogeneous to fully heterogeneous in antenna pointing errors. Algorithm Research and Development Group scientific verification and regression testing was completed.



# CENTRAL DEVELOPMENT LABORATORY



*Sub-Kelvin Dewar system.*
*Photo: NRAO/AUI/NSF, J.Hellerman*

The Central Development Laboratory (CDL) mission supports the evolution of NRAO facilities by developing the technologies and expertise critical for the next generation of radio astronomy instrumentation. CDL-developed technology is integral to all NRAO-operated telescopes and to other radio telescopes around the world. Thus, CDL also provides maintenance and upgrades to these instruments.

CDL maintains a staff of ~50 personnel organized into teams of engineers and technicians working across crucial radio telescope technologies, including: digital design and signal processing; low noise amplifiers; millimeter and submillimeter detectors; optics and electromagnetic components; and new receiver architectures. The lab is the world leader in the application of many of these technologies to radio astronomy. In service to this mission, CDL also supports the greater NRAO mission of developing the next generation of instrumentation engineers and scientists by:

- Hosting Jansky post-doctoral instrumentation engineers and scientists,
- Advising, mentoring, and employing undergraduate and graduate engineering and astronomy students, and
- Participating in undergraduate and graduate co-operative engineering programs.

While NRAO continued to operate the world's most powerful and unique radio interferometers and, in collaboration with the U.S. radio astronomy community at-large, planned and developed an engineering design for a next generation Very Large Array (ngVLA), CDL actively supported this process throughout 2019 by participating in several Integrated Product Teams.

Additionally, CDL continued to engage in cross-Observatory repair, maintenance, support, and in several programmatic and work-for-other construction projects, all while carrying out design and development of technologies for future instrumentation, especially ngVLA. In addition, CDL continued investigating new and emerging technologies that have the potential to advance the state-of-the-art in instrumentation. The cornerstone of this work was focused on the superconducting Traveling Wave Kinetic Inductance Parametric Amplifier (TKIP), which will continue in 2020. CDL will also form partnerships with other research institutions working on 3D printing/additive manufacturing techniques that could lead to devices applicable to radio astronomy instrumentation.

**Four CDL proposals received funding for ALMA Cycle 7 development studies:**

- Ubiquitous Quantum-Limited Wideband 4-Kelvin Amplifiers for Radio Astronomy (Noroozian et al.);
- Investigation into improvement of Front End Local Oscillator sideband noise for ALMA Band 6 (Saini et al.);
- Band 6v2 SIS mixer development (Kerr et al.); and
- ALMA Central LO Improvements and Upgrades (Jacques et al.).

## Repair, Maintenance, Production & Support

The 2019 CDL core repair, maintenance, production, and support activities are described below.

**Low Noise Amplifiers (LNAs):** The CDL Amplifier Group continued to produce replacement low noise amplifiers (LNAs) and/or repair amplifiers for the VLA, VLBA, GBO, and ALMA telescopes. Several amplifiers were repaired in 2019, and more units are in the repair queue.

Amplifier production via the contract to manufacture 160 amplifiers for ALMA Band 1 cartridges continued during 2019. Thirty-six Band 1 amplifiers were built and accepted by ASIAA. Another 12 Band 1 amplifiers have been submitted for acceptance review. This multi-year project will continue into 2020. During this period, Diramics High Electron Mobility Transistors (HEMT) were successfully qualified in ALMA Band 1 amplifiers as an alternative for Cryo 3 devices.

These newly available, commercial transistors from Diramics were also proven to have equivalent performance when used in Band 6 IF preamplifiers (4–12 GHz) compared to the original Cryo-3 transistors (no longer available since the wafer is depleted) successfully providing a solution to the Cryo-3 dielectric cavity resonance issues in the original design. These preamplifiers were integrated into the mixer-preamplifier assemblies, which were subsequently qualified to be compliant with requirements.

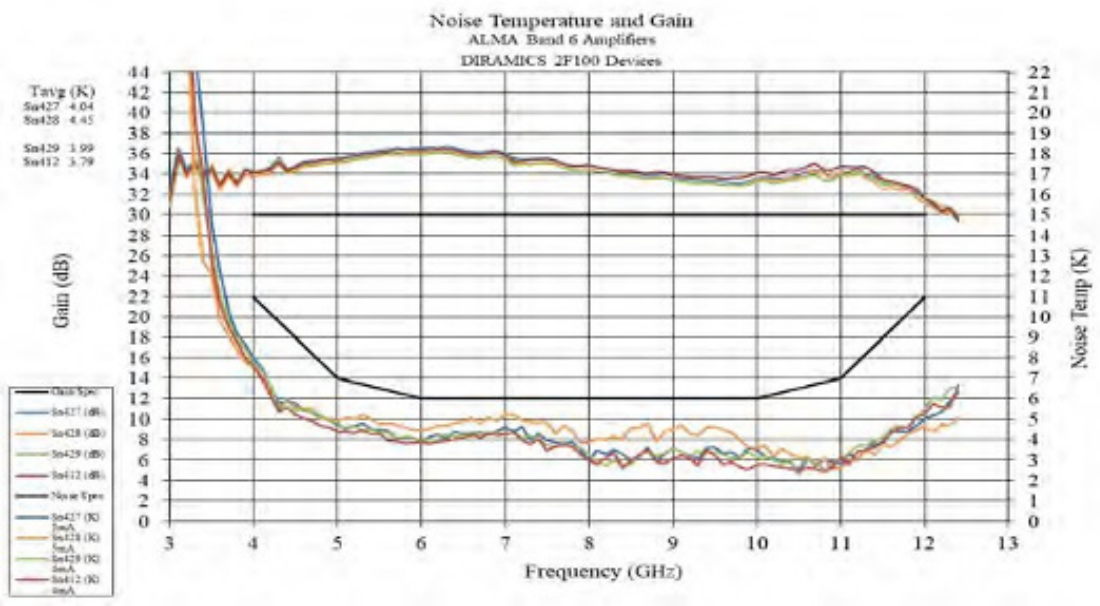



*Figure: Performance of four ALMA Band 6 IF preamplifiers based on the commercial Diramics HEMTs. Note the excellent gain repeatability, which is essential for good image rejection when used in 2SB configured mixer-preamplifiers.*

**Millimeter and Submillimeter Receivers:** During 2019, CDL continued to support offsite maintenance of the ALMA Band 6 receivers built by NRAO, maintaining a sufficient quantity of spare mixers and preamplifiers. CDL also supported community projects, such as the Large Millimeter Telescope (University of Massachusetts), Arizona Radio Observatory, the South Pole Telescope, the Taiwanese Greenland Telescope (a Vertex ALMA prototype antenna), and outfitting millimeter/submillimeter telescopes for Very Long Baseline Interferometry. With the exception of ALMA support, these activities were outside the Observatory's NSF award and carried out as Work For Others, undertaken only when not interfering with work for the NSF.

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. During 2019, the problem of oscillations with alternate strategy of using Low Noise Factory (LNF) preamplifiers (devised and qualified in the prior fiscal year) came to light. A method was developed for stabilizing the LNF IF amplifiers when operating with SIS mixers with high IF output impedance, and mixer-preamplifiers assembled and tested with this modification. Mixer- preamplifiers were also built using chip-and-wire amplifiers built using commercial Diramics devices and qualified for use in Band 6 cartridge repair work. To help expedited acceptance testing of Band 6 cartridges, second cartridge test setup was resurrected and prepared for use during this period.

**Integrated Receiver Development:** The Integrated Receiver Development (IRD) group continued to support and nurture NRAO-heritage telescopes such as the VLA and VLBA by providing construction and repair services on the multi-chip modules used in those facilities.

**ALMA Offsite Hardware Support:** The CDL offsite hardware support team provided extensive support to ALMA operations during 2019, including diagnosis consultancy, on-site visits, software and firmware support, and repair and return of malfunctioning Line Replaceable Unit (LRU) hardware. In all, 28 Front End LRUs (including receiver cartridges), 58 Warm Cartridge Assembly LRUs, and 31 Back End Local Oscillator and Photonics LRUs were returned to the ALMA site after repairs. LRUs repaired in 2019 included: Band 6 cold cartridge assemblies, Front End (FE) bias modules, FE Monitor & Control (M&C) modules, warm cartridge/local oscillator assemblies at various bands, Line Length Correctors, and Local Oscillator Photonic Receivers. Lower level hardware repair was carried out on 161 sub-assemblies. Hardware for the FE Test & Measurement Systems including the IF processor modules and tilt tables were also repaired/replaced during 2019. A new batch of Cartridge Power Distribution System M&C boards were fabricated as spares.

**Work For Others:** CDL teams worked on the following WFO projects to deliver the requested hardware and/or services to the larger radio astronomy community:

- ALMA Band 1 Cryogenic Amplifiers for NAOJ/ASIAA (48x);
- ALMA Band 1 FE Local Oscillator assemblies for ASIAA (20x);
- ALMA style Band 6 horn, Ortho Mode Transducer (OMT), and mixer-preamplifier sets (2x) for East Asia Observatory;
- Band 9 Active Multiplier Chain (ALMA design) repair for the Netherlands Research School for Astronomy;
- W-Band cryogenic Isolator evaluation for Micro Harmonics Corporation; and
- Reflectionless filter technical support (and design work) for Mini-Circuits Inc.

A collaboration was launched with Mini-Circuits Inc. to develop transmission-line reflectionless filters at millimeter-wave frequencies. CDL also constructed and delivered five compact water vapor radiometers for the ngVLA.

## Research and Development

CDL Research and Development (R&D) efforts were aimed at supporting these strategic goals:

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

**Low Noise Amplifiers:** During 2019, the CDL collaboration with Jet Propulsion Laboratory Deep Space Network (JPL/DSN) continued under a memorandum of understanding, and information on models and measured results of X- and Ka-band amplifiers was exchanged.

In addition to qualifying commercial Diramics transistors for ALMA Band 6 preamplifiers, design modifications to the ALMA Band 6 mixer-IF preamplifiers coupling circuit were studied and implemented to achieve flatter noise temperature versus IF.

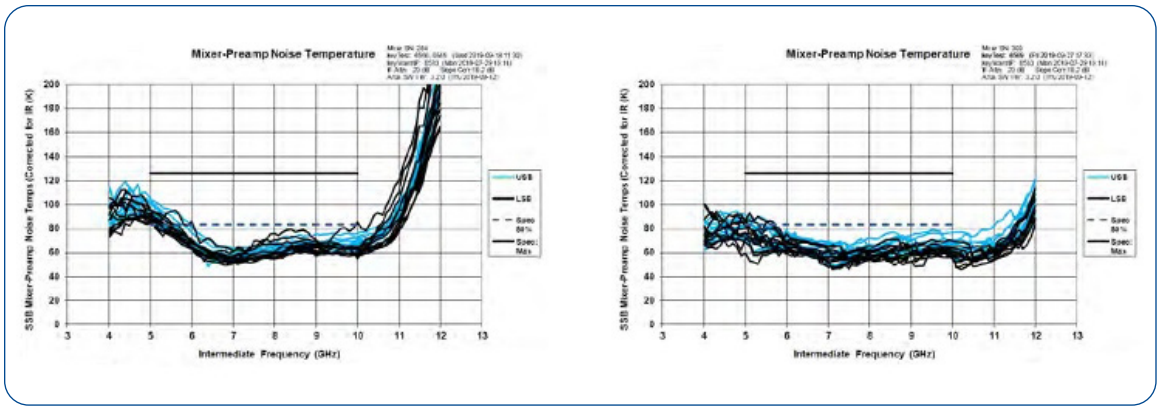



*Figure: Comparison of the noise temperature of mixer-preamplifiers with the original coupling circuit (left) and those with the reoptimized coupling circuit (right). Both preamplifiers used commercial Diramics transistor devices.*

**Millimeter and Submillimeter Detectors:** In 2019, CDL and the University of Virginia Microfabrication Lab (UVML) continued to develop technology for the next generation of ALMA receivers, including a new generation of SIS mixers and development of ALMA-compatible TKIP amplifiers.

A Conceptual Design Review (CoDR) for the ALMA Band 6 receiver upgrade was held, following which, a Cycle 7 study proposal was submitted for the development of wideband SIS mixers for an expanded Band 6 (211-280 GHz) with Nb/AlN/Nb and Nb/AlOx/Nb junctions. Also, to incorporate the recommendations from the CoDR, a request for modifying the existing balanced amplifier study was submitted to incorporate the following elements:

- Complete the development of the 4–12 GHz balanced IF amplifier based on superconducting hybrids.
- Investigate extending the balanced amplifiers design for 4–16 GHz operation.
- Evaluate IF amplifiers using a ferrite isolator and compare cost effectiveness with balanced amplifiers.

These proposals were successful.

TKIP amplifiers developed in recent years at Caltech with quantum computing applications hold great potential for 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 characteristics. 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 ALMA SIS receiver (Bands 3 to 10), TKIP amplifiers would result in a reduction of receiver noise temperature of ~10-15K. Receiver noise temperatures are now 30-50K in ALMA Bands 3–6. Thus, TKIP technology may offer a major improvement in sensitivity.

As this is a relatively new field of development at CDL, equipment and instrumentation were procured and installed to enable this work. A microwave (IF) testbed was developed and calibrated down to 10 mK, and was used to test a first item TKIP device fabricated at JPL. Initial evaluation of JPL TKIP devices at elevated temperatures of up to 5 K occurred during 2019.

The ALMA Development Cycle 5 TKIP study was completed, and a new Cycle 7 study proposal was submitted. The proposal was successful and ensures continuation of this work in 2020.

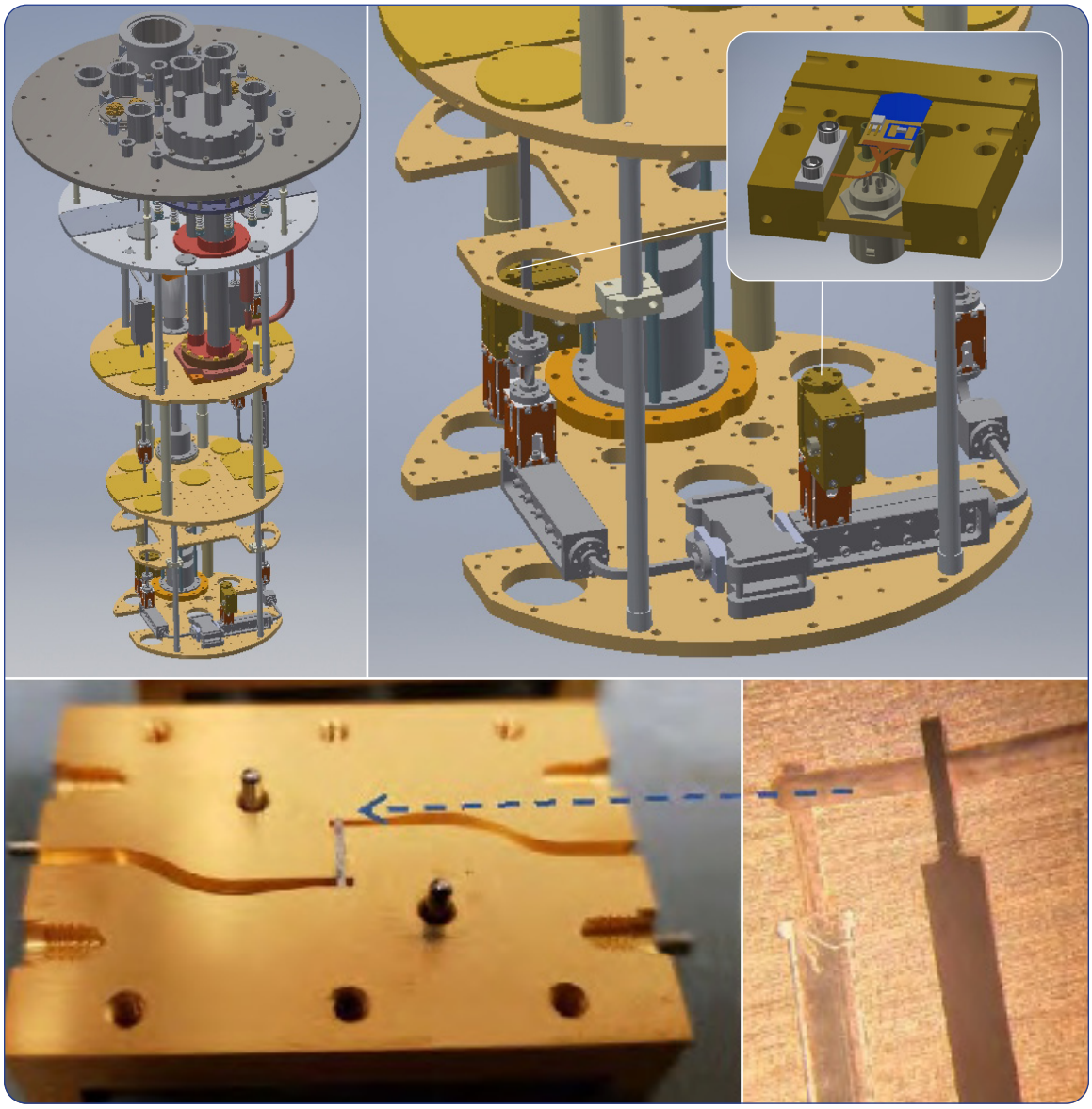


*Figure (Top): Waveguide testbed for noise and gain measurement was designed for W-band (65-115 GHz) testing at CDL. (Bottom) Chip and packaging for a 65–150 GHz TKIP amplifier with a zoom-in of the waveguide-to-chip transition area.*

**Optics and Electromagnetic Components:** In 2019, analysis was performed on the reference design of the ngVLA antenna to optimize the antenna efficiency and temperature to arrive at an optimum design for the antenna and feed horn optics. CDL engaged in prototyping of feed horns with wide flare-angles with application to ngVLA optics—a C- and W-band axially corrugated horn were fabricated and measured.

Simulations of antenna patterns of the GBT were carried out for a quad-ridged horn between 700–4000 MHz. A short-backfire antenna feed was designed for the GBT for mapping the absolute sky brightness at 310 MHz. The spillover of this feed is predicted to be less than half from the existing feed at this band.

In an effort to relax machine tolerances for various electromagnetic designs/structures, a study was started to evaluate electromagnetic band-gap (EBG) structures and their application to this problem. The EBG idea was applied to a split-block ALMA Band 2 (67–92 GHz) machined turnstile, and this should relax tolerances for unintended gaps.

During 2019, work was started on developing test methodologies to evaluate 3D-printed dielectric structures at cryogenic temperatures. An aperture coupled resonator test setup is being evaluated for these measurements, and this effort will continue into 2020, with Lincoln Laboratory providing 3D-printed low-loss dielectrics to the CDL for the evaluation of the cryogenic temperature dependence of the dielectric constant and loss tangent.

**Digital Signal Processing and Correlators:** Most of the ngVLA Central Signal Processor (CSP) activities planned for 2019 were devoted to the consolidation of the baseline design. The focus was on assessing candidate technologies such as field-programmable gate arrays (FPGAs) and embedded general-purpose graphic processing units (GPGPUs) for the pulsar engine component of the CSP. Software simulations of the ngVLA beamformer and channelizer demonstrator were carried out.

The digital team started work in 2019 on a hardware demonstrator of the Scalable Reconfigurable Modular (SCREAM) architecture for the ngVLA Central Signal Processor. This architecture:

- Is designed for efficiency according to ngVLA requirements;
- Is scalable to any telescope size and needs;
- Will be used as the basis for a future ALMA correlator upgrade; and
- Is most efficient for interferometry.

The hardware prototyping work is ongoing and is expected to continue into 2020.

NRAO/CDL had commenced the ALMA correlator upgrade project (CUP) after completing the preliminary design review and receiving an ALMA board approval. During 2019, in the process of implementing the new custom ASIC chip, significant issues in the execution of the CUP initiative came to light. In response, NRAO conducted an engineering re-baselining review of the project, seeking to understand the problems, and find a path forward.

Several significant assumptions made at the Preliminary Design Review (PDR) were judged to be inaccurate, including: NRAO ability to recruit new staff in a timely way to lead the project and develop hardware and the level of technical documentation of the existing correlator that would allow a new team to assume the project in a modern digital engineering environment. As a consequence, knowledge transfer from the original correlator team to the team at CDL proved much more difficult than anticipated and significant disagreements arose regarding technology choices.

Many of the attractive aspects of a “modest, low-cost upgrade of the correlator” upon which the project was founded were proven incorrect. All available avenues were explored to continue or recover the CUP, but preliminary analysis indicated that the CUP was likely to incur significant (50%+) increases in cost and schedule alongside de-scoping of key scientific features (e.g., no double bandwidth operation). The level of risk in continuing the current project was considered too high.

As a result, NRAO management terminated the current CUP effort. NRAO/CDL plan to reinitiate an effort to build a joint correlator design for a system that will serve ALMA and ngVLA. In collaboration with the Joint ALMA Observatory, CDL will continue to explore the opportunity to produce an identical “fifth quadrant” of the current correlator using spares and inventory, which could be used for software testing.

**Local Oscillator Reference and Timing:** This CDL study is helping to assess the requirements of the ngVLA frequency and timing distribution to identify possible engineering solutions, make tradeoffs, identify areas of risk mitigation, and conduct studies and tests for preliminary assessment of candidate solutions. Key issues include: technique and performance of frequency distribution and synchronization; timing requirements and array time distribution design; LO implementation on the telescope; and assessment of impact of fiber infrastructure on design. The study includes an investigation of new technologies and components that could improve array performance or reliability, or reduce array cost. This work will continue into 2020.

**Integrated Receiver Development (IRD):** The IRD program strives to develop compact, mass-producible, and field-replaceable front-end hardware for the next generation of radio telescope facilities. Specific goals include early digitization, as near to the focal point of the telescope as possible, and the relatively seamless integration of analog, digital, and photonic technologies into lightweight, low-overhead front-end modules. The architecture is optimized to exploit the complementarity of integrated construction techniques and digital signal processing (DSP), achieving a level of precision and stability that is unmatched by current state-of-the-art radio astronomy receivers.

In recent years, CDL built a dual-polarization, W-Band front-end with faster sample rates, broader bandwidth, and greater flexibility than earlier prototypes. The construction of a millimeter-wave, polarized hot-/cold-load test set for calibration and testing of the Digital Orthomode Transducer (DOMT) was also completed. In 2019, these two developments were brought together to demonstrate a complete end-to-end receiver system—testing of a dual-polarization, W-Band Front End with faster sample rates, broader bandwidth, and greater flexibility than previous prototypes demonstrated utilizing a wide variety of novel IRD concepts, with 32 Gbps of data being transmitted over 10km of fiber while performing calibrated sideband-separation in real-time.

Another 2019 achievement was that tests of the unformatted serial link demonstrated its operation over 40 km, from two front-end modules simultaneously over separate 10 km spools, or up to 28 Gbps/lane.

**ngVLA IRD:** During 2019, the ngVLA custom serial analog-to-digital (10 Gbps prototype) ASIC chips were received from the vendor. The evaluation boards were designed and are in the layout/PCB fabrication stage. The replacement drop-in circuit board design for the W-band front-end utilizing this new chip will enable a fair comparison to be made to highlight the tremendous size, weight, and power advantages of this novel technology (AUI holds patents for this technology). This work will continue in 2020.

The ngVLA Band 3 module design was started in 2019, and its fabrication and testing will continue in 2020.

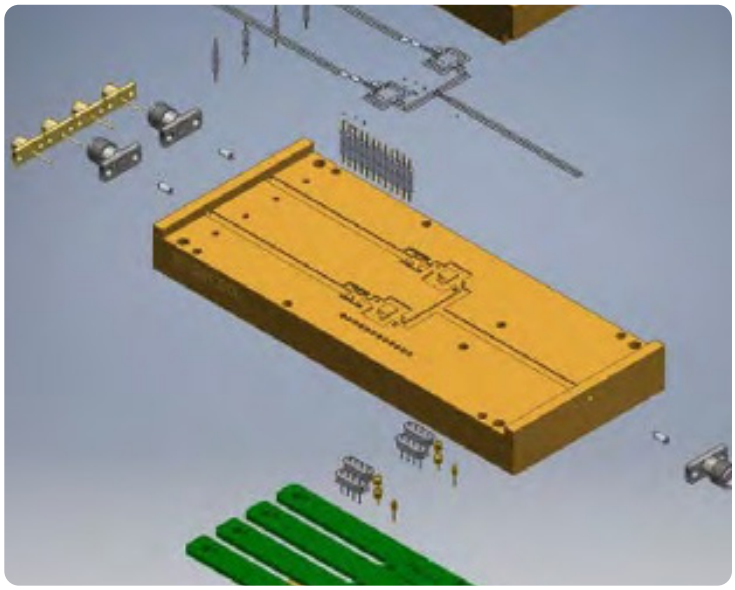


*Figure: A rendering of the model of the ngVLA Band 3 module designed by the CDL IRD team.*

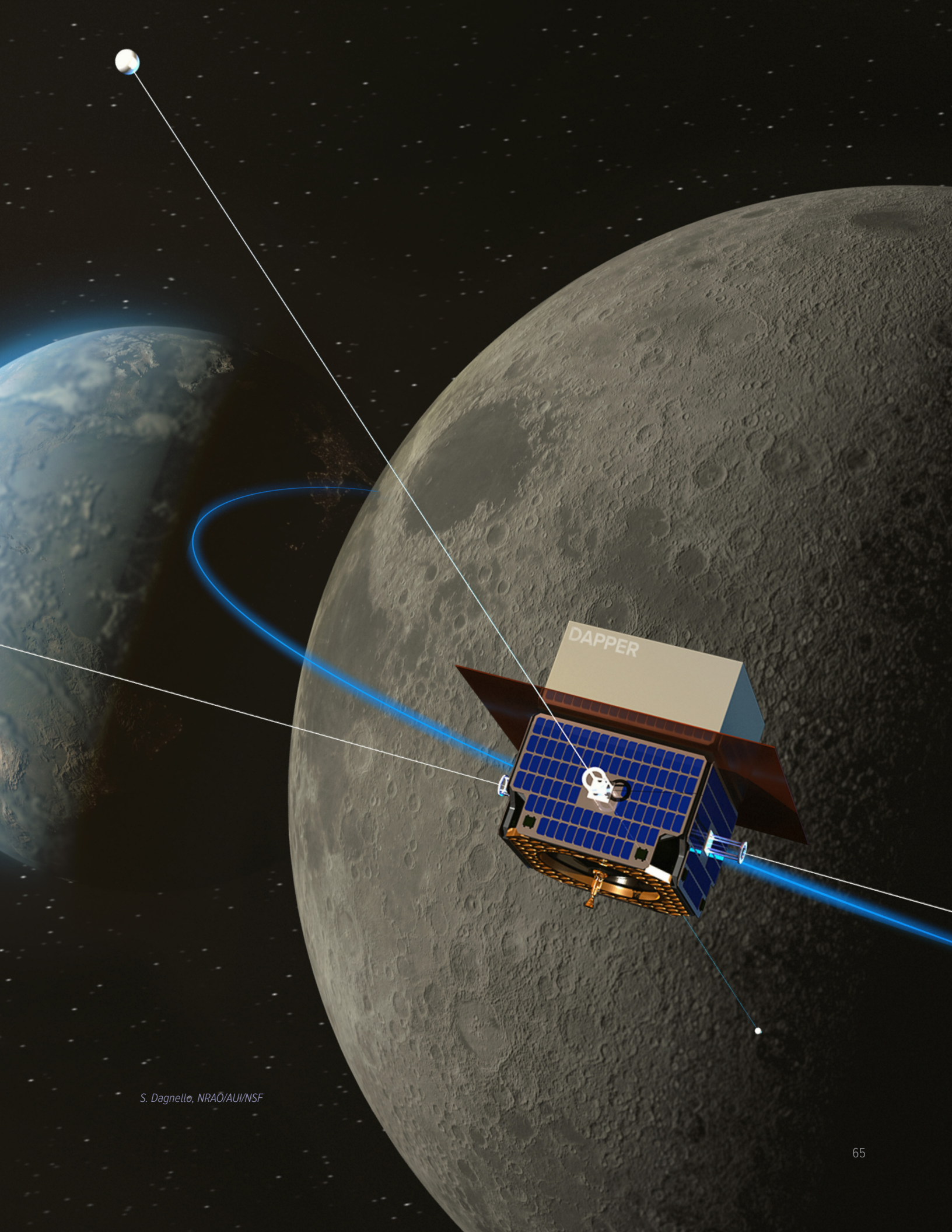
**Hydrogen Epoch of Reionization Array:** The Hydrogen Epoch of Reionization Array (HERA) is a scientific road map investigation aimed at exploring the large-scale structure in the baryonic universe via the 21 cm line of hydrogen. Funding was acquired as a sub-award from the Moore Foundation (via the Massachusetts Institute of Technology, MIT). The goals of the three-year work package (June 2017–May 2020) include: (1) assist MIT researchers to develop designs for a 60–120 MHz narrow band feed and a 60–200 MHz wideband feed for the existing HERA dishes to extend the frequency range; and (2) 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.

The focus in 2019 was on the thorough analysis of the Vivaldi wide-bandwidth feed previously chosen for HERA in Phase 1. The feed was deployed at the GBO for measurements of the frequency dependent reflection coefficient and radiation beam pattern on the 14m diameter HERA dish. OrbComm-based pattern measurements will be extended in frequency using drone-mounted signal sources that are flown in a pattern above the antenna under test. The experimental drone system is under development and continues into 2020.

**Network for Exploration and Space Science (NESS):** The NASA-funded 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) will be 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 UVA over July 2017–June 2022.

In 2019, the focus was on the enhanced second-generation CTP based on the successful proof-of-concept demonstrated in 2018. Improvements in gain tracking stability with the goal of maintaining < 10 ppm variation over long integration periods were investigated. Effort was invested in improving the backend throughput using an FPGA-based data acquisition and processing platform. An undergraduate intern deployed a higher frequency version of the CTP at the GBO during summer 2019. The results are being used to further characterize and extend the dynamic polarimetry method while providing test data for the development of machine learning algorithms by our colleagues. Work will continue in 2020 with the eventual goal of deploying the second-generation CTP and using it for stand-alone evaluation and sky measurements, as an engineering development platform for space-based systems, and to aid the development of multi-signal pattern recognition algorithms.

**Dark Ages Polarimeter Pathfinder (DAPPER) SmallSat Mission Concept:** The concept study report for DAPPER was completed and the spacecraft is being proposed as a Discovery-class mission. Planning for prototype development was carried out in 2019 and laboratory infrastructure requirements for the fabrication and evaluation of flight hardware were examined. A letter of intent, which included the estimated costing for the development the radio frequency portion of the science instrument, was submitted.




*S. Dagnello, NRAO/AUI/NSF*

# EDUCATION & PUBLIC OUTREACH

The EPO team undertook an ambitious set of projects in 2019. News and Public Information kept pace with NRAO science discoveries and stretched into new areas with quarterly feature articles, offering professional development workshops for press officers, and hosting press receptions. The VLA visitor center underwent additional improvement with new multimedia content, and welcomed 20,000+ visitors for guided tours, self-guided tours, and open houses. The multimedia group supported all these efforts and took the lead on new web pages, broader dissemination of NRAO content, and new video formats.

## STEAM Education and Outreach

The Science Technology Education Arts & Mathematics (STEAM) Education team was slowed by a turnover in senior staff in 2019, but made significant progress in building relationships, especially in the Socorro and Charlottesville communities.

Sister Cities and Observatories is an NRAO-funded program that partners two high school students who live near the VLA in New Mexico with two high school students who live near the ALMA site in northern Chile in a joint cultural/learning exchange, using a scientific experiment as a thread of inquiry between them. Informed by a needs assessment conducted last year, the program transitioned to a 10-day exchange. The first cohort from Magdalena, NM traveled to San Pedro and ALMA in the spring, and the first cohort from Chile traveled to New Mexico in October.

The Radio Astronomy & Physics – New Mexico (RAP-NM) residential summer camp transitioned to a day camp in 2019. The one-week day camp on the NM Tech campus offers access to remote telescopes through the Skynet Junior Scholars program, Spider 300a, and a VLA tour. The camp strives to provide a learning environment for rising ninth grade students to participate in an immersive science research experience. Students engage in lessons and hands-on activities designed to enhance their knowledge and enthusiasm for science, physics, and astronomy, with extra emphasis on radio astronomy and physics. In spite of a rigorous recruiting effort, the camp was cancelled for low enrollment.

Community outreach in Charlottesville and Socorro was supported by the STEAM Ed team. Events included:

- New Mexico Enchanted Skies Star Party
- Civil Air Patrol's celebration of the 50th anniversary of Apollo 11
- Sarracino Middle School Science Night, Socorro
- Parkview Elementary School Science and Math Night, Socorro
- RAP-NM recruiting visits to Magdalena and Sarracino middle schools
- Lunar eclipse education sessions at Socorro and Magdalena libraries
- Universe of Stories at Socorro Public Library summer reading program
- NM Tech Technical Communication class
- Piedmont VA Community College (PVCC) Career Fair
- Astronomy Festival on the National Mall
- Burley Middle School in Charlottesville

The NRAO STEAM Ed team partnered with Charlottesville African American Teaching Fellows (AATF) to pilot a STEAM Education Think Tank Program. The Think Tank created a set of 20 cross-curriculum scaffolded lesson plans for elementary through high school classrooms. The lesson plans are tied to the Virginia Standards of Learning (SOLs) and Common Core standards. The pilot program ran 15 October 2018–30 June 2019 with six members who delivered the first set of lesson plans. EPO surveyed the influencers in local NM and VA communities to identify the needs of these communities and inform future plans.

# EDUCATION & PUBLIC OUTREACH

In 2019, the Astronomical Society of the Pacific received an NSF Division of Research in Learning Award, On-the-Spot Assessment to Improve Scientist Engagement with the Public, with NRAO EPO as a subaward. In April, NRAO convened a meeting of the grant stakeholders and advisors, including members of the American Astronomical Society (AAS) and American Association for the Advancement of Science (AAAS) professional development teams working with scientists to improve their outreach communication skills. This meeting has informed the development of professional development modules that will be implemented by NRAO EPO staff at the winter AAS workshop.

## News & Public Information

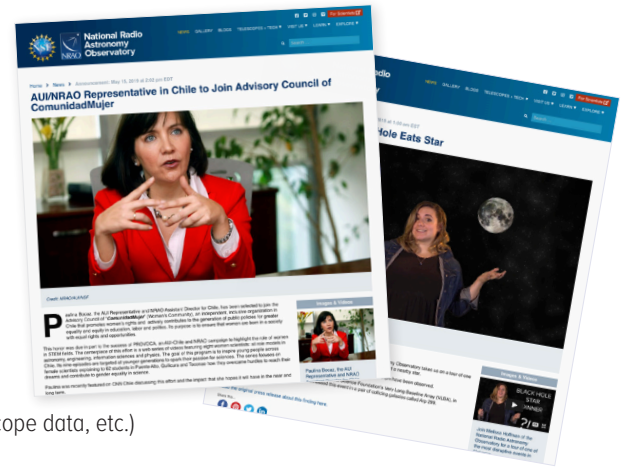
Throughout the year, staff members work closely with the AAS and the AAAS press offices to identify and publicize newsworthy results at their flagship scientific meetings, which draw a large contingent of national and international news media. NRAO hosted a workshop for public information officers at the January 2019 AAS Meeting in Seattle to address the changing needs of reporters, a reporter reception to feature the new initiatives of the Observatory, and two press conferences to highlight discoveries at ALMA and the VLA.

The news staff took steps to move from traditional hard news press release writing to also offer more feature-oriented writing. The goal to publish one feature story each quarter was met.

As part of the NRAO collaboration with its ALMA partners, the NRAO public information office coordinates its ALMA media relations efforts with each partner and the Joint ALMA Observatory. This ensures the broadest possible exposure for ALMA news while maintaining the autonomy and individual outreach goals for each partner.

Media relations also supports NRAO projects by developing media plans and providing outreach expertise for NRAO projects like the next generation Very Large Array (ngVLA) and the VLA Sky Survey. The Green Bank Observatory (GBO) ended its Service Level Agreement with NRAO for media relations support since a GBO media specialist was hired.

## 2019 Press Releases & Announcements

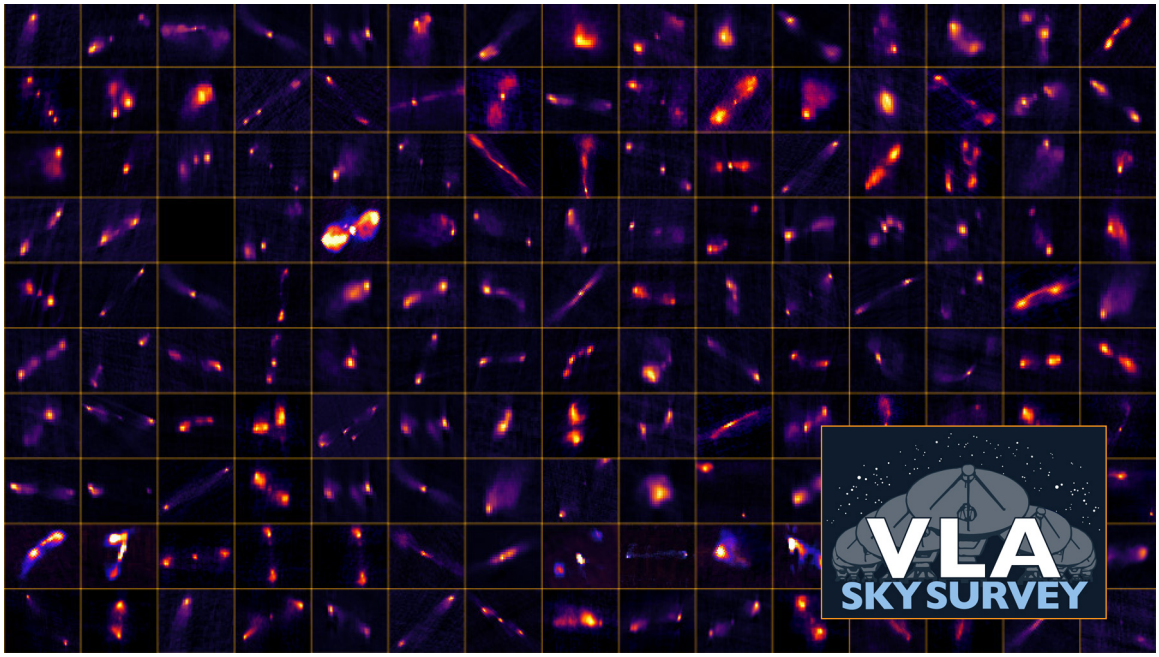



- ALMA 19 Press releases
- VLA 7 media releases
- VLBA 4 media releases
- ngVLA 2 media releases
- Other 9 media releases (people news, non-NRAO telescope data, etc.)

## Multimedia Engagement

A dedicated, creative team of animators, artists, illustrators, designers, writers, and web developers designed and developed unique multimedia materials, in support of the news and information page, social media, and STEAM efforts, as well as creating new products that were distributed through the public-facing website, school programs, and the VLA Visitor Center.

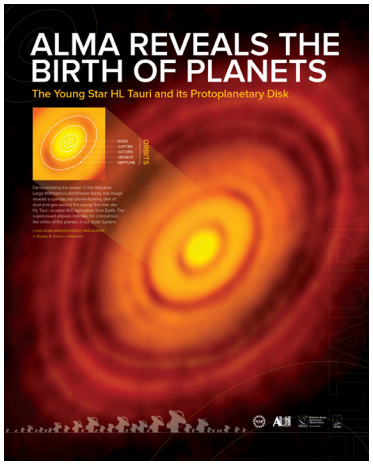
The EPO team has instituted a new workflow to outfit content, artist impressions, and science images with appropriate metadata and upload them to sites such as Worldwide Telescope, AstroPix, and Data2Dome.



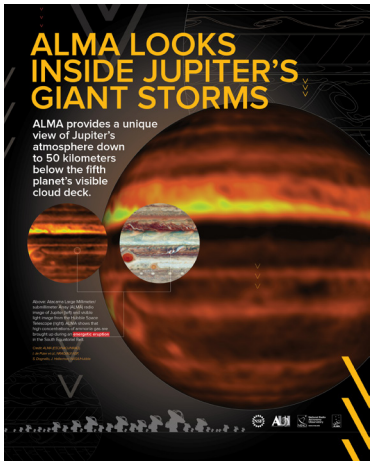

With VLASS generating large data volumes, EPO sees an opportunity to reach a wider audience by taking the first epoch images as they become available and exporting them to the Worldwide Telescope site. The pipeline for the images is not yet ready to flow images to these sources. Individual images are featured on the VLASS web page https://public.nrao.edu/gallery/vlass.

Augmented Reality (AR) is a combination of the virtual world and the real world, made by computer. After exploring AR and VR options, NRAO is poised to create virtual landscapes with ngVLA, VLA, and ALMA dishes for the Oculus platform.

Multimedia artists created a limited release set of posters that follow a set style, theme, and/or topic for ALMA discoveries. They are available for download in the online gallery. Additional promotional posters for the three NRAO Observatories were designed by Tyler Nordgren and are available for sale at the VLA Visitor Center Gift Shop.







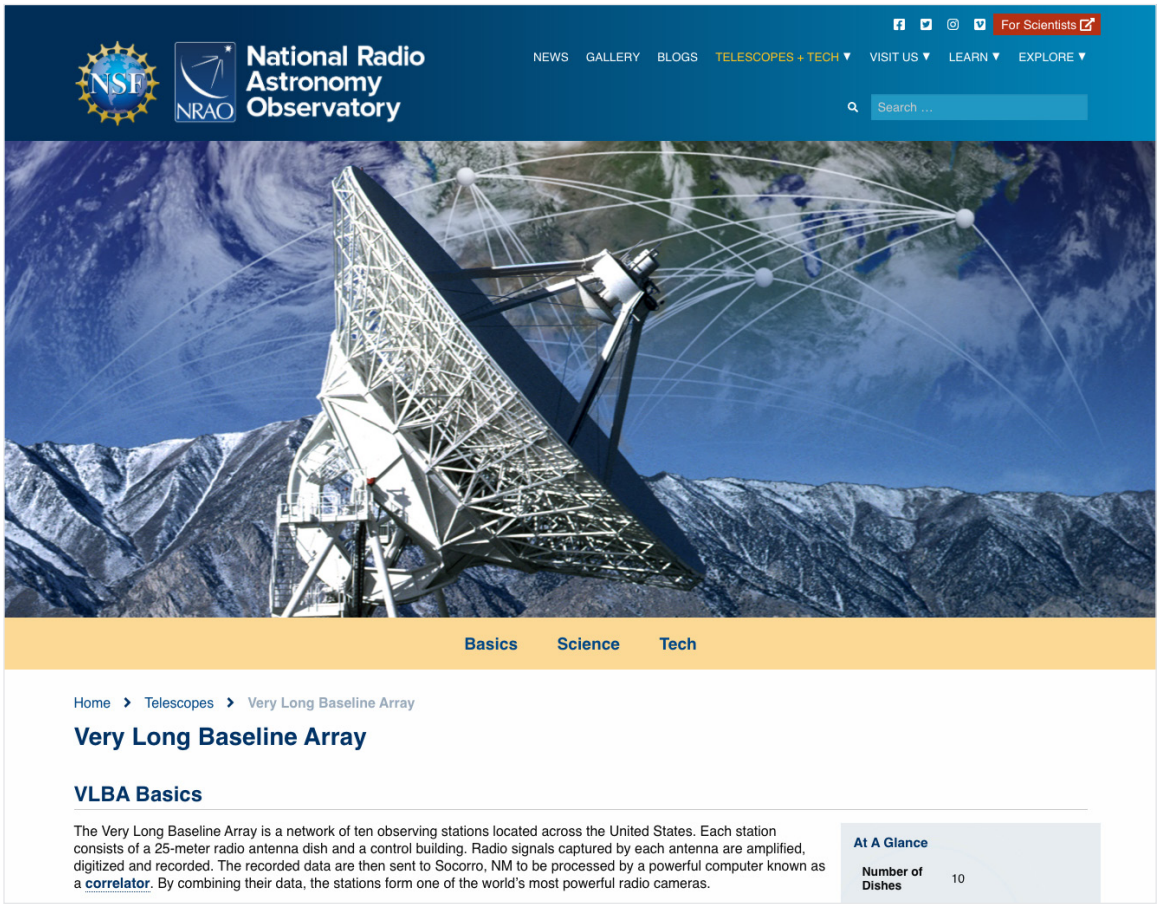
# EDUCATION & PUBLIC OUTREACH

To create a more engaging and easily shareable delivery mechanism for NRAO content, the Multimedia group researched and created a production pipeline process for timely delivery of high-quality informative video products with an on-screen host.

Followers increased on all three major social media platforms: Facebook, Twitter and Instagram. Increased efforts to coordinate with influencers like NASA on themes related to radio astronomy content (i.e, Black Hole Week) and NSF have led to positive cross postings boosts in followers.

EPO has designed a dedicated blog to interpret the science cases through stories, images, and data visualizations. Nineteen blogs were published on the public website (https://public.nrao.edu/blogs/) in 2019.

With the reintegration of VLBA into NRAO, the appropriate breadth of the VLBA presence on the public site was reviewed and established. In coordination with VLBA leadership, EPO will plan and develop the VLBA web presence and integrate content where appropriate.



## Visitor Center Operations

NRAO operates a small visitor center at the VLA. The site has indoor and outdoor public exhibits, a small auditorium, a gift shop, and monthly tour program. The VLA served 22,755 visitors over FY2019, plus 1287 local and international students and tour groups received special tours.

EPO continued to make incremental upgrades to improve the visitor experience:

- The tours were updated to include information about VLASS and ngVLA.
- The informational posters were updated to reflect the reintegration of VLBA into NRAO
- New posters were created to share the vision for ngVLA.
- The lobby was renovated, walls patched and painted, new posters mounted.
- A Penny Crunching Machine installed.
- The Amazing Cart of Science was delivered and is ready to integrate hands on activities and demonstrations into the visitor experience.

The VLA hosts Open House events on the first Saturday of April and October. These events waive the admission fee and call on over a dozen volunteers from the operations, science, and engineering staff to assist with enhanced tours and demonstrations at the array site. Attendance was 513 persons at the April 2019 Open House.

# MANAGEMENT & ADMINISTRATION

## Senior Management Organization

The NRAO organization in 2019 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 & Public Outreach, and Science Support & Research.

**Phil Jewell** continued as Assistant Director for the North American 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 and the VLBA.

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

Assistant Director **Suzanne Gurton** led the Education & Public Outreach department. The NRAO EPO program provides major components of the public's return-on-investment, marshaling NRAO resources in support of Science, Technology, Engineering, Art, and Math (STEAM) education. EPO also inform the science-interested public about the Observatory, its facilities, and the latest technical and scientific achievements of its users and staff.

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

# MANAGEMENT & ADMINISTRATION

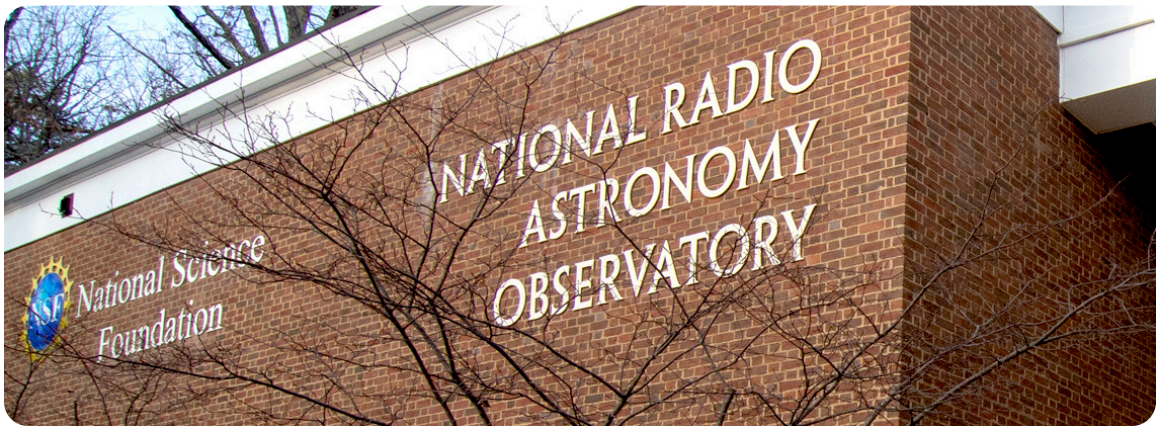
The Central Development Laboratory (CDL) led by Assistant Director **Bert Hawkins** supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to build the next generation of radio astronomy instruments. CDL accomplishes this through development of the enabling technologies: low-noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components, including feeds and phased arrays.

Based in Charlottesville and led by Assistant 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.

Assistant Director **Dale Frail** (interim) 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 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 **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.



## Office of Diversity and Inclusion

The Office of Diversity and Inclusion (ODI) was established 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 2019, the ODI Director worked closely with Human Resources (HR), Education & Public Outreach (EPO), and the Science Support & Research (SSR) departments 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.

**Diversity and Cultural Awareness Training:** NRAO continued to focus on education and training related to the importance of a diverse workforce and inclusive environment. In 2019, ODI and HR introduced a fresh set of online training modules that address current and emerging diversity and inclusion, and HR-related topics. Diversity & Inclusion Advocates and Employee Diversity Group (EDG) members, summer student mentors, and hiring managers, are assigned sets of courses to take as part of their roles.

All courses were made available to NRAO staff on a volunteer basis, and include:

- Code of Conduct (required)
- Diversity in the Modern Workforce
- Managing Bias
- Treating People with Respect
- Harassment and Discrimination Prevention

While most courses are voluntary, managers and supervisors were encouraged to include diversity training in the employees' Performance Evaluation Process (PEP) goals, resulting in more employee engagement. Before serving on search committees, members are required to complete training on Implicit Bias.

The Diversity Advocates and Employee Diversity Group (EDG) members in Virginia, New Mexico, and Chile completed a comprehensive ~60 hour, 10 month training program in 2019 based upon the University Corporation for Atmospheric Research/ National Center for Atmospheric Research's Equity and Inclusion training plan, designed to increase awareness of diversity and inclusion-related issues, and to provide skills for addressing issues that arise in the workplace. There were five Diversity Advocates and seven EDG members across the Observatory (Chile, New Mexico, and Virginia).

## 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.

**National Astronomy Consortium:** The National Astronomy Consortium (NAC) placed 16 undergraduate students from community colleges and universities across the country with trained mentors at NRAO (Headquarters and Socorro), and four additional partner sites (Space Telescope Science Institute, University of Wisconsin-Madison, Michigan State University, and Princeton University). Three of these participants were NAC alums returning to engage in new research experiences or continue with on-going research.

Students were recruited from partner Minority-Serving Institutions (MSI) and Historically Black Colleges and Universities (HBCU), and through targeted outreach to Hispanic-serving Institutions (HSIs). The NAC students interacted with NRAO Research Experiences for Undergraduates (REU) students for shared activities (colloquia, site visits, lectures, etc.), and worked on research projects with their mentors. The NAC program includes student participation in professional development workshops, attendance at weekly meetings with opportunities to present their research, and participation in diversity-related talks by invited speakers. New in 2019, NAC students were invited to attend a two-day workshop on Project Management at the Green Bank Observatory.

*National Astronomy Consortium (NAC) students and alums gather in Washington, DC for the 7th Annual NAC Meeting, September 2019. The NAC meeting includes research presentations, professional development, and cohort-building activities.*

The NAC VII workshop was held 13–15 September 2019 in Washington, D.C., with 13 of the 15 NAC VII cohort in attendance, along with seven NAC Grad alums. The workshop featured a Friday evening reception (networking opportunity) with representatives from the NSF, AUI, the National Society of Black Physicists (NSBP), the American Physical Society (APS), the University of Maryland, and NASA. The NAC VII workshop featured presentations by the NAC VII cohort on their summer research projects and by NAC Grad alums on their graduate research projects. Also featured were invited speakers from the NSF, NSBP, APS, the University of Maryland Graduate Resources Advancing Diversity with Maryland Astronomy and Physics program, the American Institute of Physics, and NASA. As always, an important component of the NAC workshop was the opportunity for the most recent NAC cohort to bond with the near-peer NAC Grad alums. This cohort-building goal was supported by group activities facilitated by the Grad alums, and by Dr. Renee Horton, past-president of the NSBP.

The seventh year of NAC programming, 2019, saw 66 active NAC alums. Twenty-seven are in graduate school and one is a post-doctoral fellow. Most of the remaining alums are still undergraduates. While there have been a number of successful efforts to build and maintain peer-mentoring relationships across cohorts, in 2018, NRAO collaborated with three NAC graduate students (Moiya McTier, Sinclaire Manning, and Chima McGruder) to develop a more formalized plan for NAC alum engagement and support the Council of Representatives for Engagement (CORE). In FY2019, CORE representatives organized and facilitated monthly webinars for all NAC alums designed to offer a venue for alums to strengthen their peer-network, provide a mechanism for NAC students to report barriers to their success, and offer students emotional-social support and professional development opportunities.

**Louis Stokes Alliance for Minority Participation:** NRAO participation in the NSF-awarded Louis Stokes Alliance for Minority Participation (LSAMP) resulted in internships for two CDL students. 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 to take advantage of the additional resources.

**Radio Astronomy Data Imaging and Analysis Labs:** The Radio Astronomy Data Imaging and Analysis Labs (RADIAL) mission is to use radio astronomy as a means to develop a diverse STEM workforce with transferable skills relevant for a rapidly changing workplace and society. RADIAL has been designed from the outset as a coordinated network of partners including, but not limited to, the NRAO, a diverse group of MSIs in the U.S., industry, non-governmental organizations, and international partners in Honduras, South Africa, and Trinidad and Tobago. RADIAL's objective is to provide MSIs with computer hardware and data sets for MSIs to use radio astronomy's big data problem as the science problem to improve their offering in astronomy and data science through the development of a hands-on curriculum, professional development program, and experiential training opportunities.

The RADIAL concept was introduced at the NSBP meeting in Columbus, Ohio in November 2018, and was followed by an Expression of Interest Meeting in Atlanta, Georgia in January 2019. Based on the level of interest received, a Project Director for RADIAL was appointed in May 2019 to initiate the project, secure partners, and start the fundraising process. The first RADIAL Development Lab was held in Washington, D.C. in September 2019, during which NRAO and its RADIAL partners defined the project scope and outlined an implementation plan for the first three years of the project. RADIAL's goal is to have a network consisting of ten partner MSIs–it has already secured five partners, four from the U.S., and one from Trinidad and Tobago.

*Anja Fourie, Project Director: Broader Impact*

**ngVLA – Next Generation Very Large Array:** ODI, in partnership with EPO, worked with the ngVLA leadership team to develop a Broader Impacts (BI) plan that takes advantage of the many opportunities, across disciplines, for broadening the ngVLA project impact to a wide range of stakeholders. BI will deliver knowledge and Broadening Participation opportunities to scientists and engineers, the public, K-12 through graduate students, and the next generation of scientists and engineers in astronomy. The ngVLA BI plan includes an IPT lead who will focus on identifying, developing, and tracking the many available BI activities. In 2019, ODI worked closely with EPO to identify areas of potential collaboration, to include facilitating NAC and NINE (see below) student participation and resources to increase Broadening Participation in ngVLA science, engineering, EPO, and other activities.


## International Partnerships

**NRAO International Exchange Program:** The NRAO International Exchange Program (NINE) provides practical skills development opportunities for participants from under-represented minorities or developing countries. Participants complete an intense summer training program at NRAO designed to teach skills relevant to the design, construction and operations of a radio astronomy observatory, as well as project management. Each participant is then required, upon returning home, to establish a NINE Hub and take on the role of a NINE trainer. The anticipated outcome of this program will be worldwide partnerships with fast-growing radio astronomy communities designed to facilitate the exchange of NINE trainers.
Two new NINE Hubs were created in FY2019: National Autonomous University of Honduras (UNAH) and Texas Tech University (TTU), a Hispanic-Serving Institution (HSI).

The 2019 NINE participants–Saravia (National Autonomous University of Honduras) and Heather Harbin (Texas Tech University)–completed technical projects in which they built Python command-line tools using Raspberry Pi hardware and VLASS imaging. Saravia and Harbin also drafted a project plan for the establishment of the Honduras NINE Hub and Texas Tech Hub, respectively. The participants were mentored by NRAO Scientist, Brian Kent (Technical), and RADIAL Project Director, Anja Fourie (Project Management).

Establishment of the Honduras Hub is the next step in the development and strengthening of a regional NINE Hub in the Caribbean and Central America, following participation by Jason Renwick from the University of the West Indies in 2018. NRAO also reached agreement with AlphaCen, an association of Central American astrophysicists with the goal to support the development of astrophysics research in the area, to invest in the development of a regional NINE Hub.

**Chile Research Experience for Undergrads:** The Chile REU program, led by Antonio Hales, provided research experiences to three students from December 2018–March 2019. Students accepted in the ODI-Chile summer research program come from universities without research opportunities, limiting graduate school opportunities.

## Science Communications

The Science Communications Office (SciCom) collaborated with scientific staff and the Director's Office to communicate NRAO science, vision, accomplishments, and plans to the science community, NRAO/AUI staff, and key external stakeholders, including NRAO advisory committees, and the NSF.

SciCom organized an effective Observatory presence at major 2019 science community meetings, including the semi-annual AAS meetings, the AAAS Annual Meeting, and the annual SuperComputing conference (SC19).

The winter AAS meeting was 6–10 January 2019 at the Washington State Convention and Trade Center in Seattle. Four NRAO event proposals were accepted for this AAS meeting: (1) an evening NRAO Town Hall and reception; (2) a Special Session titled *Theoretical Advances Guided by Radio-Millimeter-Submillimeter Arrays;* (3) a Special Session titled *Exploring our Cosmic Origins: New Results from the Atacama Large Millimeter/submillimeter Array;* and (4) a Special Session focused on the science and opportunities of the Very Large Array Sky Survey. SciCom also organized and led NRAO participation at this winter AAS in: (a) the four-day Exhibition; (b) the Undergraduate Orientation and Graduate Student Fair that immediately preceded the Opening Reception; (c) the Student Pavilion that was open throughout the meeting; and (d) local EPO events sponsored by AUI and the AAS.

The summer AAS meeting was held 9–13 June 2019 in St. Louis, Missouri. SciCom organized and led NRAO participation at the summer 2019 AAS in: (a) the four-day Exhibition; (b) the Undergraduate Orientation and Graduate Student Fair; (c) the Student Pavilion; and (d) local EPO events sponsored by AUI and the AAS.

To help communicate NRAO science to the broader scientific community, SciCom worked with the Director's Office and the ngVLA Project Office to propose and organize a science symposium for the 2019 AAAS Annual Meeting, which was held 14–17 February 2019 in Washington D.C. Titled *Multi-Messenger Astrophysics: Gravitational and Radio-wave Synergies,* this 90-minute symposium chaired by ngVLA Project Scientist Eric Murphy featured three speakers.

A science symposium proposal was organized and proposed by SciCom in April 2019 for the 2020 AAAS Annual Meeting (13–17 February 2020, Seattle, Washington) and has been accepted. Titled *Detecting Extraterrestrial Technologies and Life,* this symposium will feature a diverse set of speakers who will describe how the extraordinary progress in the astronomical discovery and characterization of exoplanets is motivating renewed investment in the search for extraterrestrial intelligence at NASA, in the private sector, and among philanthropic organizations. This symposium will also examine how technosignature research and development is rapidly advancing and influencing the astronomy community's exoplanet research strategies and tactics.

SciCom designed and published the 2018 NRAO Annual Report. This report features calendar year 2018 science highlights from the community and NRAO scientific staff; major accomplishments at NRAO operational facilities; R&D progress for next-generation facilities; community support activities; and public outreach and diversity highlights. This report is available online at the NRAO Science website and in hardcopy.

SciCom continued to edit, improve, publish, and expand the subscription base for the Observatory's monthly electronic newsletter, NRAO eNews, and the periodic electronic announcements series, NRAO Announcements, with 9,000+ subscribers in North America and around the world. SciCom also updated the NRAO Research Facilities brochure prior to the winter 2019 AAS meeting.

## Spectrum Management

The ability to observe without harmful radio frequency interference (RFI) is fundamental to NRAO science. The 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. The 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 New Mexico Operations Interference Protection Office coordinates spectrum usage for the VLA site, as described in the following paragraphs.

NRAO responds to requests for Special Temporary Authority submitted through the NSF from the National Telecommunications and Information Administration. 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 antenna, 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.

NRAO informs external spectrum users at the U.S. Space Command, the tethered aerostat radar system (TARS) sites, and other military and commercial shared-spectrum users of NRAO and National Astronomy and Ionosphere Center (NAIC) 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.

NRAO monitors 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 goodwill discussions with the responsible spectrum user with the goal of interference reduction or elimination via technical means.

NRAO performs RF emissions tests on incoming commercial or NRAO-designed equipment and reviews the results to determine interference potential. Equipment found to exceed the detrimental limits are either rejected, modified, shielded, or resubmitted for redesign.

### National and International Spectrum Management

Satellite coordination with SpaceX was handled by NSF's Electromagnetic Spectrum Management Unit that successfully concluded a coordination agreement to allow SpaceX to operate their 2018-era satellite constellation compatibly with radio astronomy operations in the 10.6–10.7 GHz band. This agreement may have to be renegotiated concurrent with SpaceX's updates to the planned operation of their constellation. Initial monitoring observations of the radio spectrum around 10.6 GHz were taken at the GBT to establish a baseline free of satellite emissions. Extensive discussions among SpaceX, the AAS, and the U.S. optical astronomy community were instituted after SpaceX's initial launch of 60 satellites, given the potential of the reflections from these satellites to interfere with operations at the Vera C. Rubin Observatory and other optical/infrared telescopes.

Satellite coordination with OneWeb had been in limbo since June 2016 but with the impending launch of the OneWeb constellation, NRAO filed a comment with the Federal Communications Commission (FCC) noting the lack of progress in reaching a mutually satisfactory agreement. Thereafter OneWeb re-initiated their contacts with NSF and further negotiations between OneWeb, NRAO, and NSF are underway.

Monitoring observations of the spectrum used by Iridium were undertaken at the GBT in May 2019. These observations revealed that the Iridium constellation was illuminating Green Bank over the full allowed bandwidth 1618–1626.5 MHz, despite promises to use a narrower bandwidth to prevent RFI in the radio astronomy frequency band at 1610.6–1613.8 MHz that is used to observe the 1612 MHz OH line. Substantial RFI in the 1612 MHz OH band was detected. Subsequent monitoring at the VLA revealed a similar situation there. These observations could eventually provide evidence for a complaint against Iridium that is required to operate without generating harmful interference under the terms of their most recent operating authorization.

## Terrestrial Issues

The most important issue concerned a proceeding whereby FCC, dismissing comments from NRAO and the Committee on Radio Frequencies (CORF), implemented a new class of temporary (but very long-lived) licenses whereby experimental devices operating above 95 GHz could be marketed for commercial sale and allowed to transmit in bands protected by footnotes US246 and RR. 5.340 to the national and international frequency allocation tables, respectively. These footnotes state that all emissions in the concerned bands are prohibited. In response, NRAO filed comments harshly criticizing FCC for misconstruing and dismissing NRAO and CORF comments, to the detriment of the protection of radio astronomy and remote sensing. Also in response, NRAO filed FCC comments noting the International Telecommunication Union-Radio (ITU-R) recent revision of rules for authorizing devices operating in derogation of the international Radio Regulations, especially RR. 5.340, independent of domestic considerations under the control of the FCC.

The FCC also acted to reclassify a frequency-hopping medical imaging device such that it was allowed to transmit at 1417 MHz in the US246 and RR. 5.340 band at 1400–1427 MHz around the 21cm HI line. NRAO filed a petition to reconsider the FCC Order, showing that the device manufacturer had grossly underestimated the RFI potential of its device, and asking the FCC to institute protection for sites like Arecibo that were not considered in the order. NRAO also asked that the ITU-R rules be recognized when operating in a frequency band like 1400–1427 MHz where no emissions are permitted internationally.

## International Issues

The NRAO spectrum manager attended ITU-R meetings in Geneva in November 2018, and February, May, and June 2019, along with a meeting of the EU spectrum management Committee on Radio Astronomy Frequencies (CRAF) in Jodrell Bank in June 2019 and the RFI2019 symposium in Toulouse in September 2019. As Chair of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), the NRAO spectrum manager arranged IUCAF's affairs, procuring the annual operating budget from the International Astronomical Union (IAU), Union Radio Scientifique Internationale (URSI), and Committee on Space Research (COSPAR). An article was prepared for the ITU-R News Magazine's just-published special pre-WRC-19 edition.

The overarching issue in 2019 was preparation for World Radio Conference (WRC-19 in October-November 2019 in Sharm El-Sheikh). As IUCAF Chair, the NRAO spectrum manager wrote comprehensive white papers summarizing radio astronomy's views on WRC-19 Agenda Items, first for use at the Conference Preparatory Meeting (CPM) in Geneva in February 2019, and again for the WRC-19 after the draft treaty text had been finalized at the CPM. Prior to the CPM, the IUCAF submitted a series of five documents marking up the individual chapters of the draft CPM treaty text to better situate radio astronomy's positions. The suggested changes to the draft text were overwhelmingly and gratifyingly adopted.

## 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**

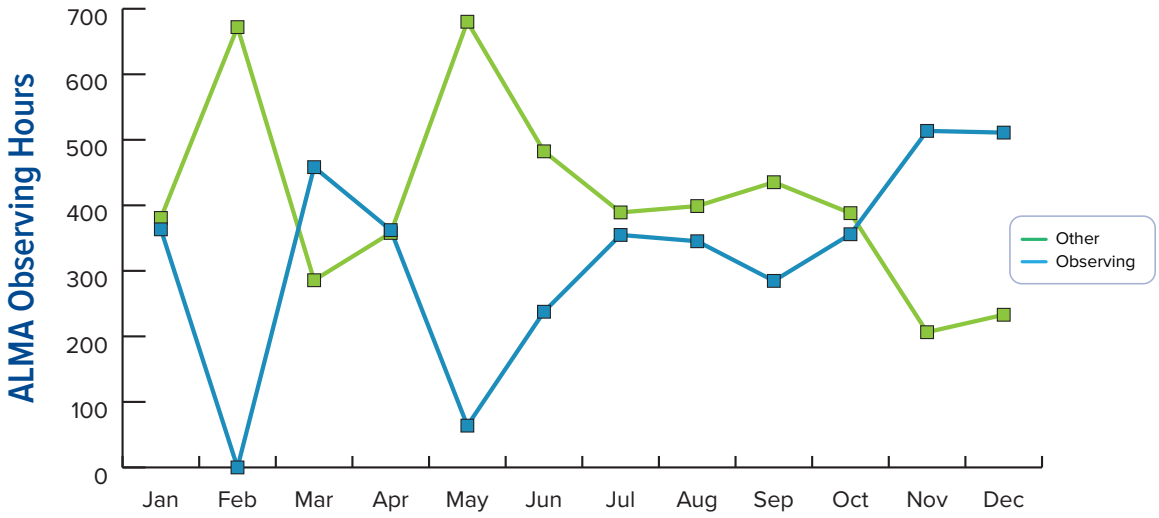
**Maintenance:** Actual hours of scheduled service of infrastructure, structure, electronics, and software.

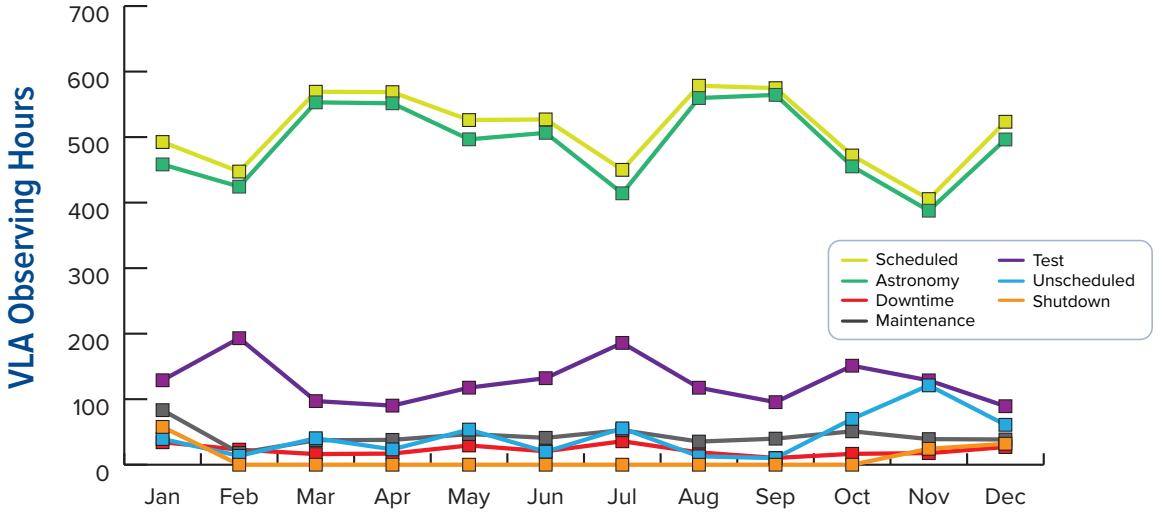
**Test:** Actual hours for test observations rather than peer-reviewed science proposals.

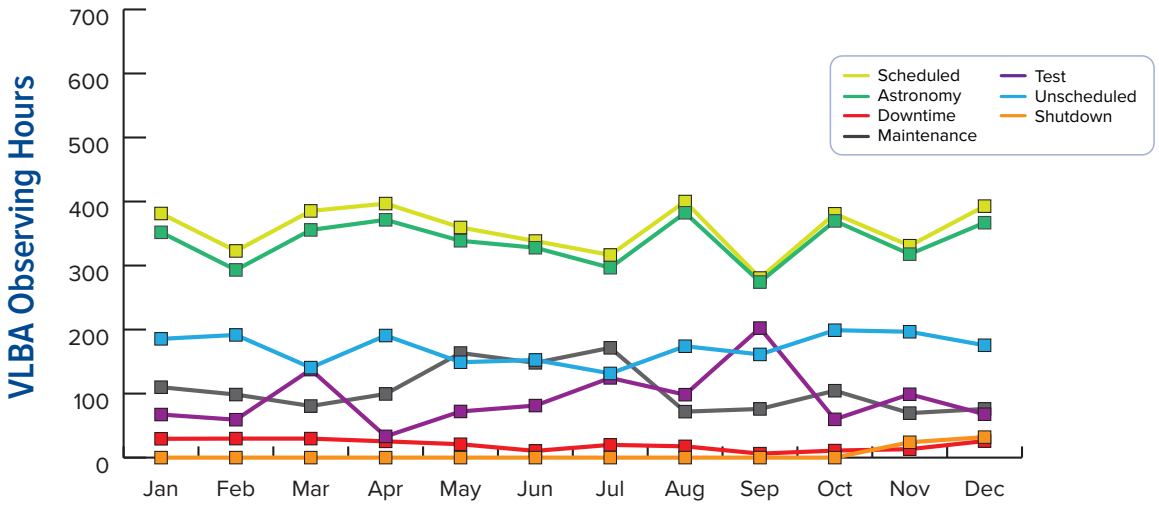
**Unscheduled:** Actual idle hours owing to gaps between observing programs that cannot be scheduled and to predicted, extended inclement weather.

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

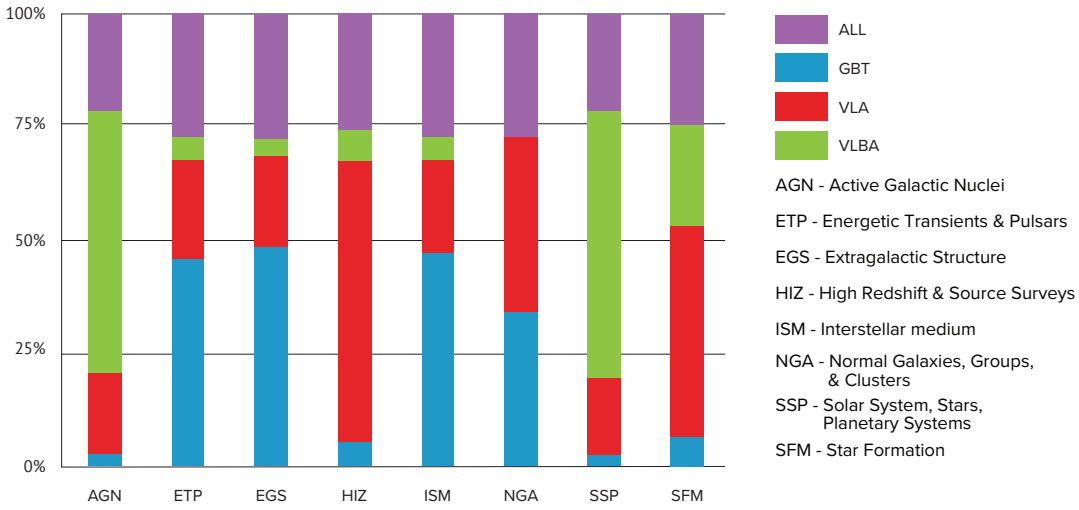
Photo by D. Finley, NRAO/AUI/NSF


ALMA Observing Hours
700
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Other
Observing


VLA Observing Hours
700
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Scheduled
Astronomy
Downtime
Maintenance
Test
Unscheduled
Shutdown

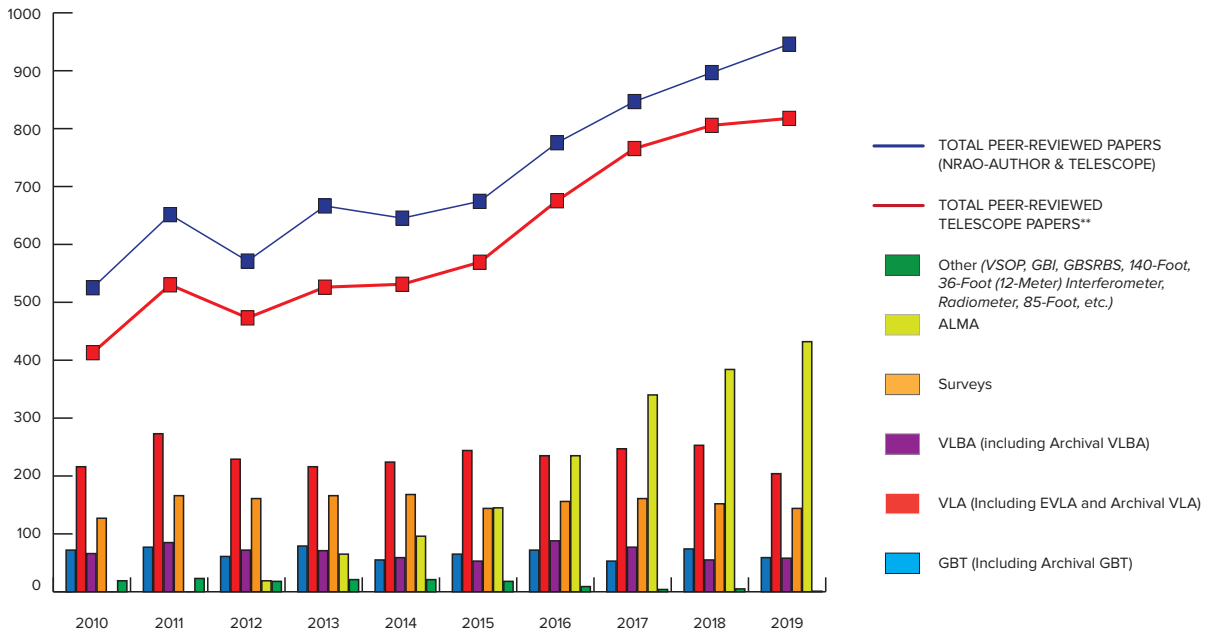

VLBA Observing Hours
700
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Scheduled
Astronomy
Downtime
Maintenance
Test
Unscheduled
Shutdown

## Observing Hours by Science Category



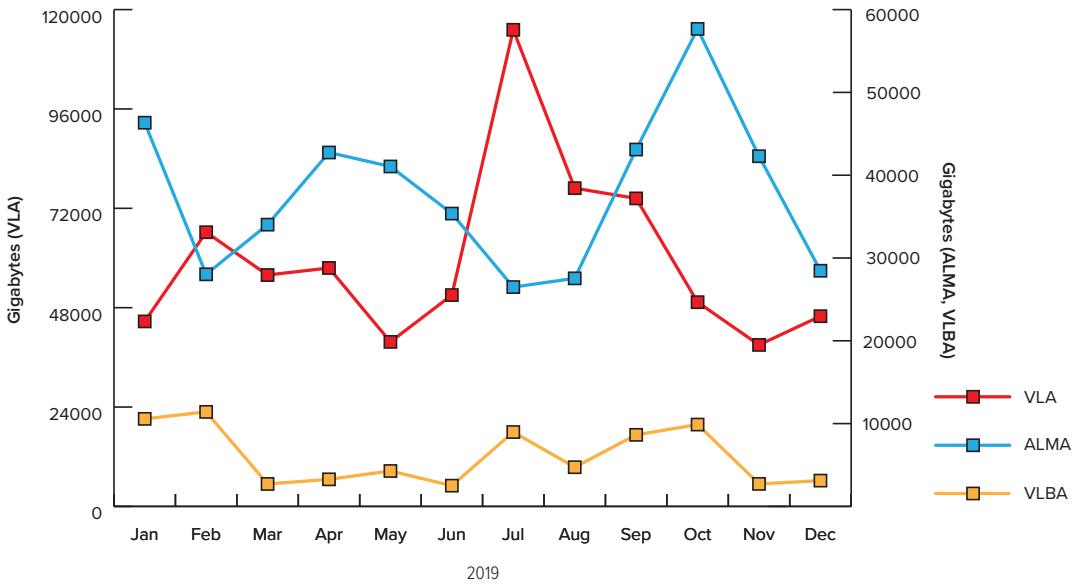

Observing hours for each of the GBT, VLA, and VLBA are tracked in the eight science categories defined in the NRAO-GBO proposal evaluation and time allocation process.

## 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

## 2019 NRAO REFEREED PUBLICATIONS


Aalto, S.; Muller, S.; König, S.; Falstad, N.; Mangum, J.; Sakamoto, K.; Privon, G. C.; Gallagher, J.; Combes, F.; García-Burillo, S.; Martín, S.; Viti, S.; Van Der Werf, P.; Evans, A. S.; Black, J. H.; Varenius, E.; Beswick, R.; Fuller, G.; Henkel, C.; Kohno, K.; Alatalo, K.; Mühle, S., "The hidden heart of the luminous infrared galaxy IC 860. I. A molecular inflow feeding opaque, extreme nuclear activity," Astronomy and Astrophysics, 627: A147, 2019.

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Agliozzo, C.; Mehner, A.; Phillips, N. M.; Leto, P.; Groh, J. H.; Noriega-Crespo, A.; Buemi, C.; Cavallaro, F.; Cerrigone, L.; Ingallinera, A.; Paladini, R.; Pignata, G.; Trigilio, C.; Umana, G., "A massive nebula around the luminous blue variable star RMC 143 revealed by ALMA," Astronomy and Astrophysics, 626: A126, 2019.

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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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Credit: NRAO/AUI/NSF, J. Hellerman

# APPENDIX B: EVENTS & MILESTONES

**22 December 2018 – 25 January 2019**
*Partial U.S. Government Shutdown*

**8-10 January 2019**
*233rd AAS meeting*
Seattle, Washington
NRAO Town Hall
NRAO Exhibit
The National Astronomy Consortium (NAC):
A Model for a Robust Student Pipeline
The National Astronomy Consortium: The Sixth Annual Meeting of the NAC Program
Special Session: *Exploring our Cosmic Origins: New Results from the Atacama Large Millimeter/submillimeter Array*
Special Session: *Theoretical Advances Guided by Radio-Millimeter-Submillimeter Arrays*
Special Session: *The VLA Sky Survey*
Summer Student Presentations
Student Orientation
Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

**9-12 January 2019**
*National Radio Science Meeting*
University of Colorado at Boulder
Boulder, Colorado

**1 February 2019**
*NRAO Semester 2019B Call for Proposals deadline*

**16 February 2019**
*American Association for the Advancement of Science Annual Meeting*
*Multi-Messenger Astrophysics: Insights from Combining Gravity and Radio Waves*
Washington, D.C.

**13-15 March 2019**
*ALMA Data Reduction Party*
Charlottesville, Virginia

**20 March – 8 April 2019**
*ALMA Ambassadors Proposal Preparation Workshops*
Various Locations

**5 April 2019**
*2019 Jansky Lectureship Nominations Deadline*
Charlottesville, Virginia

**11-12 April 2019**
*2019 NRAO Postdoctoral Symposium*
Charlottesville, Virginia

**17 April 2019**
*ALMA Cycle 7 Call for Proposals Deadline*
Joint ALMA Observatory, Chile

**13-17 May 2019**
*New Horizons in Planetary Systems*
Victoria, British Columbia, Canada

**29-30 May 2019**
*Memorial Symposium for Riccardo Giacconi*
Washington, District of Columbia

**30-31 May 2019**
*NRAO Community Day*
Texas Tech University
Lubbock, Texas

**4 June 2019**
*ALMA North American Science Advisory Committee Meeting*
Charlottesville, Virginia

**5-6 June 2019**
*NRAO Users Committee Meeting*
Charlottesville, Virginia

**9-13 June 2019**
*234th AAS Meeting*
NRAO Exhibit
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant
St. Louis, Missouri

**13 June 2019**
*X-Proposals Announcement of Opportunity*


**13-14 June 2019**
*NRAO Community Day*
University of Maryland, Baltimore County
Baltimore, Maryland

**17-20 June 2019**
*Canadian Astronomical Society Meeting 2019*
Montreal, Quebec, Canada

**25-27 June 2019**
*Radio/mm Astrophysical Frontiers in the Next Decade*
Charlottesville, Virginia

**16 July 2019**
*VLA Sky Survey Completes First Epoch All-sky Observations*
Socorro, New Mexico

**27 July – 5 August 2019**
*2019 Astronomy in Chile Educator Ambassadors Program Expedition (AUI)*
Chile (various locations)

**1 August 2019**
*Call for X-Proposals Deadline*
Charlottesville, Virginia

**1 October 2019**
*ALMA Cycle 7 Supplemental Call for Proposals Deadline*
*ALMA Cycle 7 science observations start*
Joint ALMA Observatory, Chile

**1 October 2019**
*Very Long Baseline Observatory Reintegrated with NRAO NM Operations*
Socorro, NM

**3-4 October 2019**
*6th CASA Users Committee Meeting*
Charlottesville, Virginia

**7-18 October 2019**
*7th VLA Data Reduction Workshop*
Socorro, New Mexico

**14-18 October 2019**
*ALMA2019: Science Results and Cross-Facility Synergies*
Cagliari, Sardinia, Italy

**5 December 2019**
*Jansky Lecture: Dr. Anneila Sargent*
Charlottesville, Virginia

**19 December 2019**
*ALMA Cycle 8 Call for Proposals pre-announcement*
Joint ALMA Observatory, Chile

# APPENDIX C: ADVISORY COMMITTEES

## NRAO Users Committee

The NRAO Users Committee (UC) membership includes users and potential users of NRAO facilities from across the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes. This Committee is appointed by the Director and normally meets in-person annually.

The current membership of the NRAO Users Committee is given below. In 2014, NRAO integrated the ALMA North American Science Advisory Committee (ANASAC) as a standing subcommittee of the Users Committee. Users Committee members who also serve on the ANASAC are indicated, as are the ANASAC representatives to the international ALMA Science Advisory Committee (ASAC).

Each member's last year in their UC term of service is given in parentheses.

The 2019 Users Committee meeting was convened at NRAO Charlottesville 5-6 June.

- **Edo Berger**, Harvard University (2021)
- **Ilse Cleeves**, University of Virginia (2021)
- **Christopher De Pree** (Co-Chair), Agnes Scott College (2021) CASA UC
- T**rish Henning**, University of New Mexico (2019)
- J**in Koda**, Stony Brook University (2021) ANASAC
- **Shih-Ping Lai**, National Tsing-Hua University (2020) ANASAC
- **Casey Law**, University of California at Berkeley (2022)
- **Laurent Loinard**, Universidad Nacional Autónoma de México (2021)
- **Dan Marrone** (Chair), University of Arizona (2019) ANASAC/ASAC
- **Susan Neff**, NASA – Goddard Space Flight Center (2022)
- **Giles Novak**, Northwestern University (2020) ANASAC/ASAC
- **Rachel Osten**, Space Telescope Science Institute (2020) ANASAC
- **Kate Su**, University of Arizona, (2021) ANASAC
- **Fabian Walter**, Max Planck Institut für Astronomie (2019)
- **Stephen White**, Kirtland Air Force Base (2020) ANASAC/ASAC
- **Christine Wilson**, McMaster University (2020) ANASAC/ASAC.

## ALMA North American Science Advisory Committee

The ALMA North American Science Advisory Committee (ANASAC) provides scientific advice to the NRAO Director on the science operation of ALMA and the North American ALMA Science Center, as representatives of the wider North American astronomical community.

Each member's last year in their ANASAC term of service is given in parentheses.

The 2019 ANASAC meeting was held at NRAO Charlottesville on 4 June.

- **Giles Novak** (Chair), Northwestern University (2020)
- **Stephen White**, North American ASAC Vice-Chair, Kirtland Air Force Base (2020)
- **Jin Koda**, Stony Brook University (2021)
- **Shih-Ping Lai**, National Tsing-Hua University (2020)
- **Dan Marrone**, University of Arizona (2019)
- **Rachel Osten**, Space Telescope Science Institute (2020)
- **Kate Su**, University of Arizona (2021)
- **Christine Wilson**, McMaster University (2020).

Photos by Pablo Carrillo

# APPENDIX C: ADVISORY COMMITTEES

## AUI Visiting Committee

The 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 Committee membership in 2019 follows. Each member's last year in their Visiting Committee term of service is given in parentheses.

**Rachel Akeson** (Chair), Infrared Processing & Analysis Center, California Institute of Technology (2020)
**Paul Gueye**, Michigan State University (2022)
**James Jackson**, Boston University (2020)
**Brian Keating**, University of California, San Diego (2022)
**Patricia McBride**, Fermi National Accelerator Laboratory (2021)
**Margaret Meixner**, Space Telescope Science Institute (2020)
**David Reitze**, Laser Interferometer Gravitational-Wave Observatory (2021)
**Luis Rodriguez**, Universidad Nacional Autónoma de México (2020)
**Greg Taylor**, University of New Mexico (2022)
**Belinda Wilkes**, Chandra X-ray Center (2021)

## NRAO Time Allocation Committee

The individuals listed below served on the NRAO Time Allocation Committee (TAC) for NRAO Semesters 2019B and 2020A. The scientific purview of each TAC member is indicated.

**Semester 2019B**

**Kristine Spekkens**
Extragalactic Structure (EGS)
Royal Military College of Canada

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

**Denise Gabuzda**
Active Galactic Nuclei (AGN)
University College Cork Ireland

**Loreto Barcos**
Normal Galaxies, Groups & Clusters (NGA)
National Radio Astronomy Observatory

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

**Christina Lacey**
Interstellar Medium (ISM)
Hofstra University

**Betsy Mills**
Star Formation (SFM)
Boston University

**Wen-fai Fong**
Gravitational Waves and Energetic Transients (GWT)
Northwestern University

**Craig Heinke**
Pulsars and Compact Objects (PCO)
University of Alberta

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**Semester 2020A**

**Cannon John**
Extragalactic Structure (EGS)
Macalester

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

**Denise Gabuzda**
Active Galactic Nuclei (AGN)
University College Cork Ireland

**Loreto Barcos**
Normal Galaxies, Groups & Clusters (NGA)
National Radio Astronomy Observatory

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

**Christina Lacey**
Interstellar Medium (ISM)
Hofstra University

**Betsy Mills**
Star Formation (SFM)
Boston University

**Wen-fai Fong**
Gravitational Waves and Energetic Transients (GWT)
Northwestern University

**Craig Heinke**
Pulsars and Compact Objects (PCO)
University of Alberta

## CASA Users Committee

The NRAO Data Management and Software Department established a Common Astronomy Software Applications (CASA) Users Committee (CUC) to advise it on matters important to CASA users. The scope of the committee's responsibility includes the capabilities, usability, reliability, and performance of CASA with ALMA and VLA data from the perspective of the CASA users community.

The CUC includes five members appointed by the NRAO Assistant Director for Science Support and Research (SSR); two appointed by the East Asian ALMA Regional Center (ARC) manager at the National Astronomical Observatory of Japan; two appointed by the European ARC manager at ESO, and one appointed by the head of the JAO Department of Science operations.

The 6th CASA Users Committee meeting was held at NRAO Charlottesville on 3-4 October 2019.

**D. J. Pisano**, Chair, University of West Virginia (North America)
**Michael Bietenholz**, Deputy Chair, York University (North America)
**Adam Avison**, University of Manchester (Europe)
**Ilse van Bemmel**, Joint Institute for VLBI ERIC (Europe)
**Alessandra Corsi**, Texas Tech University (North America)
**Chris DePree**, Agnes Scott College (North America)
**Hauyu Baobab Liu**, Academic Sinica Institute of Astronomy and Astrophysics (North America)
**A-Ran Lyo**, Korean Astronomy and Space Science Institute (East Asia)
**Shigehisa Takakuwa**, National Astronomical Observatory of Japan (East Asia)

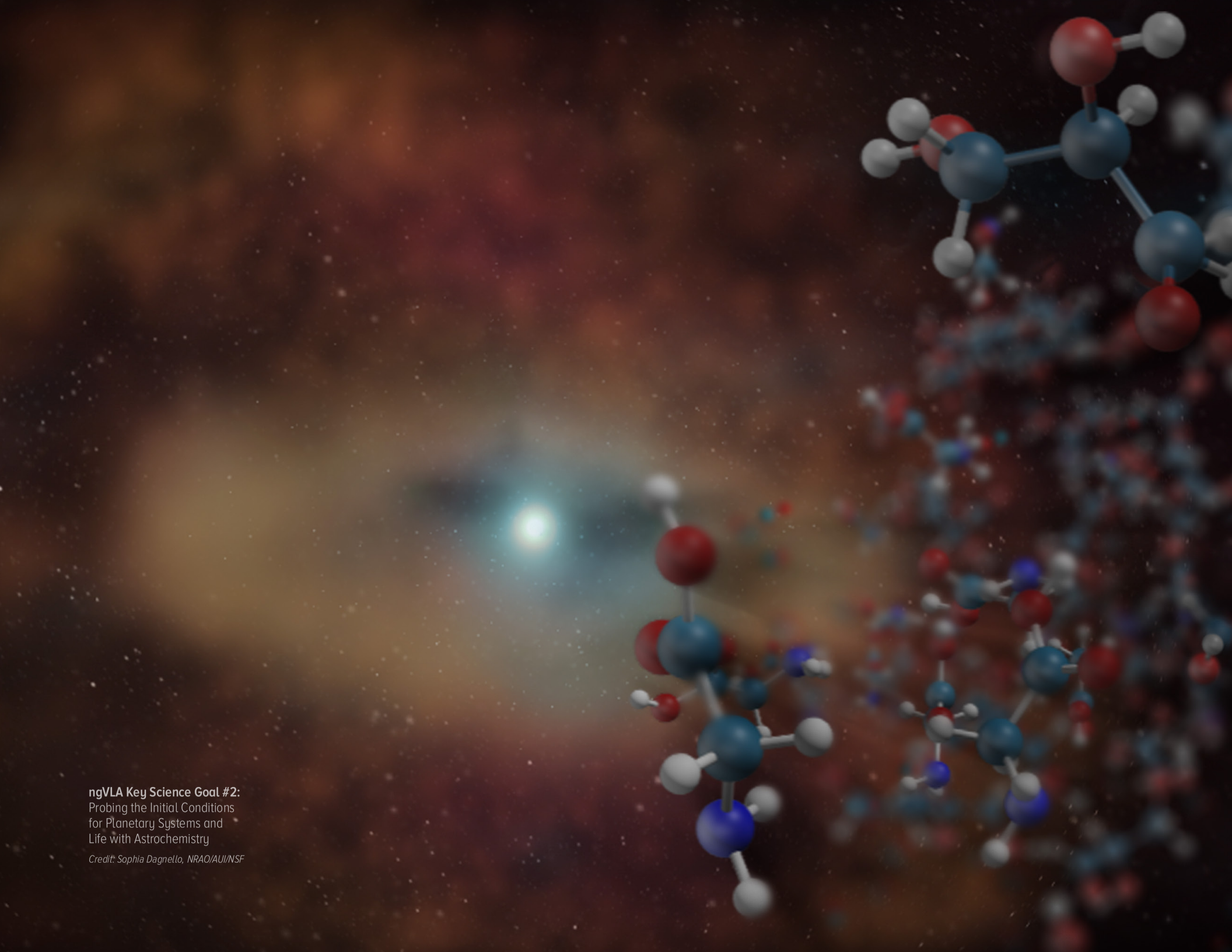

Photo by Pablo Carrillo

# APPENDIX D: FISCAL YEAR 2019 FINANCIAL SUMMARY

(all figures are $k USD)

| Functional Work Breakdown Structure Element | GBO | VLA/ngVLA | VLBA | ALMA | GB Ops | NM Ops | HQ & CV Ops | CDL | External Grants | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Administrative Services | $3,402.2 | $2,256.2 | $3,445.5 | $10,702.0 | $177.5 | $2,043.3 | ($22.6) | – | – | $22,004.2 |
| Development Programs | – | $5,328.4 | – | $3,904.8 | – | – | $203.1 | $2,735.8 | – | $12,172.0 |
| Director's Office | $679.2 | – | $550.1 | $5,124.5 | – | $3.3 | $3,863.0 | – | – | $10,220.1 |
| Education & Public Outreach | $367.0 | – | – | $560.7 | $69.2 | – | $706.8 | – | – | $1,703.7 |
| Science Operations | $704.3 | $12.0 | $0.5 | $10,240.8 | – | – | $9,379.7 | $108.4 | – | $20,445.7 |
| Telescope Operations | $4,524.1 | $9,333.9 | $6,287.9 | $12,417.9 | $289.9 | $5.3 | $890.9 | $8.4 | – | $33,758.4 |
| External Grants | – | – | – | – | – | – | – | – | $5,171.8 | $5,171.8 |
| **Grand Total** | **$9,676.9** | **$16,930.5** | **$10,284.0** | **$42,950.6** | **$536.6** | **$2,051.9** | **$15,020.9** | **$2,852.6** | **$5,171.8** | **$105,476.0** |

Fiscal Year 2019 = 1 October 2018 – 30 September 2019



**ngVLA Key Science Goal #2:**
Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

*Credit: Sophia Dagnello, 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 |
| ACEAP | Education Ambassadors Program |
| ACS | ALMA Common Software |
| ACU | Antenna Control Unit |
| AGN | Active Galactic Nuclei |
| ALMA | Atacama Large Millimeter/submillimeter Array |
| ANASAC | ALMA North American Science Advisory Committee |
| AOS | Array Operations Site |
| AR | Augmented Reality |
| ARC | ALMA Regional Center |
| arcsec | arcsecond |
| ASIAA | Academia Sinica Institute for Astronomy and Astrophysics |
| ASIC | Application Specific integrated Circuit |
| ASKAP | Australian Square Kilometre Array Pathfinder |
| AST | NSF Division of Astronomical Sciences |
| AU | Astronomical Unit |
| AUI | Associated Universities, Incorporated |
| BI | Broader Impacts |
| CARF | Committee on Radio Astronomy Frequencies |
| 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 |
| CHILES | Cosmos HI Large Extragalactic Survey |
| CHTC | Center for High Throughput Computing |
| CIRADA | Canadian Initiative for Radio Astronomy Data Analysis |
| CIS | Computing Information Systems |
| CoDR | Conceptual Design Review |
| CO-I | Co-Investigator |
| COR | Council of Representative for Engagment |
| CORF | Committee on Radio Frequencies |
| COSPAR | Committee on Space Research |
| CPM | Conference Preparatory Meeting |
| CSA | Cooperative Support Agreement |
| CSIRO | Commonwealth Scientific and Industrial Research Organization |
| CSP | Central Signal Processor |
| CTP | Cosmic Twilight Polarimeter |
| CUP | Correlator upgrade Project |
| DA | Diversity Advocate |
| DAPPER | Dark Ages Polarimeter Pathfinder |
| DMS | Data Management & Software |
| DOMT | Digital Orthomode Transducers |
| DSACore | Dynamic Scheduling Algorithm |
| DSN | Deep Space Network |
| DSP | Digital Signal Processing |
| EBG | Electromagnetic Band Gap |
| EDG | Employee Diversity Group |
| EGS | Extragalactic Structure |
| EHT | Event Horizon Telescope |
| EM | Electromagnetic |
| EMSS | ElectroMagnetic Software and Systems |
| EoI | Expression of Interest |
| EPO | Education and Public Outreach |
| ESO | European Organisation for Astronomical Research in the Southern Hemisphere |
| ETP | Energetic Transients and Pulsars |
| FCC | Federal Communications Commission |
| FE | Front End |
| FEHV | Front End Handling Vehciles |
| FPGA | Field Programmable Gate Array |
| FRB | Fast Radio Bursts |
| FTE | Full Time Equivalent |
| GBO | Green Bank Observatory |
| GBT | Green Bank Telescope |
| GDMS | General Dynamics Mission Systems |
| GHz | Gigahertz |

GMVA. . . . . Global 3mm VLBI Array
GO . . . . . General Observing
GOST . . . . . General Observing Setup Tool
GRB . . . . . Gamma Ray Burst
GW. . . . . Gravitational Wave
HBCU. . . . . Historically Black Colleges and Universities
HEMT. . . . . High Electron Moblity Transistor
HERA . . . . . Hydrogen Epoch of Reinonization Array
HiLS. . . . . Hardware in the Loop Simulations
HIZ. . . . . High Redshift & Source Surveys
HPC . . . . . High Performance Computing
HR . . . . . Human Resources
HSA . . . . . High Sensitivity Array
HSI. . . . . Hispanic Serving Institutions
HST . . . . . Hubble Space Telescope
IAU. . . . . International Astronomical Union
IEEE . . . . . Institute of Electrical and Electronics Engineers
IF . . . . . Intermediate Frequency
IRD. . . . . Integrated Receiver Development
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
kpc. . . . . kiloparsec
KSG . . . . . Key Science Goals
LA . . . . . Los Alamos
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 Stokes Alliance for Minority Participation
LWA . . . . . Long Wavelength Array
MA. . . . . Main 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
MSV3. . . . . Measurement Set Version 3
Myr . . . . . Megayear
NA . . . . . North American
NAASC . . . . . North American ALMA Science Center
NAC. . . . . National Astronomy Consortium
NAOJ . . . . . National Astronomical Observatory of Japan
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
NRC-HIA . . . . . National Research Council of Canda-Herzbrg Astronomy and Astophysics
NRL . . . . . Naval Research Laboratory
NRQZ. . . . . National Radio Quiet Zone
NSF . . . . . National Science Foundation
NSBP . . . . . National Society of Black Physicists
OCA. . . . . Office of Chilean Affairs

# APPENDIX E: ACRONYMS

| | |
|---|---|
| ODI | Office of Diversity and Inclusion |
| OMT | OrthoMode Transducer |
| OPT | Observation Preparation Tool |
| OSF | Operations Support Facility |
| pc | parsec |
| PDR | Preliminary Design Review |
| PEP | Performance Evaluation Process |
| PHT | Proposal Handling Tool |
| PI | Principal Investigator |
| PIO | Public Information Officer |
| PM | Program Management |
| PST | Proposal Submission Tool |
| PT | Pie Town |
| QA | Quality Assurance |
| R&D | Research & Development |
| RADIAL | Radio Astronomy Data Imaging and Analysis |
| RAP-NM | Radio Astronomy and Physics in New Mexico |
| REU | Research Experiences for Undergraduates |
| RF | Radio Frequency |
| RFI | Radio-Frequency Interference |
| RfP | Request for Proposall |
| RHEL | Red Hat Enterprise Linux |
| RMS | Radio-Millimeter-Submillimeter |
| RSRO | Resident Shared Risk Observing |
| SBA | Short Baseline Array |
| SAC | Science Advisory Council |
| SADC | Serial Analog to Digital Converter |
| SciCom | Science Communications Office |
| SC | Saint Croix |
| SCG | Science Computing Group |
| SCO | Santiago Central Office |
| SCR | Silicon Controlled Rectifiers |
| SDM | Science Data Model |
| SFM | Star Formation |
| SIS | Superconductor–Insulator–Superconductor |
| SKA | Square Kilometre Array |
| SMBH | Supermassive Black Hole |
| SOC | Scientific Organizing Committee |
| SOL | Standard of Learning |
| 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 |
| TKIP | Traveling-wave Kinetic Inductance Parametric |
| TTA | Telescope Time Allocation |
| U/LIRG | Ultraluminous/Luminous Infrared Galaxies |
| UC | Users Committee |
| URSI | International Union of Radio Science; Union Radio Scientifique Internationale |
| 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 |
| VLT | Very Large Telescope |
| VM | Virtual Machine |
| VME | VLBA Versa Model Eurocard |
| WFO | Work for Others |
| WIDAR | Wideband Interferometric Digital Architecture |
| WRC | World Radio Conference |
| WVR | Water Vapor Radiometer |
| YUPP | Y Ultimate Pulsar Processing Instrument |

*Credit: Drew Meglin*

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