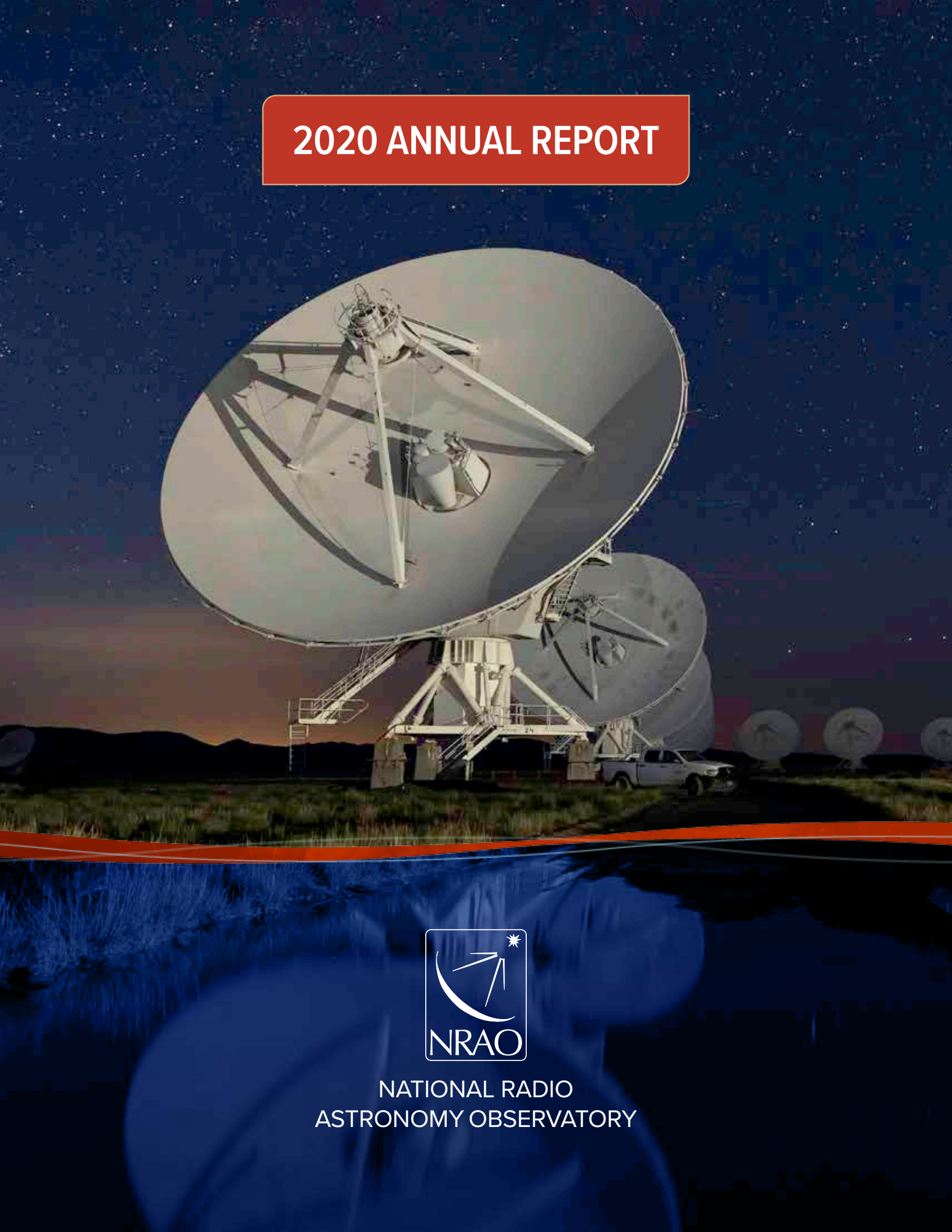
# 2020 ANNUAL REPORT



NRAO

NATIONAL RADIO
ASTRONOMY OBSERVATORY

*Credit: Sophia Dagnello, NRAO/AUI/NSF*

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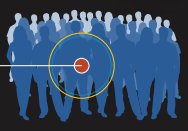

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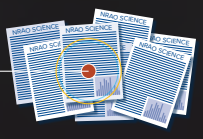


**COVER:** *The VLA during monsoon season. Photo Credit: NRAO/AUI/NSF, J.Hellerman*
**LEFT:** *Exoplanet illustration.Credit: NRAO/AUI/NSF, S. Dagnello*

# DIRECTOR'S REPORT

TONY BEASLEY
*NRAO Director*

The coronavirus (COVID-19) pandemic took an enormous toll around the globe in 2020, affecting millions, including the people of the National Radio Astronomy Observatory (NRAO) and Associated Universities, Inc. (AUI). Nonetheless, despite complex, often quick-changing challenges, NRAO/AUI successfully adapted and maintained safe science operations at the Karl G. Jansky Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Observatory (GBO). Owing to its greater remoteness and vulnerability, the international partnership that operates the Atacama Large Millimeter/submillimeter Array (ALMA) halted science operations on 20 March.

The NRAO Environmental Safety & Security team, in collaboration with NRAO leadership, developed a comprehensive response to the pandemic. Every NRAO unit enacted new policies, protocols, and procedures. Protecting the staff was always the primary concern and consideration. Skeleton crews operated each site while the majority transitioned to telework or remote work. Meetings became virtual and travel was eliminated except in extraordinary circumstances.

We took our responsibility to help drive the national situation back to normal, adopting a strong stance on vaccinations, social distancing, mask use, and other protections.

I want to express appreciation to everyone who worked to make our facilities as safe as possible through the pandemic surges. I am proud of our proactive response and our ability to adapt to the COVID landscape. Going forward, we must guard against "COVID fatigue." We must not relax until there is a lasting positive change in the COVID environment.

Our science mission continued, though at somewhat reduced efficiency, and our users crafted science from their NRAO data that impacted nearly every field of modern astrophysics. The Very Large Array Sky Survey (VLASS) continued and yielded fine science. Funding for design and development of a next generation Very Large Array (ngVLA) project accelerated and an international vision for the future of ALMA was built. Significant effort was invested in developing a next generation Very Large Array and its enormous scientific potential was defined by the community and presented to the Astro2020 Decadal Survey committees and process.

The NRAO also made excellent progress in 2020 on key strategic initiatives that are improving the Observatory's scientific capabilities and the community's ease-of-use, such as the Science Ready Data Products initiative that will soon fundamentally change radio astronomy. On the technology side, the Central Development Lab is leading research and development efforts that are enriching the tools with which we study the Universe, extending our reach.

Our people are, of course, our greatest asset. We support the growth of a diverse and inclusive astronomical community via our Jansky Fellowships, Reber Fellows, student programs, Student Observing Support funding, the National Astronomy Consortium, and much more. With cross-Observatory support, these programs are contributing to the recruitment, retention, and success of under-represented and under-served persons across our field.

The NRAO staff are operating, maintaining, and continuously improving the world's most capable observatories for radio astronomy, with the strong support of the NSF and AUI. Despite COVID-19, this Annual Report documents an NRAO year that protected its people and facilities while also supporting the needs and interests of our scientific community.

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

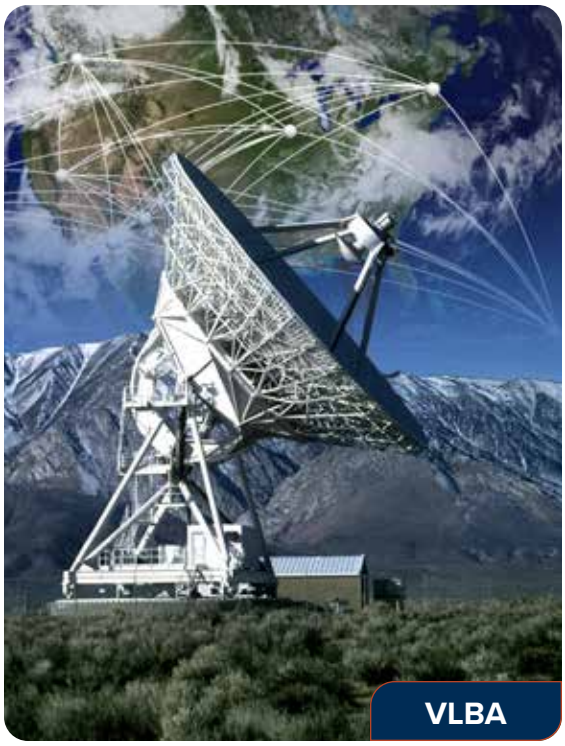

Credit: ALMA (ESO/NAOJ/NRAO); A. Marinkovic

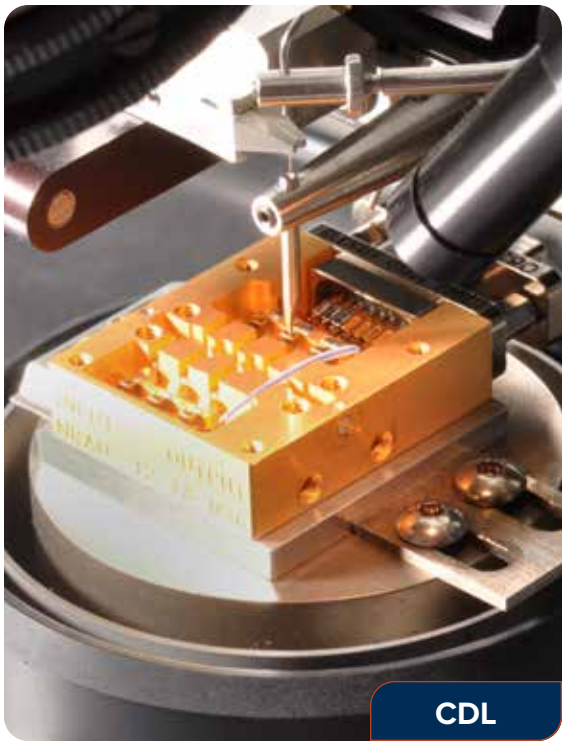

Created in 1956 by the NSF and AUI, the NRAO designs, builds, and operates the most capable astronomical telescopes and instruments at radio wavelengths. In 2020, the NRAO operated a complementary suite of three world-class telescopes, each the world leader in its domain: the international **Atacama 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 2020 with optical, infrared, and X-ray telescopes to open new frontiers across a broad range of modern astrophysics: proto-planetary disks and extrasolar planet formation; astrochemistry; the early phases of star formation; fundamental physics; molecular gas in early galaxies; the environments of supermassive black holes; cosmology; and much more.

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

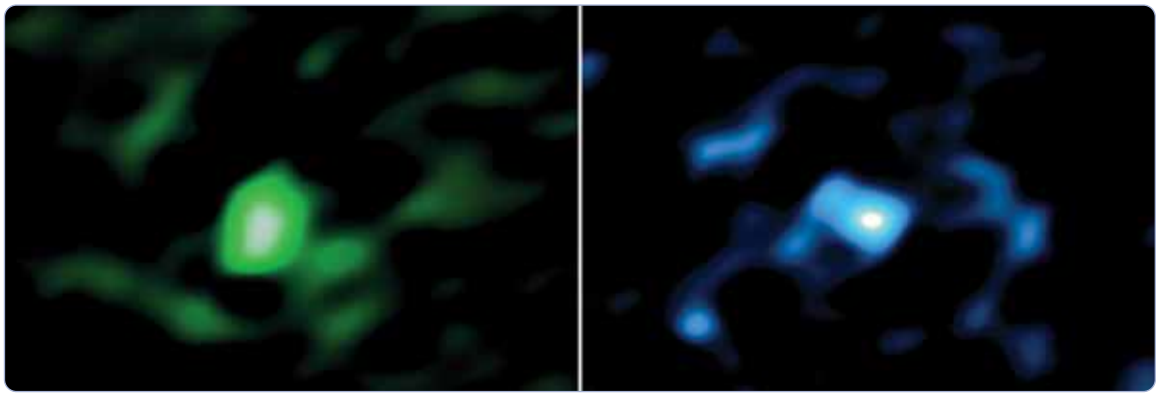
After more than six decades of continual improvement under AUI management, the NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for the astronomy community in the U.S. and around the world.

# SCIENCE HIGHLIGHTS

*Illustration by: Sophia Dagnello, NRAO/AUI/NSF*

## The Formation of Exo-comets

Comets spend most of their lives at large distances from any star, during which time their interior compositions remain relatively unaltered. Cometary observations can therefore provide direct insight into the chemistry that occurred during their birth at the time of planet formation. To date, there have been no confirmed observations of parent volatiles (gases released directly from the nucleus) of a comet from any planetary system other than our own. Here, the authors present high-resolution interferometric observations of Comet 2I/Borisov, the first confirmed interstellar comet, obtained using the **Atacama Large Millimeter/submillimeter Array (ALMA)** on 15–16 December 2019. These observations reveal emission from hydrogen cyanide (HCN) and carbon monoxide (CO) coincident with the expected position of 2I/Borisov's nucleus, with production rates $Q(HCN) = (7.0 \pm 1.1) \times 10^{23}$ per second and $Q(CO) = (4.4 \pm 0.7) \times 10^{26}$ per second. While the HCN abundance relative to water (0.06–0.16%) appears similar to that of typical, previously observed comets in our Solar System, the abundance of CO (35–105%) is among the highest observed in any comet within 2 Astronomical Units (AU) of the Sun. This shows that 2I/Borisov must have formed in a relatively CO-rich environment—probably beyond the CO ice-line in the very cold, outer regions of a distant protoplanetary accretion disk, as part of a population of small icy bodies analogous to our Solar System's own proto-Kuiper belt.



*ALMA HCN* **[Above]** *and CO* **[Above Right]** *observations of Comet 2I/Borisov.* **[Right]** *Hubble Space Telescope image of 2I/Borisov.* **[Far Left]** *Artist impression of the interstellar comet 2I/Borisov as it travels through our solar system.*

**Publication: M.A. Cordiner (Catholic University) et al., *Unusually High CO Abundance of the First Active Interstellar Comet,* Nature Astronomy, 4, 861 (20 April 2020).**

## New Insight into Brown Dwarf Atmospheres

Zonal (latitudinal) winds dominate the bulk flow of planetary atmospheres. For gas giant planets such as Jupiter, the motion of clouds can be compared with radio emissions from the magnetosphere, which is connected to the planet's interior, to determine the wind speed. In principle, this technique can be applied to brown dwarfs, the most common stellar type, and/or directly imaged exoplanets, if periods can be determined for the infrared and radio emissions. In this paper, the authors apply this method to measure the wind speeds on the $40M_J$ brown dwarf 2MASS J10475385+2124234. The difference between the radio period of 1.751 to 1.765 hours measured with the **Karl G. Jansky Very Large Array**, and infrared period of 1.741 ± 0.007 hours measured with the Spitzer Space Telescope, implies a strong wind proceeding eastward of 650 ± 310 meters per second, 6X the winds on Jupiter. This could be due to atmospheric jet streams and/or low frictional drag at the bottom of the atmosphere.

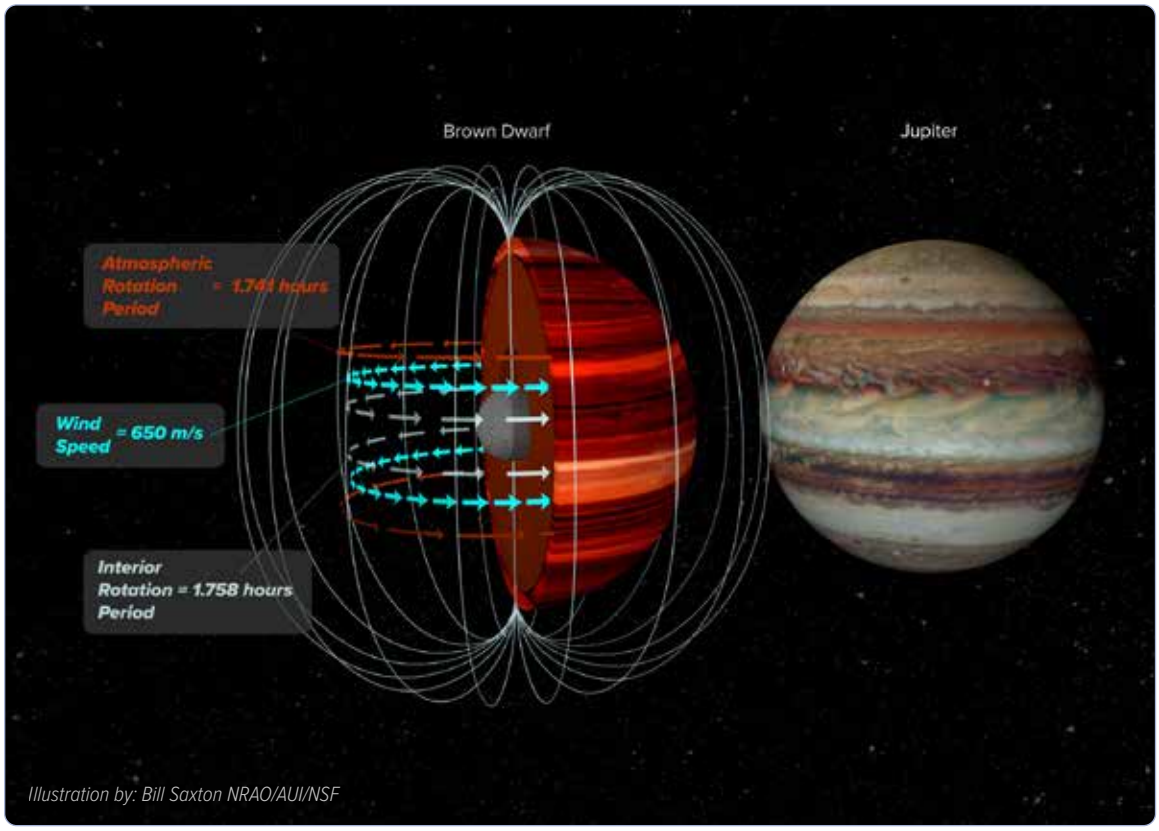



*Figure:* **[Left]** *Brown dwarf and* **[Right]** *Jupiter. Artist's conception of brown dwarf illustrates magnetic field and atmosphere's top, which were observed at different wavelengths to determine wind speeds. Credit: Bill Saxton, NRAO/AUI/NSF.*

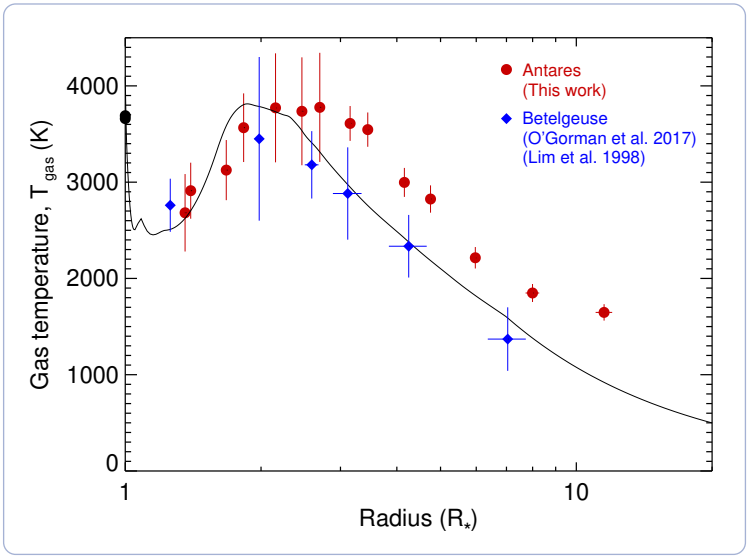
**Publication: Katelyn Allers (Bucknell University) et al., *A Measurement of the Wind Speed on a Brown Dwarf,* Science, 368, Issue 6487, 169 (10 April 2020).**

## The Lukewarm Chromosphere of Antares

The authors present spatially resolved ALMA and Jansky VLA continuum observations of the early-M red supergiant Antares to search for the presence of a chromosphere at radio wavelengths. The free-free emission of the Antares atmosphere is resolved at 11 unique wavelengths between 0.7 mm (ALMA band 8) and 10 cm (VLA S band). The projected angular diameter is found to continually increase with increasing wavelength, from a low of 50.7 milli-arcseconds (mas) at 0.7 mm, up to a diameter of 431 mas at 10 cm, which corresponds to 1.35 and 11.6 times the photospheric angular diameter, respectively.

All four ALMA measurements show that the shape of the atmosphere is elongated, with a flattening of 15% at a similar position angle. The disk-averaged gas temperature of the atmosphere initially rises from a value of 2700 K at 1.35 $R_\star$ (i.e., 0.35 $R_\star$ above the photosphere) to a peak value of 3800 K at ~2.5 $R_\star$, after which it then more gradually decreases to 1650 K at 11.6 $R_\star$. The rise in gas temperature between 1.35 $R_\star$ and ~2.5 $R_\star$ is evidence for a chromospheric temperature rise above the photosphere of a red supergiant. The authors detect a clear change in the spectral index across the sampled wavelength range, with the flux density $S\nu \propto \nu^{1.42}$ between 0.7 mm and 1.4 cm, which they associate with chromosphere-dominated emission, while the flux density $S\nu \propto \nu^{0.8}$ between 4.3 cm and 10 cm, which they associate with wind-dominated emission. The authors show that Antares's outer atmosphere is transparent at their observed wavelengths, and the lukewarm chromosphere that was detected is thus real and not just an average of the cool molecular shell and hot ultraviolet emitting gas. We then perform nonlocal thermal equilibrium modeling of the far-ultraviolet radiation field of another early-M red supergiant, Betelgeuse, and find that an additional hot (i.e., > 7000 K) chromospheric photoionization component with a much smaller filling factor must also exist throughout the chromospheres of these stars.

*Figure: Comparison of the temperature structure of the extended atmospheres of the early-M supergiants Antares and Betelgeuse. The filled red circles are the measurements summarized in this work for Antares, and the filled blue diamonds are the measurements for Betelgeuse from previous work. The gas temperature error bars include the uncertainty in absolute flux density scale. The overlapping filled black circles at $R_\star$ = 1 represent the photospheric effective temperatures of Antares and Betelgeuse. The solid black line is the temperature profile of the semiempirical model for the extended atmosphere of Betelgeuse discussed in this paper.*




**Publication: E. O'Gorman (Dublin Institute for Advanced Studies) et al., *ALMA and VLA Reveal the Lukewarm Chromospheres of the Nearby Red Supergiant Antares and Betelgeuse,* Astronomy & Astrophysics, 638, A65 (2019).**

## A Census of the Orion Protostars

Tobin et al. conducted a survey of 328 protostars in the Orion molecular clouds with ALMA at 0.87 mm at a resolution of ~0.14 milli-arcseconds (40 AU), including observations with the Jansky VLA at 9 mm toward 148 protostars at a resolution of ~0.08 milli-arcseconds (32 AU). This is the largest multiwavelength survey of protostars at this resolution by an order of magnitude. The authors use the dust continuum emission at 0.87 and 9 mm to measure the dust disk radii and masses toward the Class 0, Class I, and flat-spectrum protostars, characterizing the evolution of these disk properties in the protostellar phase. The mean dust disk radii for the Class 0, Class I, and flat-spectrum protostars are $44^{+5.8}_{-3.4}$, $37^{+4.9}_{-3.0}$ and $28.5^{+3.7}_{-2.3}$ AU, respectively, and the mean protostellar dust disk masses $25.9^{+7.7}_{-4.0}$ , $14.9^{+3.8}_{-2.2}$, and $11.6^{+3.5}_{-1.9}$ $M_{\oplus}$, respectively. The decrease in dust disk masses is expected from disk evolution and accretion, but the decrease in disk radii may point to the initial conditions of star formation not leading to the systematic growth of disk radii or that radial drift is keeping the dust disk sizes small. At least 146 of these protostellar disks – 35% of 379 detected 0.87 mm continuum sources plus 42 nondetections – have disk radii greater than 50 AU. These properties are not found to vary significantly between different regions within Orion. The protostellar dust disk mass distributions are systematically larger than those of Class II disks by a factor of more than four, providing evidence that the cores of giant planets may need to at least begin their formation during the protostellar phase.

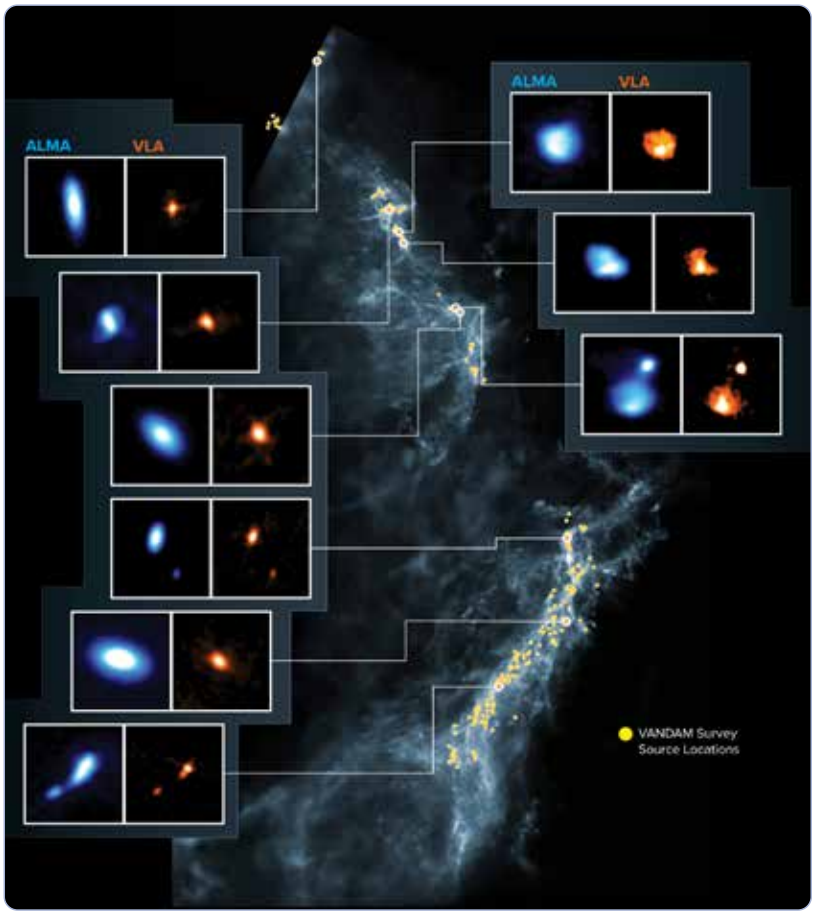



*Figure: Herschel infrared image of the Orion Molecular Cloud [Insets] VLA 32 GHz and ALMA 250 GHz, sample images of protostars in the VANDAM sample.*

**Publication: John J. Tobin (National Radio Astronomy Observatory) et al., *The VLA/ALMA Nascent Disk and Multiplicity (VANDAM) Survey of Orion Protostars. II. A Statistical Characterization of Class 0 and Class I Protostellar Disks,* Astrophysical Journal, 890, 130 (20 February 2020).**

## Megamaser Cosmology: A Better Hubble Constant

The authors present a measurement of the Hubble constant made using geometric distance measurements to megamaser-hosting galaxies. They have applied an improved approach for fitting maser data and obtained better distance estimates for four galaxies previously published by the Megamaser Cosmology Project: UGC 3789, NGC 6264, NGC 6323, and NGC 5765b. Combining these updated distance measurements with those for the maser galaxies CGCG 074-064 and NGC 4258, and assuming a fixed velocity uncertainty of 250 km $s^{-1}$ associated with peculiar motions, this work constrains the Hubble constant to be $H_0$ = 73.9 ± 3.0 km $s^{-1}$ $Mpc^{-1}$ independent of distance ladders and the cosmic microwave background. This best value relies solely on maser-based distance and velocity measurements, and it does not use any peculiar velocity corrections. Different approaches for correcting peculiar velocities do not modify $H_0$ by more than ±1σ, with the full range of best-fit Hubble constant values spanning 71.8 – 76.9 km $s^{-1}$ $Mpc^{-1}$. The authors corroborate prior indications that the local value of $H_0$ exceeds the early-Universe value, with a confidence level varying from 95% to 99% for different treatments of the peculiar velocities.

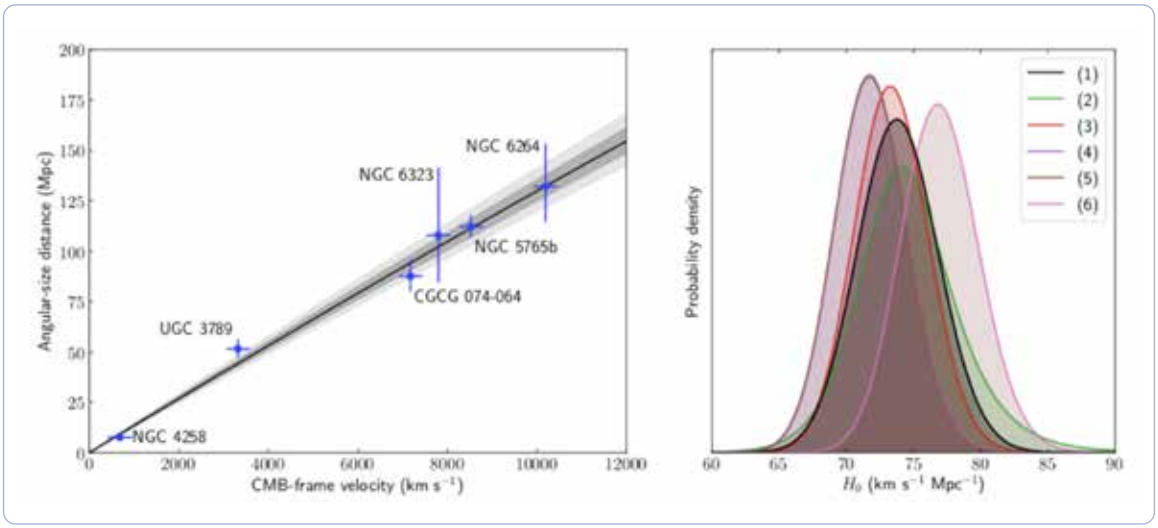



*Figure:* **[Left]** *Distance to the megamaser galaxies.* **[Right]** *Probability distribution for $H_0$ for the six galaxies.*

**Publication: D.W. Pesce (Harvard-Smithsonian Center for Astrophysics) et al., *The Megamaser Cosmology Project. XIII. Combined Hubble Constant Constraints,* Astrophysical Journal Letters, 891, L1 (1 March 2020).**

## A New Type of Cosmic Explosion

The authors discuss ZTF18abvkwla (the "Koala"), a fast blue optical transient (FBOT) discovered in the Zwicky Transient Facility (ZTF) One-Day Cadence (1DC) Survey. ZTF18abvkwla has features in common with the groundbreaking transient AT 2018cow: blue colors at peak light, a short rise time from half-max of under two days, a decay time to half-max of only three days, a high optical luminosity, a hot featureless spectrum at peak light, and a luminous radio counterpart. At late times (Dt > 80 days), the radio luminosity of ZTF18abvkwla at 10 GHz is most similar to that of long-duration gamma-ray bursts (GRBs). The host galaxy is a dwarf starburst galaxy (M ~ 5 x $10^8$ $M_\odot$ and SFR ~ 7 $M_\odot$ per year) that is moderately metal-enriched (log[O/H] ~ 8.5), similar to the hosts of Gamma Ray Bursts (GRBs) and superluminous supernovae.

As in AT2018cow, the radio and optical emission in ZTF18abvkwla likely arises from two separate components: the radio from fast-moving ejecta and the optical from shock-interaction with confined dense material. These FBOTs likely begin the same way as certain supernovae and gamma-ray bursts. The differences are seen in the aftermath of the initial explosion. FBOTS are much brighter than supernovae, but not as bright as GRBs, suggesting a mildly relativistic jet engine in a dense environment. The authors find that transients in the FBOT rise-luminosity phase space are at least two to three orders of magnitude less common than core-collapse supernovae. They discuss strategies for identifying such events with future facilities such as the Vera C. Rubin Observatory, as well as prospects for detecting accompanying X-ray and radio emission.

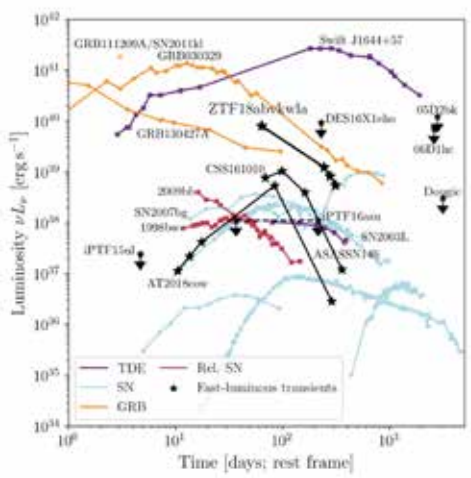



*Figure:* **[Above]** *Radio light curves for several cosmic explosion types. The Koala is marked with an arrow. The FBOTS (black stars) are all much brighter than supernovae, but not as bright as GRBs, suggesting a mildly relativistic jet engine in a dense environment.* **[Right]** *Artist's impression of an FBOT. .*

**Publication: Anna Ho (California Institute of Technology) et al., *The Koala: A Fast Blue Optical Transient with Luminous Radio Emission from a Starburst Dwarf Galaxy at z=0.27,* Astrophysical Journal, 895, 49 (26 May 2020).**

## Finding the Youngest Radio Jets

The authors present new sub-arcsecond Karl G. Jansky Very Large Array (VLA) imaging at 10 GHz of 155 ultra-luminous ($L_{bol}$~$10^{11.7–14.2}L_{\odot}$) and heavily obscured quasars with redshifts z ~ 0.4–3. The sample was selected to have extremely red mid-infrared to optical color ratios based on data from the Wide-Field Infrared Survey Explorer (WISE) along with a detection of bright, unresolved radio emission from the NRAO VLA Sky Survey (NVSS) or Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) Survey. High-resolution VLA observations have revealed that the majority of the sources in this sample (93 of 155) are compact on angular scales < 0.2 arcseconds (≤ 1.7 kpc at z ~ 2). The radio luminosities, linear extents, and lobe pressures of these sources are similar to young radio active galactic nuclei (AGN) but their space density is considerably lower. Application of a simple adiabatic lobe expansion model suggests relatively young dynamical ages (~$10^{4–7}$ years), relatively high ambient interstellar medium densities (~1–$10^4$ $cm^{-3}$), and modest lobe expansion speeds (~30–10,000 km $s^{-1}$). The authors find their sources to be consistent with a population of newly-triggered, young jets caught in a unique evolutionary stage in which they still reside within the dense gas reservoirs of their hosts. Based on their radio luminosity function and dynamical ages, the authors estimate only ~20% of classical large scale FRI/II radio galaxies could have evolved directly from these objects. They speculate that the WISE-NVSS sources might first become Gigahertz Peaked Spectrum or Compact Steep Spectrum sources, of which some might ultimately evolve into larger radio galaxies.

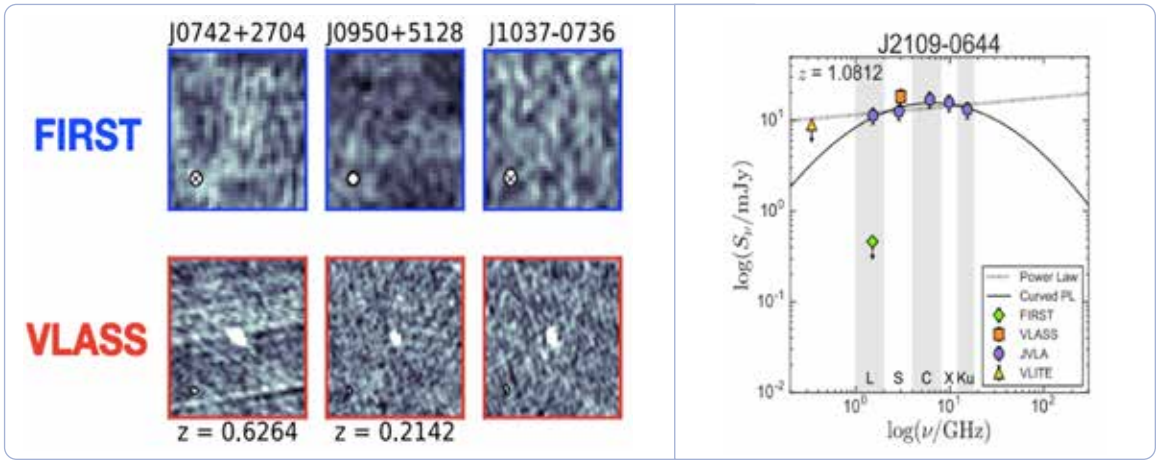



*Figure:* **[Left]** *VLA Sky Survey and FIRST images of the emerging radio loud quasar population.* **[Right]** *VLA spectrum of one source showing the flat radio spectrum.*

**Publication: M.A. Cordiner (Catholic University) et al., *Unusually High CO Abundance of the First Active Interstellar Comet,* Nature Astronomy, 4, 861 (20 April 2020).**

## A Massive Rotating Disk in the Early Universe

Massive disk galaxies like the Milky Way are expected to form at late times in traditional models of galaxy formation, but recent numerical simulations suggest that such galaxies could form as early as a billion years after the Big Bang through the accretion of cold material and mergers. Observationally, it has been difficult to identify disk galaxies in emission at high redshift to discern between competing models of galaxy formation. In this contribution, the authors report imaging, with a resolution of ~1.3 kiloparsecs, the 158-micrometre emission line from singly ionized carbon, the far-infrared dust continuum, and the near-ultraviolet continuum emission from a galaxy at a redshift of 4.2603, identified by detecting its absorption of quasar light. These observations show that the emission arises from gas inside a cold, dusty, rotating disk with a rotational velocity of ~272 kilometers per second. The detection of emission from carbon monoxide in the galaxy yields a molecular mass that is consistent with the estimate from the ionized carbon emission of ~72 billion $M_{\odot}$. The existence of such a massive, rotationally supported, cold disk galaxy when the Universe was only 1.5 billion years old favors formation through either cold-mode accretion or mergers, although its large rotational velocity and large content of cold gas remain challenging to reproduce with most numerical simulations.

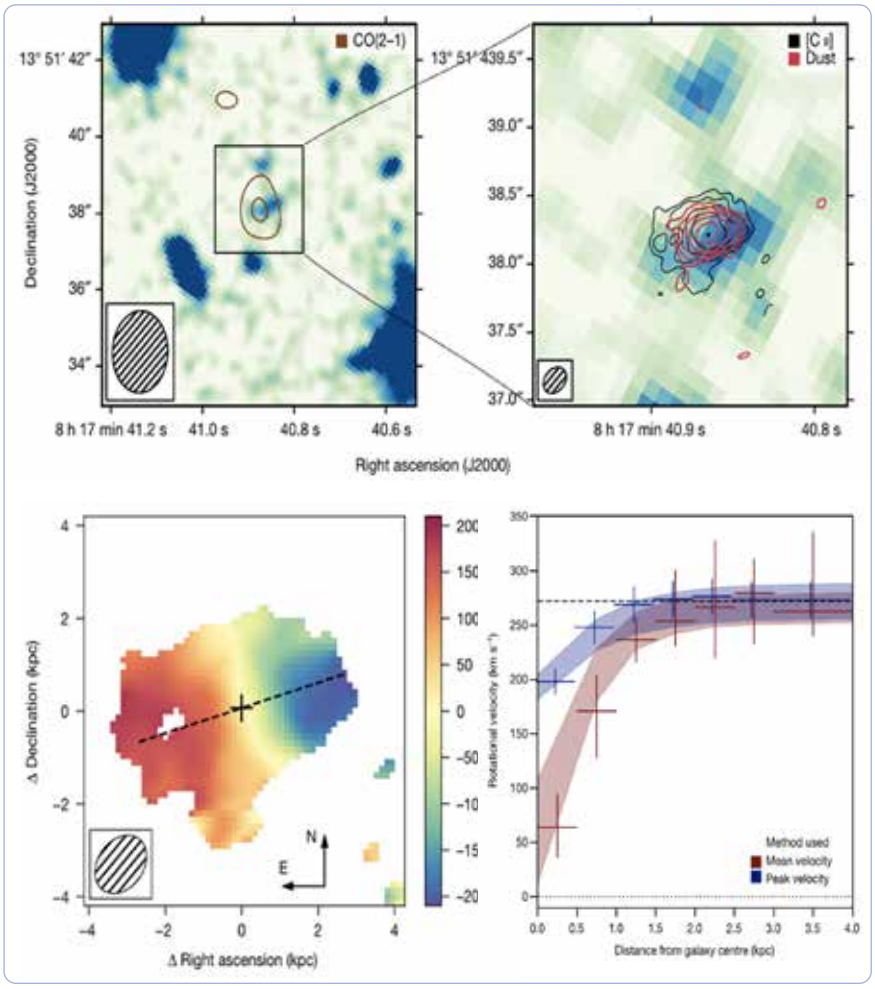



*Figure:* **[Top Left & Top Right]** *VLA CO (2-1) contours, and ALMA contours of the [CII] and thermal dust emission from the z=4.3 Wolfe galaxy.* **[Bottom Left & Bottom Right]** *[CII] velocity field, and the rotation curve.*

**Publication: Marcel Neeleman (Max Planck Institute for Astronomy) et al., *A Cold, Massive, Rotating Disk Galaxy 1.5 Billion Years after the Big Bang,* Nature, 581, 269 (20 May 2020).**

## Gas & Dust in a Galaxy at z = 8.3

Studies of galaxies have now pushed into the Epoch of Reionization, z > 7, when. The very first stars and AGN formed in the Universe. ALMA is a key resource to determine source redshifts and to study the cool gas and dust fueling star formation, and has now extended these studies to  z = 8.3.

In this contribution, the authors report on the detection of the [CII] 157.7 µm emission from the Lyman break galaxy (LBG) MACS0416 Y1 at z = 8.3113, by using **ALMA**. From previous campaigns, the luminosity ratio of [OIII] 88 µm, to [CII] is 9.3 ± 2.6, indicative of hard interstellar radiation fields and/or a low covering fraction of photo-dissociation regions. The emission of [CII] is cospatial to the 850 µm dust emission (90 µm rest-frame, from previous campaigns), however the peak [CII] emission does not agree with the peak [OIII] emission, suggesting that the lines originate from different conditions in the interstellar medium. The authors failed to detect continuum emission at 1.5 mm (160 µm rest-frame) down to 18 µJy (3σ). This non-detection places a strong limit on the dust spectrum, considering the 137 ± 26 µJy continuum emission at 850 µm. This suggests an unusually warm dust component (T > 80 K, 90% confidence limit), and/or a steep dust-emissivity index (βdust > 2), compared to galaxy-wide dust emission found at lower redshifts (typically T ~ 30 – 50 K, βdust ~ 1 – 2). If such temperatures are common, this would reduce the required dust mass and relax the dust production problem at the highest redshifts. Thus, the authors warn against the use of only single-wavelength information to derive physical properties, recommend a more thorough examination of dust temperatures in the early Universe, and stress the need for instrumentation that probes the peak of warm dust in the Epoch of Reionization.

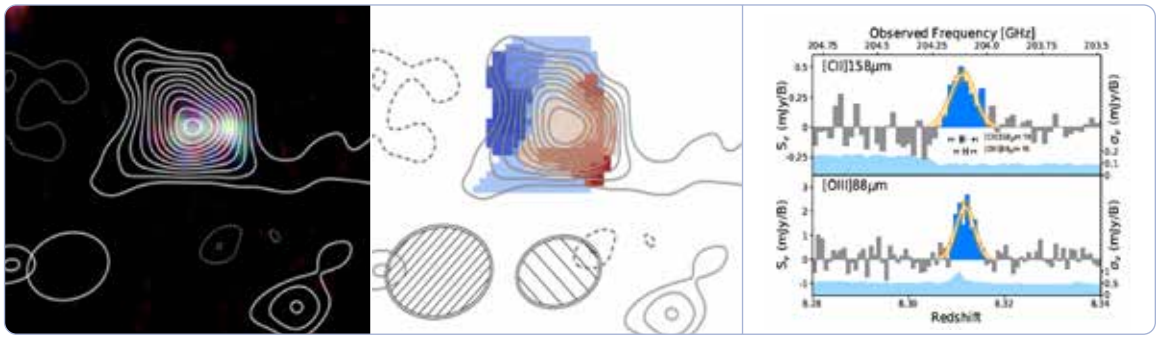



*Figure:* **[Left]** *ALMA image of [CII] emission from a z=8.3 galaxy, and the Hubble Space Telescope near-infrared image.* **[Center]** *[CII] velocity field.* **[Right]** *[CII] and [OIII] emission from ALMA..*

**Publication: Tom J.L.C. Bakx (Nagoya University) et al., *ALMA Uncovers the [C II] Emission and Warm Dust Continuum in a z = 8.31 Lyman Break Galaxy,* Monthly Notices of the Royal Astronomical Society, 493, Issue 3, 4294.**

## VLBA Measures the Ephemeris of Saturn

Jones et al. report results from multi-epoch radio astrometry of the Cassini spacecraft with the Very Long Baseline Array (VLBA). These observations are part of a program to determine accurate positions for the Saturn system barycenter in the inertial International Celestial Reference Frame (ICRF) and to use these position measurements to improve our knowledge of Saturn's orbit in the planetary ephemeris. The VLBA observations reported here cover the full duration of the orbital phase of the Cassini mission, from Saturn orbit insertion in 2004 to the end of mission in 2017. This period covers more than one-third of Saturn's orbital period, allowing the team to obtain good orbit constraints for Saturn, particularly on the inclination and ascending node longitude. During the early years of Cassini's orbital mission, their VLBA data dominated the determination of orbit orientation, while later in the mission range measurements become more significant. The orientation of Saturn's orbit is now known to ~ 0.25 milli-arcseconds (1.25 nrad), an order of magnitude improvement since the start of Cassini observations. Continuing improvements in the ICRF position accuracy for the phase reference sources, and possible improvements in the final orbit solutions for Cassini, may lead to a still better Saturn orbit over the coming years.

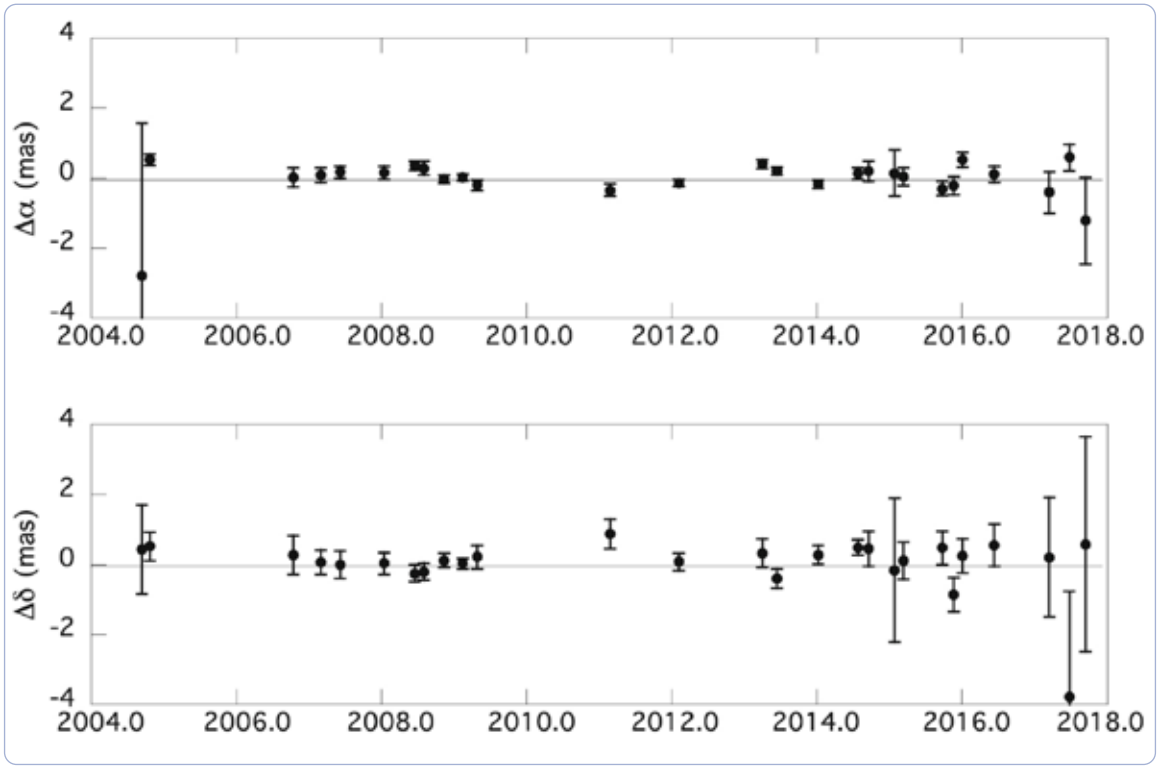



*Figure: Post-fit residuals of Saturn's orbit fit to the VLBA determined position for the Saturn system barycenter, in right ascension and declination*

**Publication: Dayton L. Jones (Space Science Institute) et al., *Very Long Baseline Array Astrometry of Cassini: The Final Epochs and an Improved Orbit of Saturn,* Astronomical Journal, 159, 75 (20 January 2020).**

## Large-scale Gas Distribution Around Protoplanetary Disks

While protoplanetary disks often appear to be compact and well organized in millimeter continuum emission, CO spectral line observations are increasingly revealing complex behavior at large distances from the host star. Huang et al. present deep **ALMA** maps of the J = 2–1 transition of $^{12}CO$, $^{13}CO$, and $C^{18}O$, as well as the J = 3–2 transition of $DCO^+$, toward the T Tauri star RU Lup at a resolution of ~0.3 arcseconds (~50 AU). The CO isotopologue emission traces four major components of the RU Lup system: (1) a compact Keplerian disk with a radius of ~120 AU; (2) a non-Keplerian "envelope-like" structure surrounding the disk and extending to ~260 AU from the star; (3) at least five blueshifted spiral arms stretching up to 1000 AU; and (4) clumps outside the spiral arms located up to 1500 AU in projection from RU Lup. The authors comment on potential explanations for RU Lup's peculiar gas morphology, including gravitational instability, accretion of material onto the disk, or perturbation by another star. RU Lup's extended non-Keplerian CO emission, elevated stellar accretion rate, and unusual photometric variability suggest that it could be a scaled-down Class II analog of the outbursting FU Ori systems.

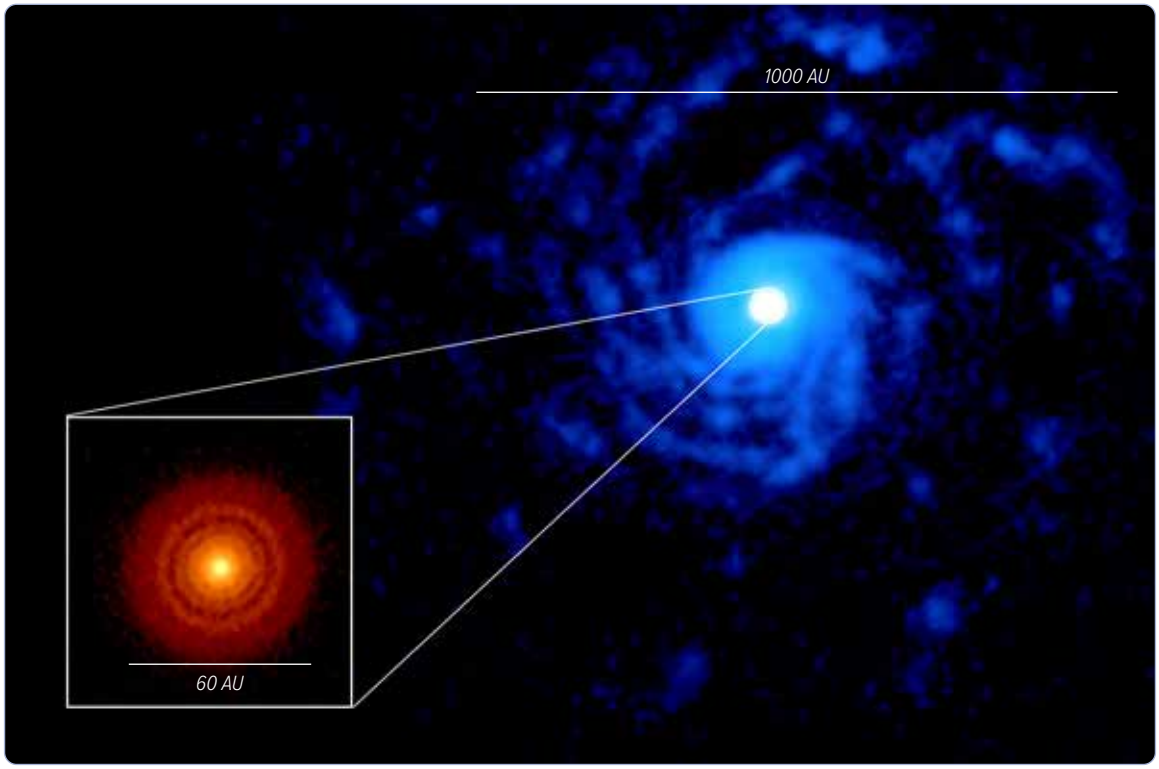
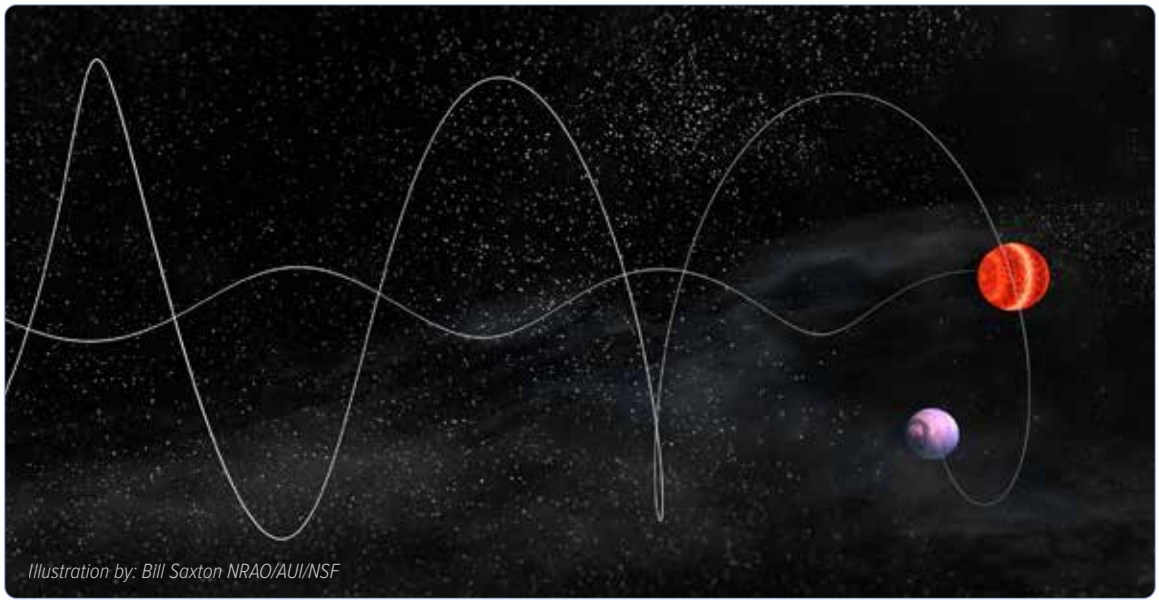



*Figure: ALMA CO 2-1 (blue) and 230 GHz dust (red) emission at 0.3 arcsec resolution of the protoplanetary disk around RU Lupus.*

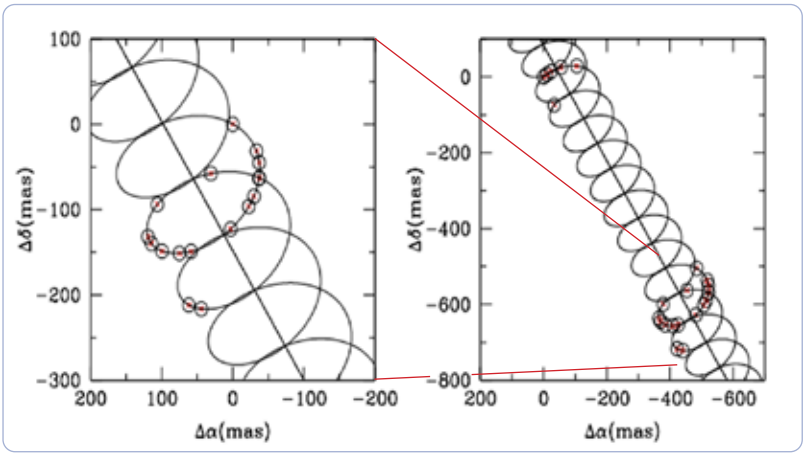
**Publication: Jane Huang et al.. *Large-scale CO Spiral Arms and Complex Kinematics Associated with the T Tauri Star RU Lup,* Astrophysical Journal, 898, 140 (3 August 2020).**

## First astrometric planet discovery using VLBI

Astrometric observations of the M9 dwarf TVLM 513–46546 taken with the VLBA reveal an astrometric signature consistent with a period of 221 ± 5 days. The orbital fit implies that the companion has a mass $m_p$ = 0.35–0.42 $M_J$, a circular orbit (e ~ 0), a semimajor axis a = 0.28–0.31 AU, and an inclination angle i = 71°–88°. The detected companion, TVLM 513b, is one of the few giant-mass planets found associated with ultracool dwarfs. The presence of a Saturn-like planet on a circular orbit 0.3 AU from a 0.06–0.08 $M_\odot$ star represents a challenge to planet formation theory. This is the first astrometric detection of a planet at radio wavelengths.




*Figures:* **[ABOVE]** *Illustration shows how the star's motion around the center of mass between it and the planet causes a "wobble" in its motion through space. The VLBA's ability to detect this minuscule effect revealed the presence of the planet.* **[RIGHT]** *Proper motion of the star TVLM 513–46546 showing the astrometric wobble due to the presence of the planet.*




**Publication: Salvator Curiel (Universidad Nacional Autonoma de México) et al., *An astrometric planetary companion candidate to the M9 Dwarf TVLM 513-46546,* Astronomical Journal, 159, 72 (4 August 2020).**

## Misaligned Rings in a Protoplanetary Disk

Independent research teams have used ALMA and the Very Large Telescope (VLT) to image a set of misaligned rings in a protoplanetary disk around the young, triple star system GW Orionis. This system includes an inner binary of 1 AU separation, and an outer star orbiting at 8 AU, with a different orbital plane. Young stars are surrounded by a circumstellar disk of gas and dust, within which planet formation can occur. Gravitational forces in multiple star systems can disrupt such a disk.

GW Orionis is a hierarchical triple system with a rare circumtriple disk. Bi et al present ALMA observations of 1.3 mm dust continuum and $^{12}$CO J = 2 − 1 molecular gas emission of the disk. For the first time, three dust rings are identified in the GW Ori disk at ~46, 188, and 338 AU, with estimated dust mass of 74, 168, and 245 Earth masses, respectively. The outermost ring is apparently the largest dust ring ever found in protoplanetary disks. The authors use visibility modeling of their dust continuum data to show that the disk has misaligned parts, and the innermost dust ring is eccentric. The disk misalignment is also suggested by the CO kinematics. These substructures are interpreted as evidence of ongoing dynamical interactions between the triple stars and the circumtriple disk.

Theoretical models predict that if a circumstellar disk is misaligned with the orbital plane of the stars, the disk should warp and break into precessing rings, a phenomenon known as disk tearing. Kraus et al. present ALMA and VLT observations of the triple-star system GW Orionis, and find evidence for such disk tearing. These authors imaged the GW Orionis system using submillimeter and near-infrared interferometry, which trace thermal dust emission, and using visible and near-infrared adaptive-optics imaging polarimetry at the VLT, which trace scattered light. These data allow enable Kraus et al. to constrain the dust distribution in the system. Their images show an eccentric ring that is misaligned with the orbital planes and the outer disk. The ring casts shadows on a strongly warped intermediate region of the disk. If planets can form within the warped disk, disk tearing could provide a mechanism for forming wide-separation planets on oblique orbits.

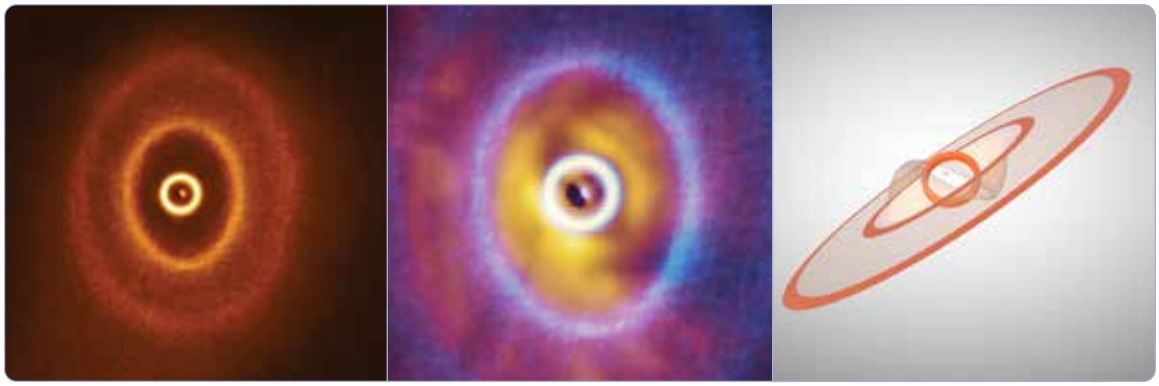


*Figure: ALMA 230GHz (left) and VLT (center) images of the misaligned protoplanetary disk around the young triple star system GW Orionis (Bi et al. 2020, Kraus et al. 2020). (right) The 3D model of the GW Orionis system, in projection.*

**Publications: Jiaquing Bi (University of Victoria) et al., GW Ori: *Interactions between a Triple-star System and Its Circumtriple Disk in Action,* Astronomical Journal, 159, 72 (4 August 2020).**

**Stefan Kraus (University of Exeter) et al., *A Triple-star System with a Misaligned and Warped Circumstellar Disk Shaped by Disk Tearing,* Science, 369, 1233 (4 September 2020).**

## The Distance to a Magnetar

XTE J1810−197 (J1810) was the first magnetar identified to emit radio pulses, and has been extensively studied during a radio-bright phase in 2003–2008. Magnetars are slowly rotating neutron stars with the largest magnetic fields measured in the Universe (>$10^{14}$ Gauss). The magnetar J1810 is estimated to be relatively nearby compared to other Galactic magnetars, and provides a useful prototype for the physics of high magnetic fields, magnetar velocities, and the plausible connection to extragalactic fast radio bursts.

Upon the rebrightening of the magnetar at radio wavelengths in late 2018, Ding et al. resumed an astrometric campaign on J1810 with the **VLBA**, and sampled 14 new positions of J1810 over 1.3 yr. The phase calibration for the new observations was performed with two-phase calibrators that are quasi-colinear on the sky with J1810, enabling substantial improvement of the resultant astrometric precision. Combining their new observations with two archival observations from 2006, they refined the proper motion and reference position of the magnetar and have measured its annual geometric parallax, the first such measurement for a magnetar.

The parallax of 0.40 ± 0.05 milli-arcseconds corresponds to a most probable distance $2.5^{+0.4}_{-0.3}$ kpc for J1810. Their new astrometric results confirm an unremarkable transverse peculiar velocity of ≈200 km/sec for J1810, which is only at the average level among the pulsar population. The magnetar proper motion vector points back to the central region of a supernova remnant (SNR) at a compatible distance at ≈70 kyr ago, but a direct association is disfavored by the estimated SNR age of ~3 kyr.

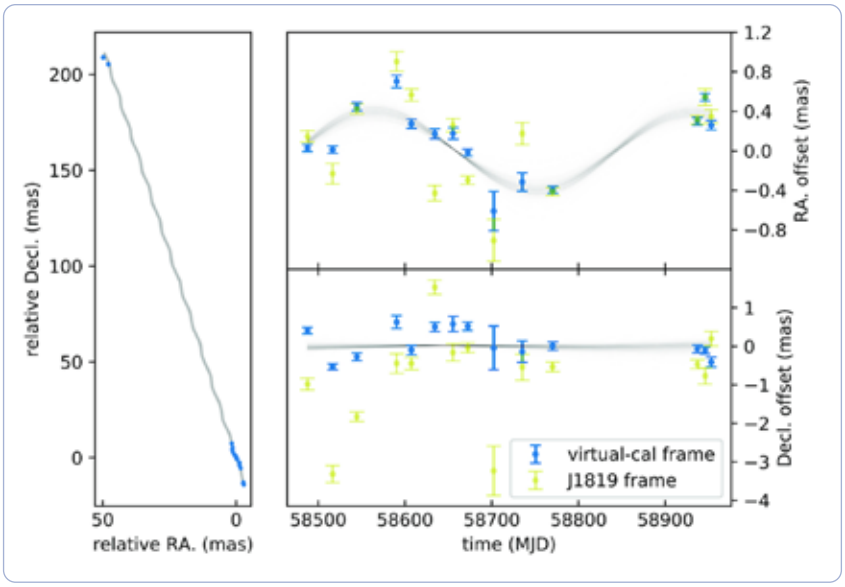



*Figure: Astrometric observations at 5.7 GHz with the VLBA, showing the proper motion relative to the phase reference source, and the annual parallax after subtraction of the proper motion, of XTE J1810.*

**Publication: Hoa Ding (Swinburne University of Technology) et al., *A Magnetar Parallax,* Monthly Notices of the Royal Astronomical Society, 498, 3736 (November 2020).**

## Axions, Magnetars, and the VLA

Axions are a leading candidate for cold Dark Matter. Axions may convert their rest energy into photons in extreme magnetic field regions, such as the > $10^{14}$ G fields that exist around Magnetars – the strongest fields known in the Universe. Such conversion would produce photons in the range of 0.2 GHz to 20 GHz.

In this paper, PI Jeremy Darling reports on a search for dark matter axion conversion photons from the magnetosphere of the Galactic Center magnetar PSR J1745-2900 using spectra obtained from the ***Karl G. Jansky VLA***. No significant spectral features are detected. Using a hybrid model for PSR J1745-2900 and canonical assumptions about the dark matter density profile, Darling could exclude axion models with axion-photon coupling $g_{a\gamma\gamma}$ > 6–34×$10^{-12}$ $GeV^{-1}$ with 95% confidence over the mass ranges 4.2–8.4, 18.6–26.9, 33.0–41.4, 53.7–62.1, and 126.0–159.3 μeV. If there is a dark matter cusp, the limits reduce to $g_{a\gamma\gamma}$ > 6–34×$10^{-14}$ $GeV^{-1}$, which overlap some axion models for the observed mass ranges >33 μeV. These limits may be improved by modeling the stimulated emission that can boost the axion-photon conversion process. The radio non-detection provides one of the best limits to date on the Axion-photon coupling constant.

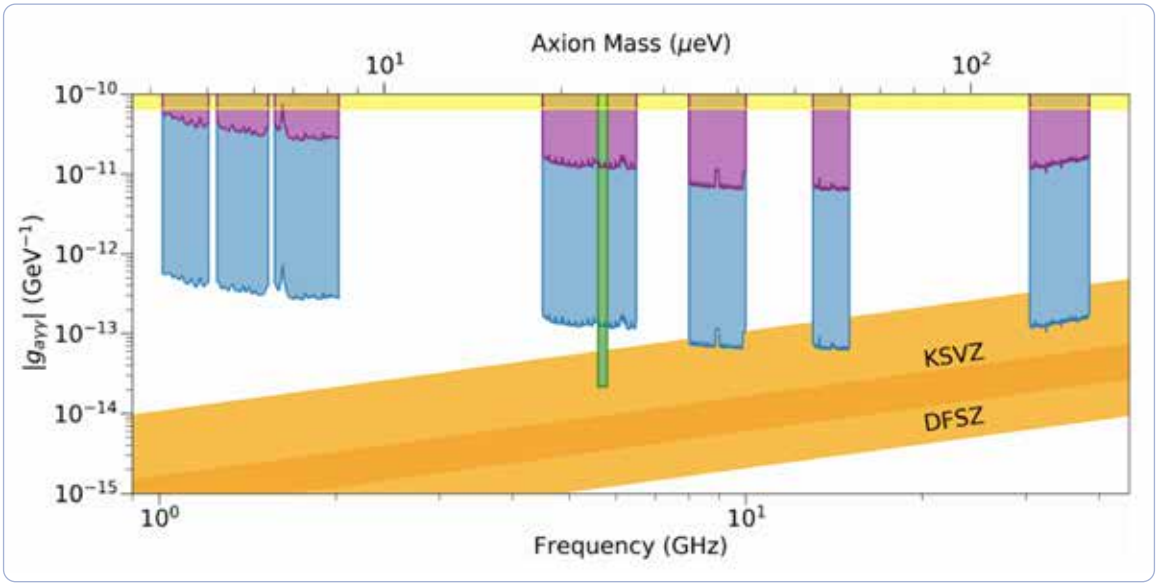



*Figure: Limits on the Axion-photon coupling constant from the VLA in PSR J1745-2900). Yellow regions are current models for the Axion magnetic coupling constant for a reasonable range in Axion mass. The green box indicates the best laboratory limits to date.*

**Publication: Jeremy Darling (University of Colorado), *Search for Axionic Dark Matter Using the Magnetar PSR J1745-2900,* Physics Review Letters, 125, 121103 (17 September 2020).**

## Imaging the Accretion Zone in M87

Kravchenko et al. report on high angular resolution polarimetric observations of the nearby radio galaxy M87 using the **VLBA** at 24 GHz (λ = 1.3 cm) and 43 GHz (λ = 7 mm) in 2017–2018. New images of the linear polarization substructure in the nuclear region are presented, characterized by a two-component pattern of polarized intensity and smooth rotation of the polarization plane around the 43 GHz core. From a comparison with an analogous dataset from 2007, the authors find that this global polarization pattern remains stable over a time interval of 11 years, while showing smaller month-scale variability. The authors discuss the possible Faraday rotation toward the M87 nucleus at centimeter to millimeter wavelengths. These results can be interpreted in a scenario where the observed polarimetric pattern is associated with the magnetic structure in the confining magnetohydrodynamic wind, which also serves as the source of the observed Faraday rotation.

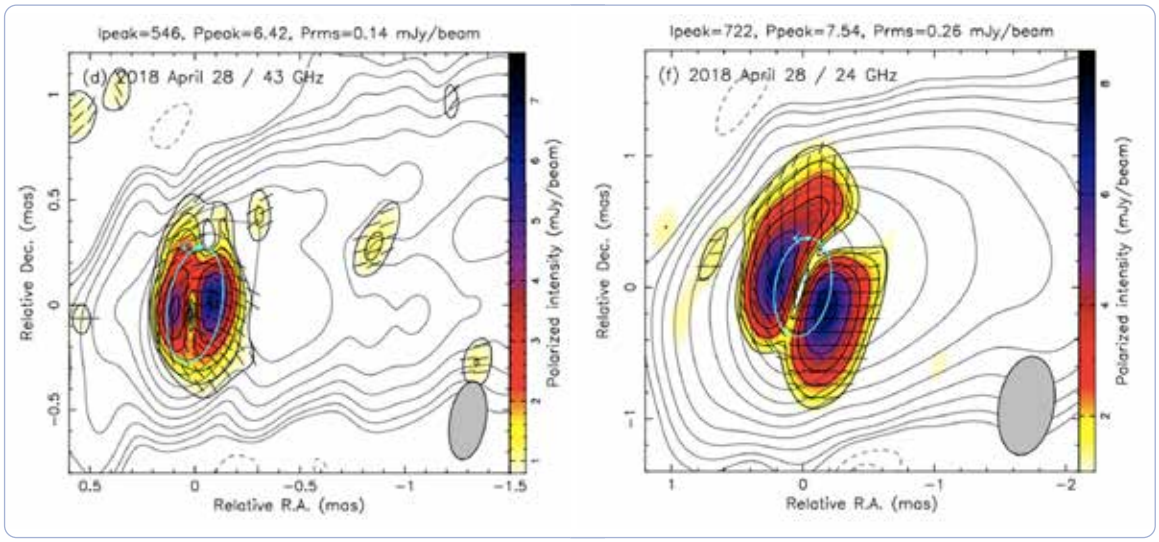


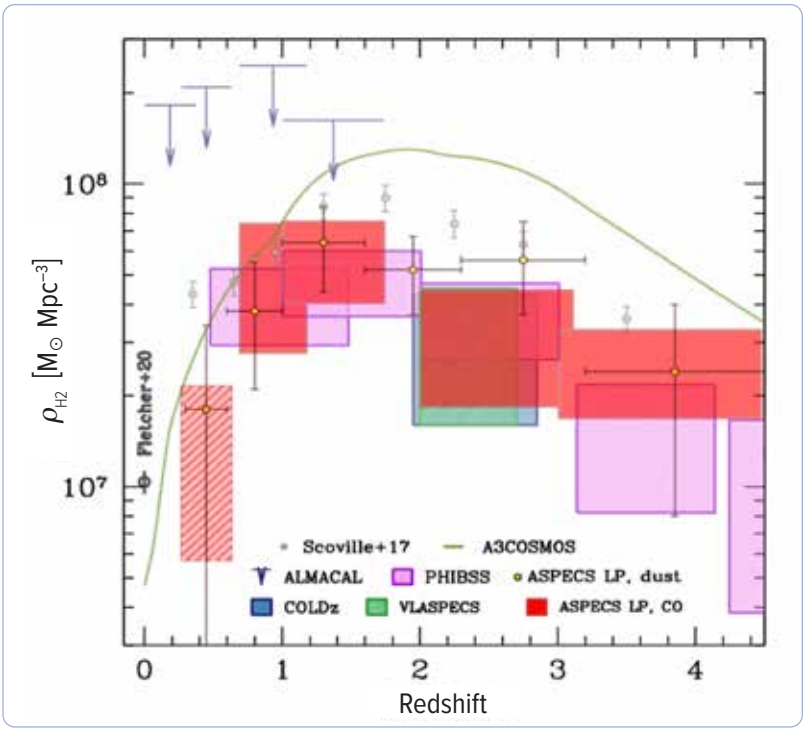

*Figure:* **[Left]** *VLBA images at 43 GHz and 24 GHz* **[Right]** *of the polarized (color) and total (gray contours) intensity from M87, plus observed position angles.*

**Publication: E. Kravchenko (Istituto di Radioastronomia, Lebedev Physical Institute) et al., *Linear polarization in the nucleus of M87 at 7 mm and 1.3 cm,* Astronomy & Astrophysics, 637, L6 (May 2020).**

## The ALMA Spectroscopic Survey Deep Field

Decarli et al. present a CO and atomic fine-structure line luminosity function analysis using the ALMA Spectroscopic Survey in the Hubble Ultra Deep Field (ASPECS). ASPECS consists of two spatially– overlapping mosaics that cover the entire ALMA 3 mm and 1.2 mm bands. We combine the results of a line candidate search of the 1.2 mm data cube with those previously obtained from the 3 mm cube. The resulting analysis shows that ~80% of the line flux observed at 3 mm arises from CO(2-1) or CO(3-2) emitters at z=1–3 ('cosmic noon'). At 1.2mm, more than half of the line flux arises from intermediate-J CO transitions (Jup=3–6); ~ 12% from neutral Carbon lines; and < 1% from singly-ionized Carbon, [C II]. This implies that future [C II] intensity mapping surveys in the epoch of reionization will need to account for a highly significant CO foreground. The CO luminosity functions probed at 1.2mm show a decrease in the number density at a given line luminosity at increasing Jup and redshift. Comparisons between the CO luminosity functions for different CO transitions at a fixed redshift reveal sub-thermal conditions on average in galaxies up to z ~ 4. In addition, the comparison of the CO luminosity functions for the same transition at different redshifts reveals that the evolution is not driven by excitation. The cosmic density of molecular gas in galaxies, $\rho_{H2}$ shows a redshift evolution with an increase from high redshift up to z ~ 1.5 followed by a factor ~ 6 drop down to the present day. This is in qualitative agreement with the evolution of the cosmic star–formation rate density, suggesting that the molecular gas depletion time is approximately constant with redshift, after averaging over the star-forming galaxy population.

*Figure: Evolution of the molecular gas density of the Universe derived from ASPECS and other methods.*




**Publication: Roberto Decarli (Istituto di Radioastronomia) et al., *The ALMA Spectroscopic Survey in the HUDF: Multi-band constraints on line luminosity functions and the cosmic density of molecular gas,* Astrophysical Journal (submitted 2020).**

# NORTH AMERICAN ALMA OPERATIONS

*Photo by: Pablo Carillo*

North American ALMA Operations (NA ALMA Ops) is the NRAO department that provides North America's scientific and technical partnership support to the international ALMA Observatory and supports the North American community in their use of ALMA. NA ALMA Ops ensures that the North American scientific community has the tools, information, support, and access to make optimal scientific use of ALMA. It 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 development program for the technical enhancement of ALMA.

NA ALMA Ops includes four divisions: (1) the North American ALMA Science Center (NAASC); (2) the Offsite Technical Maintenance and Support group, including Construction Warranty support; (3) the NA ALMA Development Program; and (4) the NRAO/AUI Office of Chilean Affairs (OCA).

**NA ALMA Ops focused on the following high-level initiatives in 2020:**

- Support JAO Operations and NA scientific community use of ALMA;
- Support the JAO and the NA science community with the Cycle 7 Supplemental Call, utilizing Distributed Peer Review;
- Support the NRAO SRDP strategic initiative while continuing to meet ALMA core deliverables;
- Facilitate NA Principal Investigators (PIs) in the publication of their ALMA results, ensuring that they have the tools, training, and assistance to be competitive with their regional peers;
- Initiate the strategic plan to expand the ALMA user-base beyond the radio, millimeter, and submillimeter experts;
- Enhance staff relations and the work environment in Chile, building toward the next collective bargaining agreement; complete the Multicancha indoor gymnasium project; and
- Participate in the implementation of the ALMA 2030 Development Roadmap through NA projects and collaborations, and collaborate on long-range visions for ALMA.

The year 2020 began smoothly for ALMA, with the JAO and NA ALMA Ops on track to meet Cycle 7 observing targets and operational milestones. Owing to the coronavirus pandemic, the JAO suspended observing operations in mid-March, and NRAO North American staff began working from home. Even though half of Cycle 7 observing was lost, many high-level initiatives were achieved.

## From the Archives

On 21 August 1998, the President of Chile, Eduardo Frei, Minister of Mining, Sergio Jimenez, Minister of National Assets Adriana Delpiano, and President of CONICYT, Mauricio Sarrazin, signed a declaration designating the ALMA area as a Site of Scientific Interest for mining purposes, which provided from the outset a significant degree of protection to our operations. In this photo taken at the signing, Eduardo Hardy (left), AUI representative in Chile, and Acting AUI President Martha Haynes (right) present President of Chile Eduardo Frei (center) with a satellite picture of the ALMA Site made by the Cornell group.

## North American ALMA Science Center

Despite the COVID-19 pandemic, the NAASC made excellent progress on its strategic goals for 2020. The NAASC supported the Science Ready Data Products (SRDP) initiative as a top priority. Several NAASC staff were matrixed into the SRDP office to enhance delivered PI data products in support of publications, and expand the NA ALMA user base. The NAASC also focused on user- and telescope-facing tasks, data analysis, and development while navigating the pandemic. All NAASC staff transitioned to Work From Home (WFH) on 16 March. ALMA opened the Cycle 8 Call for Proposals (CfP) on 17 March, but stopped Cycle 7 Observing on 19 March. Several weeks after opening, the Cycle 8 CfP was delayed a full year and the ALMA site in Chile was shut down. Nevertheless, the NAASC was able to make substantial progress and complete many of its 2020 initiatives.

**Community Support:** The NAASC continued the ALMA Ambassadors program: scientists from the community visited the NAASC for training in the use of ALMA tools and software. The Ambassadors then organized and led ALMA training events around the U.S Before the start of the pandemic, the Cycle 8 ALMA Ambassadors met for a training session in Charlottesville, VA.

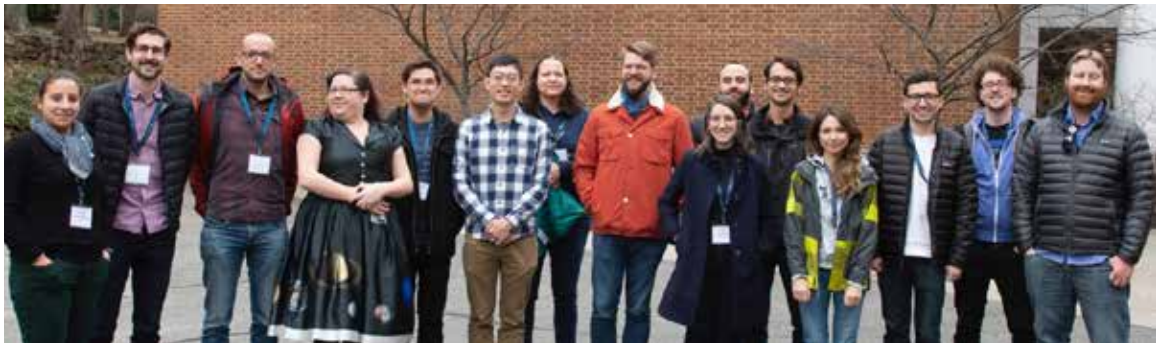


*Figure: ALMA Cycle 8 Ambassadors during the February 2020 training at NRAO headquarters in Charlottesville, VA.*

Fifteen events were planned prior to the pandemic and 13 were executed. The virtual events started 19 March and were offered continuously until 3 April, serving ~180 attendees.

**ALMA Ambassadors and their Events**

| *Dates* | *Original Location – Virtual* | *Ambassador (Affiliation)* |
|---|---|---|
| March 6, 2020 | University of Massachusetts - Amherst | Christopher Faesi (UMass) |
| March 19, 2020 | Carnegie Observatories, Pasadena | Gregory Walth (Carnegie) & Serena Perrota (UCSD) |
| March 20, 2020 | University Maryland | Veronica Allen (NASA GSFC) |
| March 23, 2020 | University of Toronto / OSU | Toby Brown (McMaster) & Amy Sardone (OSU) |
| March 24, 2020 | Haverford College | David Stark (Haverford) |
| March 25, 2020 | Universidad de La Serena | Jorge Gonzalez Lopez (UDP) & David Rebolledo (JAO/NRAO) |
| March 26, 2020 | University of Wyoming | George Privon (UFL/NRAO) |
| March 27, 2020 | John Hopkins University | Andrey Vayner (JHU) & Alexander Thelen (NASA GSFC) |
| March 30, 2020 | University of Oklahoma | Ben Tofflemire (UTexas) |
| March 31, 2020 | Columbia University | Thomas Rice (Columbia) |
| April 1, 2020 | Universidad Diego Portales | Jorge Gonzalez Lopez (UDP) & David Rebolledo (JAO/NRAO) |
| April 2, 2020 | NASA Goddard SFC | Veronica Allen & Alexander Thelen (NASA GSFC) |
| April 3, 2020 | University of Washington | Danielle Lucero (VT) |

The NAASC collaborated with their colleagues in Socorro to provide logistical and scientific support for the first virtual Synthesis Imaging Summer School (17th NRAO Synthesis Imaging Workshop) in Socorro, held 29 June – 17 July.

The NAASC was a major contributor and/or host to multiple scientific and topical meetings. Applications for this program were submitted to the NAASC for conferences in 2020. Decisions were announced within four to six weeks of submission. The list below summarizes the community proposals submitted for NAASC funding support and those meetings/workshops that were cancelled due to the COVID-19 pandemic.

- *Extreme Galactic Nuclear Activity - Ultraluminous Starbursts and AGN: A Symposium in Honor of Dave Sanders* (Honolulu, Hawaii), 9 January 2020 (Request/Award: $11–13K/$2.5K).
- *Gordon Research Seminar on Origins of Life* (Galveston, Texas), 18-19 January 2020 (Request/Award: $5K/$5K, shared with ngVLA).
- *Quenching and Transformation Throughout Cosmic Time* (Aspen Center for Physics, Aspen, Colorado) 8-13 February 2020 (Request/Award: $21K/$12K).
- *Ground and Space observatories: a Joint Venture to Planetary Science.* Planets2020 (Santiago, Chile) 2-6 March 2020 (Request/Award: $10K/$10K).
- *From Collapsing Cores to Forming Disks: Fostering Connections Between Theory, Observation, and Chemistry* (NRAO, Charlottesville, Virginia) 10-13 March 2020 (Request/Award: $14.8K/$2K).
- *ACS Symposium: Astrochemical Complexity in Planetary Systems* (Philadelphia, Pennsylvania) 22-26 March 2020 (Request/Award: $3071/$3071). Cancelled due to COVID-19.
- *Multiphase Gas in Galaxy Groups* (NRAO, Charlottesville, Virginia) 23-25 June 2020, (Request/Award: $25K/17.5K). *Postponed due to COVID-19.*
- *The Aftermath of a Revolution: Planet Formation Five Years After HL Tau* (Puerto Varas, Chile) 7-11 December 2020 (Request/Award: $15K/$15K (shared with ngVLA). *Virtual event due to COVID-19.*

The NAASC also hosted a Special Session at the American Astronomical Society (AAS) meeting in Honolulu, 4–8 January 2020. The 75th International Symposium on Molecular Spectroscopy scheduled in Champaign, Illinois 15–19 June 2020 was postponed for a year due to the COVID-19 pandemic.

**User Documentation:** Prior to the postponement of ALMA Cycle 8, the NAASC completed the documentation preparation and review activities for the Cycle 8 Call for Proposals, Proposer's/User's Guide, ALMA Primer, ALMA Technical Handbook, Guide to the NA ARC, software user guides (including CASAGuides), and the additional documentation on how to access NAASC services.

The JAO planned to continue testing the new proposal review process via a Supplemental Call for Proposals for the Atacama Compact Array (ACA, 7-m, and Total Power arrays) in mid-Cycle 7. NAASC staff were to assist the JAO in preparing for this Supplemental Proposal Call, drafting the relevant documentation and preparing the ALMA science portal. However, the supplemental call for mid-Cycle 7 was canceled due to the ALMA pandemic shutdown.

**Face to Face Visitor and Helpdesk Support:** The NAASC manages ALMA Helpdesk activities including routine ticket reviews, enforcement of ticket service level agreements, and formulation of new Knowledgebase articles based on user questions. Face-to-face (f2f) support includes hosting one to two data processing teams from NA institutions per week at the NA ALMA Regional Center (ARC) in Charlottesville or at the National Research Council (NRC) in Victoria, British Columbia. The visiting data processing teams work with the NAASC data analysts and NAASC or NRC scientific support staff on various aspects of data processing and image analysis. The NAASC continued hosting f2f visitors in 2020 by transitioning to virtual visits. The NAASC hosted 21 f2f visitors; five visitors were hosted virtually.

**Data Processing:** An important NAASC objective is the delivery of fully calibrated data and representative images of ALMA standard observing modes to PIs within 30 days of the last successful execution on the array. NAASC staff continued to work closely in 2020 with the JAO teams and delivered, on average, 30–35 datasets per week to the NA ALMA user community until the ALMA shutdown. After the shutdown, NAASC staff continued processing the more difficult datasets that needed manual calibration.

**Telescope Interface and Diagnostics:** As the NAASC technical liaison to the JAO, this group was responsible for several initiatives in 2020, including organizing and running the ALMA proposal review process. As communication and interaction between the ARCs and the JAO, especially f2f visits, are of critical importance to ALMA project success, NAASC staff were to take part in an ALMA Science Exchange with the other ARCs and the JAO. Due to the pandemic, several initiatives were cancelled; a summary of the activities achieved or cancelled follows.

**ALMA Proposal Review Process:** The NAASC provides technical expertise in support of the ALMA proposal review process, the Proposal Handling Tool (PHT) technical assessment, and technical secretary functions. Due to the ALMA shutdown and the Cycle 8 postponement, the NAASC did not participate in the Cycle 8 ALMA proposal review process nor provide technical secretaries or the Phase 1 Manager Cognizant Lead to the Review Panels and Proposal Review Committee meetings.

**Phase 2 Group (P2G):** NAASC P2G staff provide the technical expertise to review and set up Phase 2 materials (Scheduling Blocks, SBs) submitted by NA PIs for an observing cycle. This includes modifying SBs that require expert technical input, coordinating with the JAO to request calibrator searches, and ensuring that all SBs are ready to run on the telescope. During a cycle, the NAASC staff also provide any SB changes required following an approved change request or other edits requested by the PI or as needed for scheduling, and also support new programs approved mid-cycle, including Director's Discretionary Time (DDT) proposals and supplementary calls. In preparation for an upcoming cycle, NAASC staff participate in software testing of the ALMA Observing Tool (OT) and end-to-end tests, as well as related software such as the Project Tracker, and closely coordinate with the JAO and the other ARCs on developing P2G best practices at the annual P2G f2f meeting. NAASC staff continued to provide P2G support for the NA scientific community up to the ALMA shutdown. Because of travel restrictions, the annual f2f meeting was cancelled, and the group met virtually.

*Photos by Pablo Carillo*

**Contact Scientists:** NAASC staff provide oversight and support for all approved NA ALMA PI programs for an observing cycle. This includes ensuring PIs have submitted, reviewed, and approved their projects for scheduling prior to cycle start, and, if needed, providing communication between PIs and the JAO during a cycle. NAASC staff also provide oversight of PI scheduling block status and coordinate with the JAO on scheduling. All Cycle 7 observing programs were assigned a contact scientist and NAASC staff provided support to the PI observing programs until the ALMA shutdown.

**Telescope Operations in Chile:** The NAASC coordinates with the JAO and other ARCs to schedule Astronomer on Duty (AoD) shifts in support of ALMA telescope operations in Chile. In a typical year, the NA ARC covers a minimum of 14 shifts. Due to travel restrictions and the ALMA shutdown, AoD shifts were cancelled after March 2020.

**Telescope Diagnostics:** The NAASC continues to play a critical role in the JAO technical and diagnostics-related meetings and teleconferences, such as the Control System and Correlator Group weekly meetings and software readiness review meetings. The team also provides significant diagnostic support to the JAO, including identifying and coordinating critical fixes for issues. NAASC staff continue to maintain a close interaction between data processing and the telescope diagnostics teams at the JAO to ensure problems are reported and tracked efficiently. Throughout 2020, the NAASC continued to coordinate with the JAO on troubleshooting issues and problems found with the telescope systems or in data collection and analysis.
Data Analysts: The NA Data Analysts are integrated into NA ALMA Operations and are critical to user and telescope support. The Data Analyst group continued to support the following activities f2f before March 2020, and virtually thereafter.

- CASA Guides, f2f visitors, data processing workshops; NRAO Live! events, Synthesis Imaging School documentation and demonstrations, community outreach events, and Helpdesk.
- Data services, NA data processing, and weblog review (pipeline and manual); calibration survey data processing; QA3 execution and documentation.
- ALMA scientific software including involvement in ALMA pipeline and CASA software testing; CASA documentation; diagnostics investigations and Science Portal maintenance; and generating meeting webpages.

## North American ALMA Development

North American ALMA Ongoing Development Projects and Studies are described in the succeeding sections.

### Ongoing Development Projects

**Fiber Optic Project – JAO (Cycle 1):** The Operations Support Facility (OSF)–Array Operations Site (AOS)–Santiago fiber optic link is fully functional and operating pursuant to a temporary permit. The project continued to be held open in 2020 for administrative purposes while the final operating permit is being processed by the Chilean Ministry of National Assets (Ministerio de Bienes Nationales.)

**Expansion of the Central Local Oscillator Article (CLOA) to Five Subarrays – NRAO (Cycle 2):** This project procured and tested all the required modules and equipment to complete Photonic Local Oscillator (LO) subarray five. The complete chain was installed, tested, and commissioned at the AOS Technical Building. The completed system was integrated into the software control system. The project was held open in 2020 pending adjudication of final test results (after VLBI testing in August 2019) and acceptance of the final report by ALMA.

**Band 3 CCA Magnet and Heater Installation for Deflux Operations – NRC-HIA (Cycle 2):** This project is modifying the Band 3 Cold Cartridge Assembly (CCA) to add a heater element to reduce observed azimuth-dependent total power variations. The heater solution was successfully tested at NRC-HIA and underwent JAO verification testing. Project delays were caused by validation of test results and the inability to reproduce the original total power variations. The design has been finalized and NRC-HIA built and delivered the initial heater kits. Integration into each Band 3 Cold Cartridge Assembly will continue over the next three years.

**ALMA Phasing System Phase 2 (APP2) – MIT Haystack (Cycle 5):** Several initiatives will improve VLBI capabilities and ALMA performance. Major components include enabling spectral line VLBI, extending the frequency range of phasing to Bands 1–7, improving the calibration mechanism to allow observations on weaker sources, the introduction of a single-dish VLBI mode, and a pulsar mode. Two of the intended project capabilities, passive phasing and a pulsar mode, are on track for Cycle 8 release; other capabilities have been delayed for reasons beyond project team control—primarily lack of access to test time and the COVID-19 shutdown. An extension proposal to complete the full, original scope of the project was submitted.

**Variable Speed Compressor Analysis Small Project – NRAO / JAO (Cycle 7):** This conceptual design project will characterize Sumitomo FA-70 compressors modified for variable-speed operation at operational conditions. The existing Sumitomo CAN-61D compressors will soon be obsolete and are difficult to maintain. The newer-generation FA-70 compressors have multiple operational advantages that could save money and return observing time. This conceptual design project will prototype an operational system, quantify potential savings, and inform next steps for ALMA with respect to cryo-compressor operation and a replacement strategy.

### Ongoing Development Studies

The following North American ALMA Development Studies were completed in 2020.

- Quantum-Limited Very-Wideband RF and IF Amplifiers – NRAO (Cycle 5)
- Full-Mueller Mosaic Imaging with ALMA – NRAO (Cycle 5)
- NRC TALON Frequency Slice Architecture Correlator/Beamformer -- for ALMA (Cycle 7)

**Quantum-Limited Very-Wideband RF and IF Amplifiers – NRAO (Cycle 5):** The ALMA 2030 Roadmap recommended the development of receivers with larger bandwidth and better sensitivity for improving observation speed. This one-year study describes progress on the development of a breakthrough amplifier technology called the Traveling-Wave Kinetic Inductance Parametric (TKIP). These "paramps" are a new type of cryogenic power amplifier applicable in the microwave to THz range that exhibit ultralow noise reaching the fundamental quantum limits along with very wide instantaneous bandwidth. These amplifiers are considered strategic for NRAO's long-term technology program, and their successful development could substantially impact ALMA performance and future radio telescopes.

This Study describes progress in developing microwave (post-down-conversion,or IF) and millimeter-wave (pre-down-conversion or RF) paramps. Several versions of the IF were designed, fabricated, and tested with improvements in gain, bandwidth, noise, dynamic range, gain ripple, pump power level, and chip footprint. The Study demonstrated that the paramps can operate at 4 K while maintaining high gain ~15 dB) and wide bandwidth (>6 GHz). When operated at ≤1 K, the study consistently measured noise within a factor of two of the fundamental quantum limit for the IF paramps. At higher frequencies, the study designed and fabricated several RF paramps with a simulated gain of >15 dB over the 65-150 GHz band, and made significant improvements in the fabrication methods. The results from the combined efforts at NRAO/UVA and Caltech/JPL and the new testbed infrastructure have put the project team in an excellent position to continue this promising work, which is clearly synergistic with ALMA's roadmap.

**NRC TALON Frequency Slice Architecture Correlator/Beamformer (ALMA TALON Correlator/Beamformer, or AT.CBF) for ALMA (Cycle 7):** Receivers recommended for ALMA 2030 address bandwidths of 8+ GHz. This investigation studies the feasibility, cost, and impact on existing ALMA systems of utilizing NRC's Frequency Slice Architecture (FSA) and TALON technology (TALON/FSA) for a new ALMA correlator and VLBI beamformer. A TALON/FSA correlator and VLBI beamformer for ALMA can be available and deployed within five years, replacing Baseline Correlator (BLC), amd meet ALMA 2030 goals of at least 2X bandwidth. It is believed to be future-proof in its physical/electrical architecture and signal processing approach to provide ALMA, with a foundation to build on for many years. By upgrading the ALMA correlator to AT.CBF, not only will it provide much-improved science capability in the near term, but it will position ALMA to provide uninterrupted science operations while transitioning to upgraded ALMA 2030 antennas, a process that will take several years.

## The following Studies were also in progress.

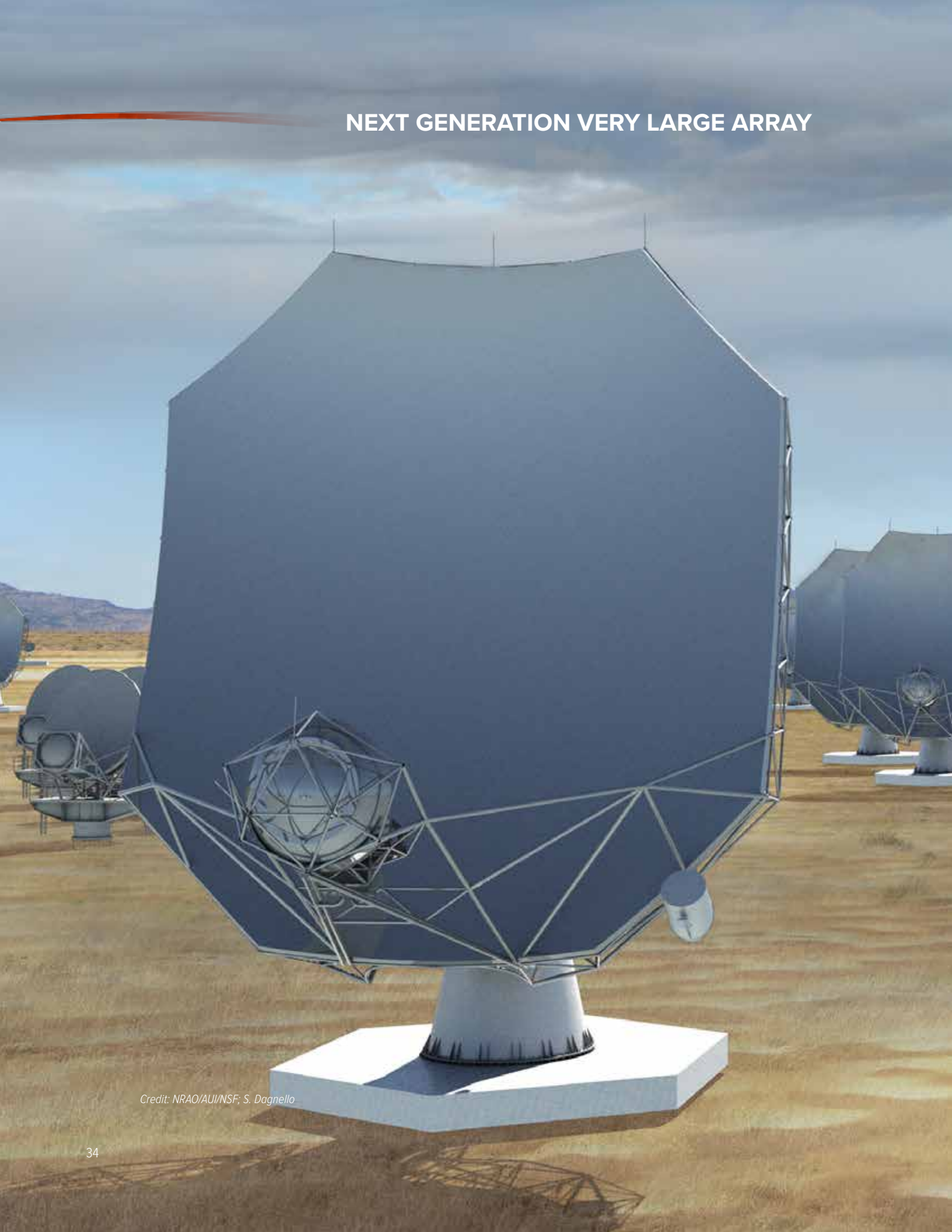
***Hardware-oriented Studies***

1. Ubiquitous Quantum-Limited Wideband 4-Kelvin Amplifiers for Radio Astronomy (Noroozian et al., Goddard Space Flight Center, NRAO).
2. Investigation into Improvement of FE LO Sideband Noise for ALMA Band 6 (Saini et al., NRAO).
3. Band 6v2 SIS Mixer Development (Kerr et al., NRAO).
4. ALMA Central LO Improvements and Upgrades (Jacques, NRAO).
5. Wideband Low-Noise Balanced IF Amplifiers for Band 6 – NRAO (Cycle 5).

***Software-oriented Studies***

1. Link CASA to the Astropy Ecosystem (Ginsburg, NRAO, University of Florida).
2. ALMA Archive Research using ADMIT (Teuben, University of Maryland)
3. ARCADE: ALMA Reduction in the Canadian Advanced Network for Astronomical Research (CANFAR) Data Environment (Kirk ,NRC)
4. Investigating the future potential of an upgraded ALMA to image planet-forming disks at sub-AU scales (Ricci .Cal State University Fullerton)

# NEXT GENERATION VERY LARGE ARRAY



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

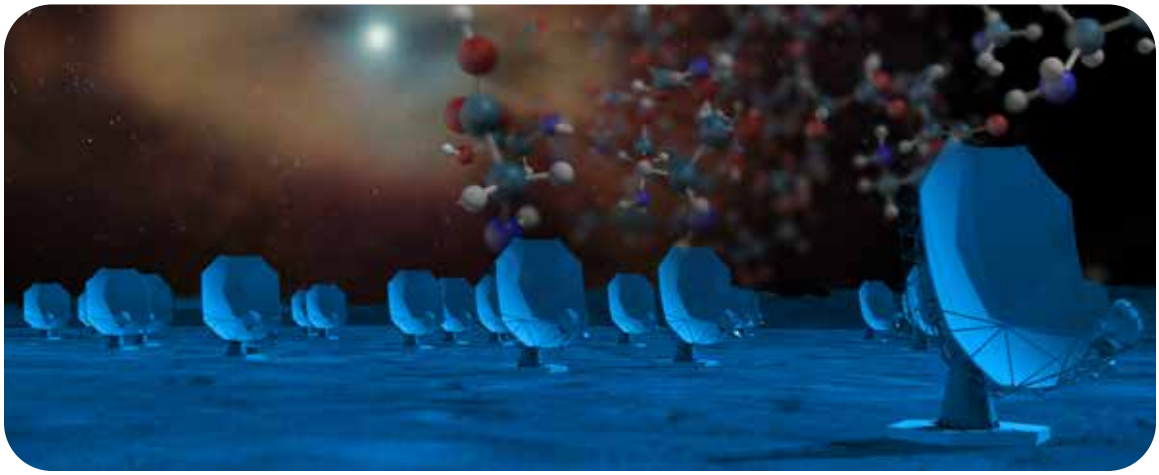
The NRAO further engaged the science and technical community in 2020 in the design of a next generation Very Large Array (ngVLA), an interferometric array with 10x the sensitivity and 10x higher spatial resolution than the VLA and the Atacama Large Millimeter/submillimeter Array (ALMA). The ngVLA will 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: (1) direct imaging of planet formation in the terrestrial zone; (2) studies of dust-obscured star formation, and the cosmic baryon cycle down to parsec-scales out to the Virgo cluster; (3) making a cosmic census of the molecular gas that fuels star formation back to first light and cosmic reionization; and (4) novel techniques for exploring temporal phenomena from milliseconds to years in this multi-messenger astrophysics era. 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.

In 2020, the ngVLA project has continued to develop 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.

## 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 (ngVLA Memo #19) are:

- Unveiling the Formation of Solar System Analogs on Terrestrial Scales;
- Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry;
- Characterizing the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time;
- Using Pulsar in the Galactic Center as Fundamental Tests of Gravity; and
- Understanding the formation and evolution of stellar and supermassive blackholes in the Era of Multi-Messenger Astronomy.



# NEXT GENERATION VERY LARGE ARRAY

## 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 up to ~8860 kilometers 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.

## ngVLA Project

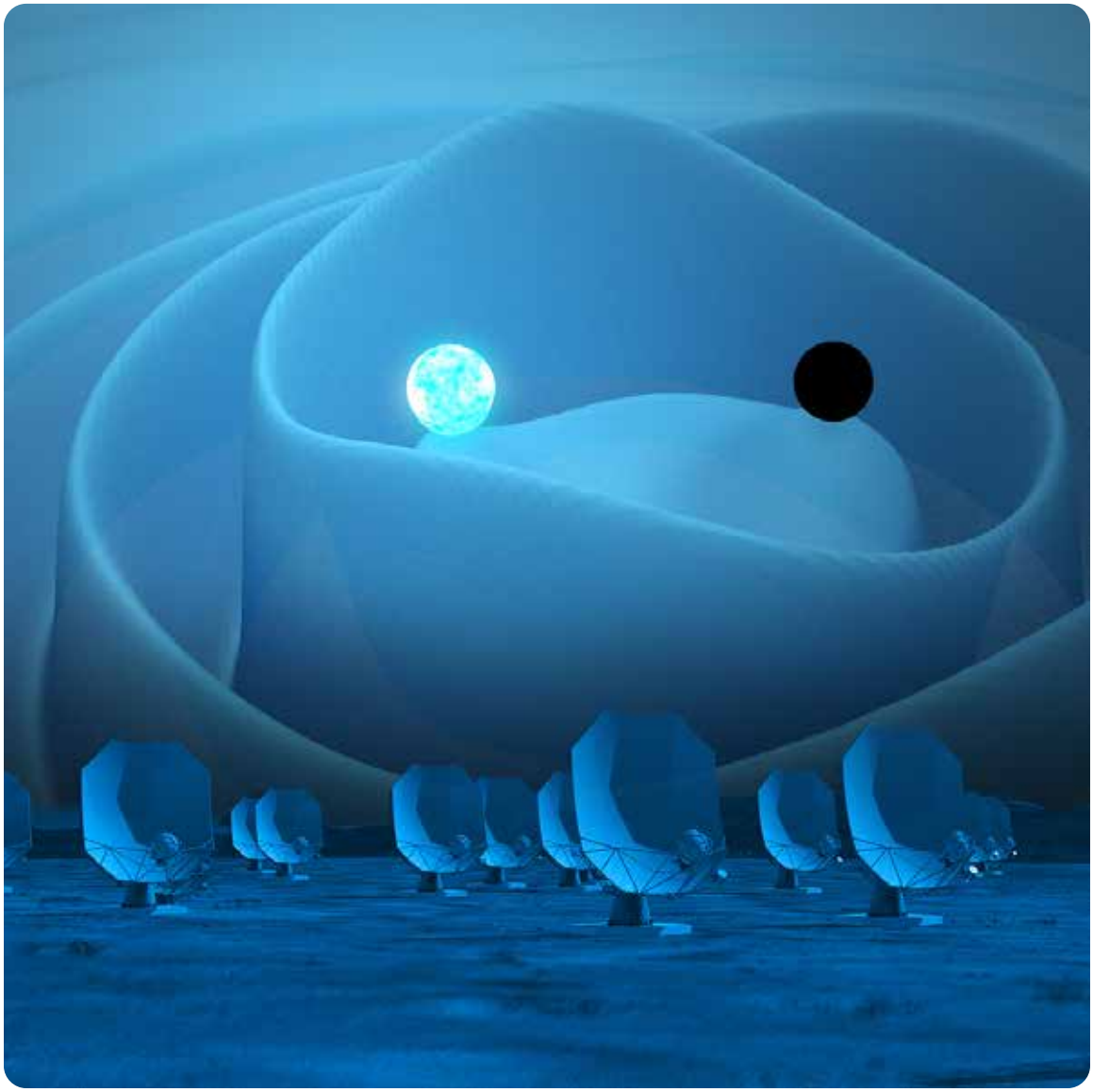
In 2020, the ngVLA Project built a structure appropriate to the Project's scale and ambition, and put in place an established leadership team with experienced members of the NRAO management team and scientific staff, including Mark McKinnon (Project Director), Rick Farnsworth (Project Manager), Eric Murphy (Project Scientist), Rob Selina (Project Engineer), and Alexia Nalewaik (Cost Analyst). The ngVLA Project structure includes 10 Integrated Product Teams (IPTs), MREFC-style project definition, and actively engaged science and technical advisory councils representing the national and international communities.
The ngVLA Project continued to build and refine the conceptual design and science case throughout 2020, driven by the community, coordinated by NRAO, and apropos to NSF Major Research Equipment and Facilities Construction (MREFC) candidacy. Additional science cases identified by the community were incorporated into the ngVLA Science Book. The Project focused on developing the detailed ngVLA conceptual design, working towards an external design review in 2022.

By the end of 2020, ngVLA accomplishments included NSF funding via its own Cooperative Support agreement, and strong national and international community engagement through the Science Advisory Committee and sponsored events. The Project updated the ngVLA requirements in 2020, retired numerous risks through management practices and systems engineering, and continued to identify and develop Broader Impact participation opportunities with the Project IPTs and a strategic communications approach. Community engagement activities in 2020 included virtual science meetings, a popular short talk series that spanned the summer, additional funding for community studies, and an online ngVLA Town Hall. Early career astronomers impressively dominated the community events.

The ngVLA Project, in collaboration with the broad astronomy community, prepared and developed a sound, strongly supported submission to the Astro2020 Decadal Survey. Preparations for Astro2020 included the coordination of community white paper submissions, the development of a reference design concept for the facility, the conduct of technical trade studies and initial development of prototypes, and active participation in Astro2020-sponsored events including NRAO/ngVLA-led science and technical meetings.

The ngVLA Project responded to an Astro2020 Program Panel request for information in December 2019 and January 2020. A comprehensive presentation describing the ngVLA science case and technical design was delivered for the Radio-Millimeter-Submillimeter (RMS) Panel in February, and the Project responded to a second RMS Panel request for information in March. The ngVLA Project submitted a Mid-Scale Innovations Program proposal to the NSF to fund the detailed design of a prototype ngVLA antenna, and validated the antenna used to support an ongoing, university-based intensity mapping experiment (i.e., the Caltech CO Mapping Array Project). An external review of the ngVLA System Requirements was conducted, and five Water Vapor Radiometers were tested on VLA antennas.

The Project continued to develop its Broader Impact participation plan, and ran an ngVLA Summer Talk series that garnered substantial community interest. The Project supported and participated in a broad range of community science and technical meetings, such as the virtual Compact Objects in the Multi-Messenger Era meeting held 14-15 July.



# NEW MEXICO OPERATIONS



*Photo: Bettymaya Foott, NRAO/AUI/NSF*

The Karl G. Jansky Very Large Array (VLA) and the Very Long Baseline Array (VLBA) are maintained and operated from New Mexico. Both instruments provide unique centimeter-wavelength capabilities to the astronomy community. During 2020, 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. Many activities are closely coordinated across the VLA and the VLBA and are carried out by the same personnel.

## 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 2020, NRAO continued to offer a suite of robust and scientifically powerful observational capabilities designed and tailored to address scientific needs.

### Science Operations

NRAO continued to offer three types of observing programs to VLA users in the Calls for Proposals issued in 2020: General Observing (GO), Shared Risk Observing (SRO), and Resident Shared Risk Observing (RSRO).

In the 2020B observing semester Call for Proposals (deadline 3 February), three capabilities were promoted from SRO to GO: Coherent-dedispersion (YUPPI) pulsar observing for all observing bands except for 4-band, P-band polarization, and Y1 observing in support of VLBA. Two capabilities were promoted from RSRO to SRO: 4-band observing in Stokes I, and the dual 4/P-band observing in Stokes I.

In the 2021A observing semester Call for Proposals (deadline 3 August 2020), no new GO or SRO capabilities were added, but refinements in subarray use were made after finding that some types of observing were causing failures in the Correlator Back-End (CBE). RSRO programs supported in 2020 included fast-dump times, data rates above 100 MB/s, 4-band polarization, 4-band coherent-dedispersion (YUPPI) pulsar observing, and more than three subarrays or subarrays with the 3-bit system.

A large fraction of the 2020 scientific staff support was invested in maintaining receiver, antenna, and array performance and ensuring that the NRAO user community had access to quality instrumentation and updated information to effectively use the VLA. Capabilities to be offered in the 2020B and 2021A semesters were defined, user documentation for all capabilities for the relevant Call for Proposals were updated, scientific testing of user tools needed to prepare proposals—e.g., Proposal Submission Tool (PST), General Observing Setup Tool (GOST), Exposure Calculator Tool (ECT)—was undertaken, and technical reviews for proposals and evaluation of proposals for RSRO contributions were performed.

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 2020B and 2021A Call for Proposals, along with the Guide to Proposing with the VLA and the Guide to Observing with the VLA on the NRAO web site.

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.

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 (ACUs) was evaluated.

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

Data quality was evaluated based on pipeline results, and test observations were run to identify and diagnose problems that were not caught by the standardized tests and engineering checks. Detailed data was collected with the array for a range of calibration purposes, including flux density scale calibrator models, and polarization and bandpass calibration.

## Array Operations

Array reconfigurations completed in 2020 comprised the moves into the D, C, and B configurations. The reconfiguration to the B array was delayed by four weeks because of the coronavirus pandemic, and the need to define and review new COVID-safe procedures before proceeding with moving the antennas. A special call for exploratory DDT proposals to fill the additional four weeks of C configuration yielded 77 proposals requesting ~1200 hours of telescope time.

The VLA continued operations from the site control room throughout the Infectious Disease Operation Status period, 16 March –1 June, while other activity at the array was delayed or postponed. Operators worked alongside their VLBA counterparts to learn how to run the VLBA instrument to add flexibility when shorthanded. This practice is ongoing as backup support for VLBA operations when needed. A backup control room was set up at the Domenici Science Operations Center in case of a COVID-19 infection in the Operations area at the VLA site, but was fortunately not needed.

## Development

**Realfast Commensal Fast Transient System:** The rapidly developing field of Fast Radio Burst (FRB) detection is attracting much scientific attention. New discoveries, including localizations—from VLA, Australian Square Kilometre Array Pathfinder (ASKAP), and Canadian Hydrogen Intensity Mapping Experiment (CHIME)—have begun to narrow the possible progenitors of these enigmatic events. The few accurate (~0.1 arcsec) localizations is still hampering our ability to further constrain the progenitor possibilities. The realfast development project is implementing a commensal fast transient system for the VLA, and investigating options 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 funded by the NSF Advanced Technologies and Instrumentation program starting FY2017. A no-cost extension by the NSF to FY2021 will complete the project and transfer its daily operations to NRAO. In 2020 the realfast system was made fully operational for observing at L- through X-bands, as well as with Very Large Array Sky Survey (VLASS) Epoch 2 observing.

**Expanded Long Wavelength Array (eLWA):** Low-frequency radio astronomy at meter wavelengths has undergone a renaissance. In support of such observations, the LWA has an NSF-funded three-year (FY2019–21) grant to provide further community access to LWA stations, and to enable LWA use in combination with the VLA 4 Band system (58–84 MHz). The NRAO has committed to contribute in-kind scientific staff and software effort. In 2020, NRAO expanded eLWA testing to all VLA antennas, and the data path from the VLA to the University of New Mexico (UNM) was demonstrated.

## Electronics Maintenance and Renewal

The New Mexico Electronics Division maintains all VLA electronic components, VLA servo and fiber systems, and the Wideband Interferometric Digital Architecture (WIDAR) Correlator. Division staff are located either at the VLA site or at the DSOC in Socorro, with maintenance and renewal activities occurring at both places. Due to the lifecycle stage of the VLA, maintenance and obsolescence management is a critical focus for the Division.

The power system for the WIDAR correlator received major maintenance and component replacements in 2020, including new batteries and Power Distribution Units for the WIDAR power plant, and power line conditioners for the power which feeds the WIDAR chamber.

## Site Maintenance and Renewal

VLA antennas continued to be cycled through the Antenna Assembly Building (AAB) for checkout and overhaul. Five antennas were planned for overhaul and were to be cycled through the AAB in 2020. The plan also specified the replacement of one antenna azimuth bearing. Due to the loss of site access during the IDOS, the antenna overhauls were descoped to four and the azimuth bearing change was canceled.


*Photo: Summer Ash, NRAO/AUI/NSF*

The two 40-year-old transporters used to move antennas during reconfigurations underwent maintenance and repair between move periods. Transporter maintenance included servicing the motors, checking the generators that maintain critical power to the antenna during a move, lubricating the moving parts, checking on the 24 wheel axles and wheels, and maintaining electrical and hydraulic systems. After a transporter collar failure, a subsequent inspection discovered fatigue cracks on these truck rotation collars. An improved rotation collar was designed. Two new collars were fabricated and installed on a transporter in FY2019 and the final two were replaced in 2020. NRAO also began a program to inspect the rotation mechanism on the remaining transporter. This transporter does not use rotation collars but has a similar design that is more robust and is not suffering the same issues.

Inspection of the VLA railroad tracks continued in 2020, checking for problems that could compromise the safety of the antenna transporters. A total of 2344 cross-ties were replaced. This was significantly lower than the goal of 5000 ties because the IDOS shut down interfered with the normal summer tie replacement schedule. Five track intersections were scheduled to be replaced, and this goal was completed. In addition to these intersections, a railroad spur and rail line to the ballast pile were also completed. This spur will greatly improve the efficiency of track ballasting operations.

The VLA site buildings, utility systems, and grounds continued to undergo routine annual inspection and preventive maintenance in 2020. The site transformers underwent yearly preventive maintenance procedures. Other regular activities included: annual road grading; general roof repairs; heating and cooling systems maintenance; pest and weed control along the railways and central site; fire brigade and emergency medical response team training; and the routine servicing of gas pumps, sewer, and water supply systems. Backup generator power and related systems also underwent preventive maintenance.

A 500 KW backup power generator was purchased to provide backup power to the control building and correlator. This generator will provide protection if the site backup power generator fails or is undergoing repairs/maintenance during a utility outage. It will be installed in FY2021. A tie plate inserter was also purchased to improve the efficiency and safety of the railroad tie replacements.

Large-scale improvements and purchases for the VLA site were carried out in 2020 as part of overall VLA infrastructure improvement. Purchases included road and parking lot improvements, track maintenance materials, new medium voltage switches, transformers, a chiller compressor, and test equipment. Several heavy equipment and vehicles were purchased..

## Observing Capability Enhancements

The VLA continued to provide new capabilities to the user community, keeping users engaged and the scientific productivity of the VLA high. Scientific staff and RSRO effort were directed to multiple observing capability enhancements in 2020.

P-band Stokes I continuum and spectral line observations are both GO, while polarization observations were offered as RSRO because of difficulties with the antenna feeds. These issues were resolved, and P-band polarization observations were offered as SRO in the 2020A Call for Proposals, with the VLA observations taking place February–October 2020. Tests carried out by the scientific staff showed the readiness of this observing mode to be GO, and it was offered as such in the 2020B Call for Proposals.

Phase-binned imaging of pulsars using the WIDAR correlator was promoted to GO in FY2019. Phased-array coherent-dedispersion–Y Ultimate Pulsar Processing Instrument or YUPPI mode–observations of pulsars with the VLA was promoted to SRO in FY2019, and to GO in FY2020, with the exception of YUPPI mode using the 4-band system. The latter was offered as RSRO in the 2021A Call for Proposals.

Simple frequency averaging (by factors of two or four) in the correlator software is already available as a GO capability. In 2020, the intent was to implement additional smoothing options, such as Hanning smoothing. However, the impact of introducing such smoothing on the downstream data processing needed to be re-evaluated, and its importance to other software development needed to be determined. Thus NRAO canceled the work associated with this capability enhancement pending internal review.

## Technical Upgrades and Enhancements

The electronics parts to repair the existing VLA ACUs are no longer available. Without replacement parts, antennas with failed ACUs would no longer be able to 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 the pointing and tracking capabilities of the antennas. The first new ACU was installed in FY2013 and the thirteenth and fourteenth new ACU units were installed in FY2020.

To continue the development of a Variable Frequency Drive (VFD) for the helium compressor in an antenna's cryogenic system, engineering staff developed a variable frequency rated test stand and custom software to characterize the performance of a lab VFD system. Buffer tanks and mechanical mounting racks were installed on an antenna. A field-ready version of the VFD compressor and electronics hardware will be developed and installed on the VLA.

Electronics hardware was developed to improve the stability of antenna network switch power when moving from commercial to battery-backup power. Over the course of FY2019 and FY2020, 26 antennas received this upgrade, reducing operational impacts during short power outages. The final two antennas will be upgraded in FY2021.

### From the Archives

18 January 1980: The first move of a Very Large Array antenna across New Mexico Route 60. According to the account in The Observer (vol. 21, no. 1, page 39), "VLA crews moved an antenna 5.2 km out the North Arm, thus necessitating the first antenna crossing of Rt. 60. Many turned out to witness the event, including NRAO personnel, news media, and the State Highway Dept., who came to measure traffic disruption and check safety procedures. Rubberneckers rubberneck, gawkers gawk and we all cheer as Route 60 is crossed with little or no effort."

## Very Long Baseline Array (VLBA)

The VLBA comprises ten 25-meter diameter antennas at locations from Hawaii to the U.S. Virgin Islands.

### Science Operations

NRAO continued to offer three types of observing programs to VLBA users in FY2020: General Observing (GO), Shared Risk Observing (SRO), and Resident Shared Risk Observing (RSRO). In the Call for Proposals for the 2020B observing semester, two capabilities were promoted to GO: VLBA 4 Gbps observing, and VLA Y1 observing with the VLBA. One new capability was offered as SRO: HSA 4 Gbps observing (excluding Arecibo). In the Call for Proposals for the 2021A observing semester, the HSA 4 Gbps observing (excluding Arecibo) was promoted from SRO to GO. RSRO programs supported in 2020 included many pulse calibration tones per channel, improved troposphere model, rapid response capability, 4 Gbps data rate at Arecibo in HSA Observations, L/P dual-band observations, Y3 observing with the VLBA, and recording wide-band VLA visibilities in parallel with Y27 VLBI.

Operational tasks carried out by the scientific staff during 2020 in support of maintaining receiver, antenna, and array performance and ensuring that the user community had access to quality instrumentation and updated information to effectively use the VLBA are listed below.

Capabilities to be offered in the 2020B and 2021A 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., Proposal Submission Tool (PST), European VLBI Network Sensitivity Calculator—was undertaken, along with technical reviews for proposals and evaluation of proposals for RSRO contributions.

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 before the 2020B and 2021A Call for Proposals. In FY2020, two new online guides were added to the NRAO web site to serve our user community: the Guide to Proposing with the VLBA, and the Guide to Observing with the VLBA.

Starting in Semester 2020A, NRAO offered extra help to novice VLBA users to assist with their observing set up, and to provide initial calibration and Quick Look images of their data. Four proposals requested this support in FY2020. However, none met the criteria defined for the program. NRAO will continue to offer the program, and may re-evaluate it in the future to improve its reach and effectiveness.

The Joint Institute for VLBI European Research Infrastructure Consortium (ERIC) (JIVE) has produced a new Python-based version of the primary software used by observers for producing observing files for the VLBA, pySCHED. NRAO evaluated this software in FY2020, with a view to using it to replace the old, Fortran-based SCHED code. However, pySCHED was found to not be ready to use in the VLBA production environment without further modifications. NRAO provided feedback to JIVE.

The sensitivity, pointing, and focus of each antenna at each band were characterized periodically, as receivers and equipment were replaced or as software was upgraded.

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

(Photo: J. Heleiman, NRAO/AUI/NSF)

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

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

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

## Array Operations

Standard scheduling and observing procedures were used during FY2020 for the VLBA. The array transitioned completely to using Mark 6 media, so the Mark 5C inventory was completely replaced and the Mark 5C system retired.

The Array Operations Division continued to administer the JIRA-based maintenance tracking system. In response to the coronavirus pandemic, the group set up alternate backup operating stations in the DSOC to mitigate possible COVID-19 infection of the main VLBA control room. In addition, the ability to operate the VLBA temporarily from an Operator's home was demonstrated.

## Development

During 2020, progress was made on two major long-term development projects.

VLBA New Digital Architecture Project (VNDA): The VNDA project (previously called Oryx) is replacing the existing aging and performance-limiting data acquisition and digital signal processing system with a modern, extensible one. The project has four phases: Conceptual Design, Preliminary Design, Final Design, and Deployment. The project team completed the first phase of VNDA during FY2020. A successful Conceptual Design Review was held in May. In September, NRAO management approved the funding and execution of phase 2. During the execution of phase 1, prototype hardware was selected and procured, critical risk reduction was performed on this hardware, and key interfaces were exercised.

E-Transfer: A special NSF award funds increasing the VLBA site connectivity to the VLBA operations center in Socorro, NM from a typical initial data rate of 1.4 Mbps to a minimum of 200 Mbps. Nine of ten VLBA sites had completed fiber network links by the end of FY2020, with the tenth station (Los Alamos) to be complete in early FY2021. Considerable effort has been made to make use of this new capability. A new diagnostic test has been developed that can verify proper timing, pointing, and tuning of the VLBA antennas within minutes of observing. First tests of real-time correlation have been performed using up to eight VLBA stations; this capability will eventually lead to additional diagnostics and scientific use cases.

## VLBA Maintenance and Renewal

The New Mexico Electronics Division is responsible for maintaining all VLBA electronic components, many mechanical systems, VLBA station infrastructure, and recording and playback hardware. Two VLBA site technicians are located at each VLBA site, and many engineers and technicians provide VLBA support from the DSOC in Socorro.

The site technicians carried out the bulk of the routine maintenance tasks at the VLBA sites. For FY2020 this work consisted of the following:

- Inspection and lubrication of Focus Rotation Mounts (FRM), Azimuth/Elevation drive motors, encoder and pintle bearings, elevation gears, elevation hoist, and changing gearbox oil.
- Check/test encoder motor tachometers, servo limits, ACU, vacuum pumps, all heating, ventilation, and air conditioning (HVAC) systems, dry air system, weather station equipment.
- Perform maintenance on ACUs and FRM controllers.
- Ensure safety equipment such as UPSs and generators, emergency power, fire alarm systems, fire extinguishers, and security systems are operating normally.
- Ensure all other preventive maintenance tasks are completed, such as check and replace motor brushes and commutators, check of Azimuth wheel position, check for metal in grease samples, perform cable wrap maintenance, and replace oil filters.
- Repair some VLBA specific modules and electronic systems to relieve some of this task from the technical staff at the DSOC and the VLA sites.
- Maintain the grounds and building infrastructure.
- Other diagnostic and repair tasks as needed.
- Support major maintenance visits to two VLBA sites.

Electronics Division staff based at the DSOC or the VLA performed the following routine VLBA work in FY2020:

**Front End and Cryogenics:**

- Overhaul ~60 receiver cold heads to keep VLBA Front Ends operating.
- Perform preventive maintenance on four helium circuits to maintain cryogenic performance.
- Repair and/or upgrade/retrofit eight VLBA FE receivers, on average.

**Local Oscillator and Intermediate Frequency (LO/IF):**

- Investigate issues with locking, fringing, output power, and general communication dropouts.
- Monitor maser performance and timing, adjusting as needed.

**Data Acquisition:**

- Repair of ~10 VLBA recording and playback modules.
- Repair of up to 50 recording disk packs.

**Multiple Groups and Systems:**

- Retrofit upgrades or additions to enhance equipment safety.
- Perform bench work on modules for repair or assembly.
- Monitor for local RFI at the VLBA sites.
- Send calibrated site weather station hardware to each site as needed.
- Support major maintenance visits to two VLBA sites.

Major Antenna and Site Maintenance: Three VLBA stations were scheduled to receive a regular major maintenance visit in FY2020, including one postponed from the prior year. The participating maintenance staff, referred to as Tiger Teams, consist of engineers, technicians, and VLBA site technicians that travel for multi-week visits to perform key preventive maintenance actions and corrective repairs on antennas and site infrastructure. During these visits, outstanding or critical issues are resolved in addition to maintenance and inspections. Examples include Focus Rotation Mount irregularities, HVAC system leaks or contamination, cryogenic receiver system problems, and mechanical drive system maintenance.

The first of these campaigns was carried out in October at the Brewster, WA site. This trip was done ~six months early clear the schedule in mid-2020 for the remaining trips needed. This approach was fortunate due to the unanticipated COVID-related shutdown of nearly all travel beginning in late Q2. The second planned campaign, an out-of-state trip, was cancelled due to safety concerns and travel restrictions.

After state travel restrictions were eased in New Mexico, the postponed FY2019 maintenance visit to the Los Alamos site was completed. To avoid LANL personnel restrictions and logistics issues, multiple day-trips were carried out from Socorro by an Electronics Division specialist. This approach allowed for deep preventive maintenance work and inspections on the servo, motor, and electronics systems while not fully shutting down the antenna.

A special trip was undertaken by two VLBA site techs to support the Maunakea site techs in resolving an ongoing HVAC system issue that could not be resolved by island contractors. Maintenance support on other Maunakea systems and the installation of a new electronics rack was also performed.

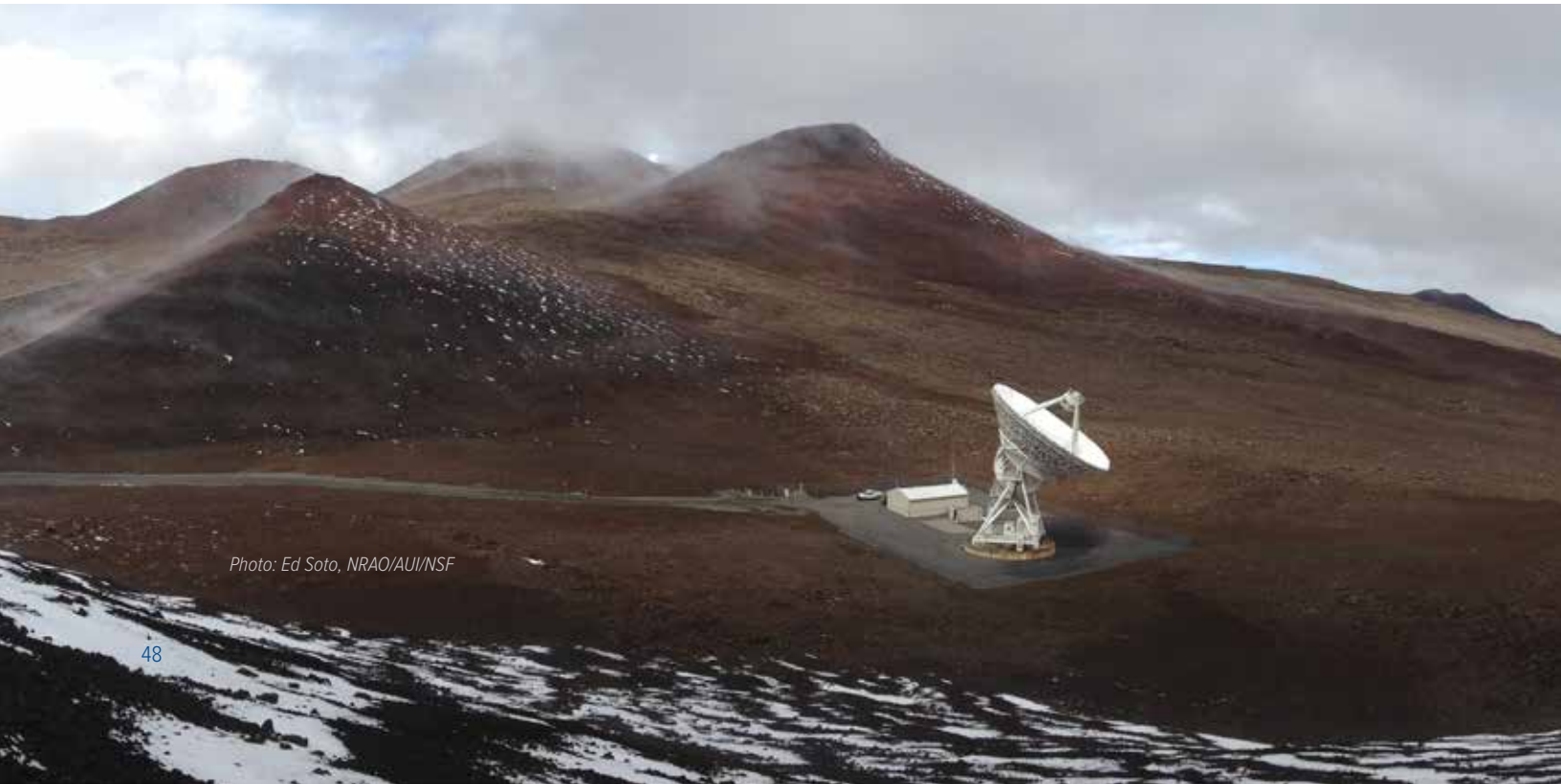


*Photo: Ed Soto, NRAO/AUI/NSF*

## Observing Capability Enhancements

The VLBA continued to provide new capabilities to the user community to optimize and enhance the science that can be done with the array. Scientific staff and RSRO effort were directed to the following observing capability enhancements in FY2020.

During FY2020, the Mark 6 recorder systems became the sole VLBA data recording system. The observing mode enabling twice the sustainable bandwidth—up to 4 Gbps data rate or 512 MHz bandwidth per polarization—was made available as a GO capability, first on the VLBA, then on the HSA (excluding Arecibo).

The ability to include just one VLA antenna (Y1 observing mode) with the VLBA provides a critical short baseline that enables the imaging of structures more extended than those accessible to the VLBA alone. This observing mode was made available as a GO capability in FY2020.

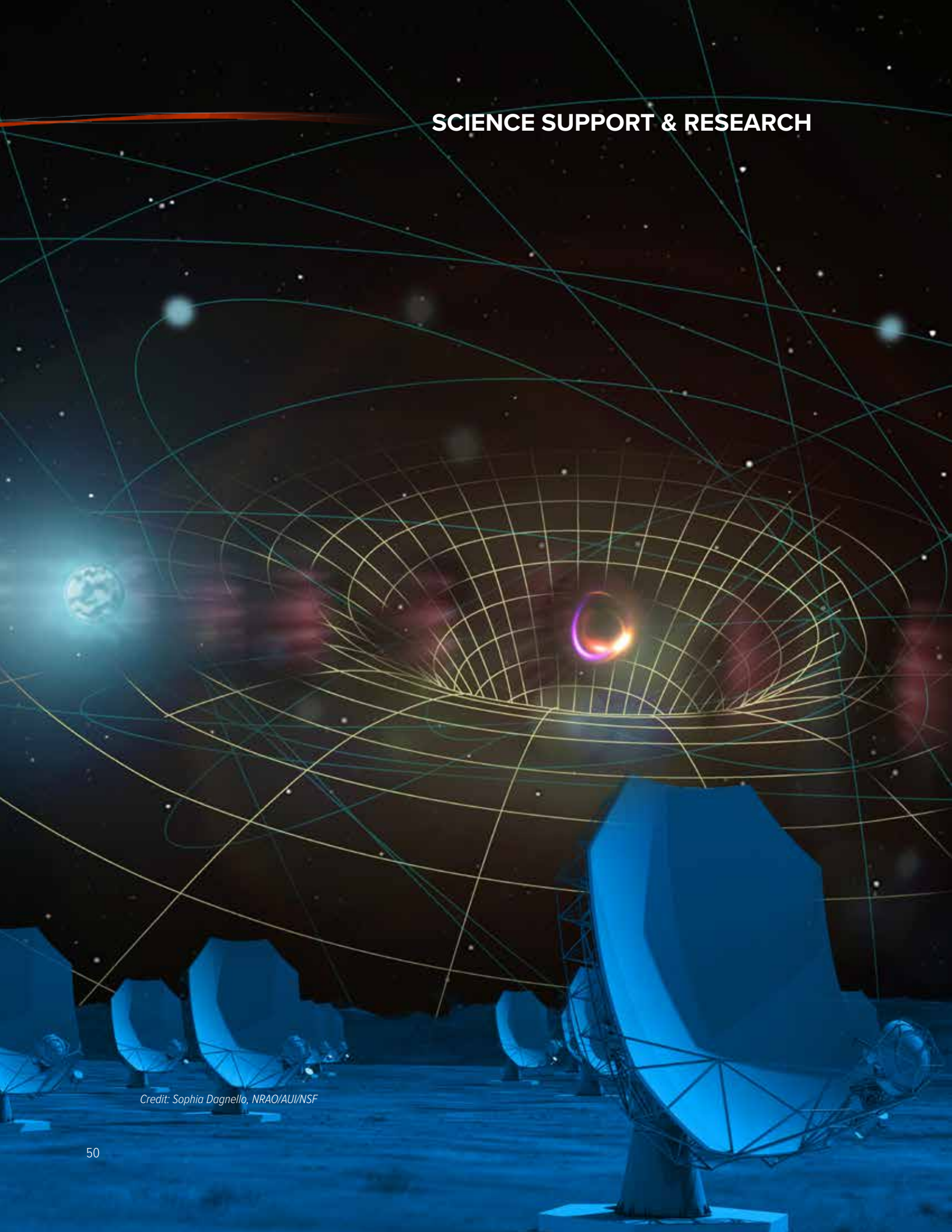
### Technical Upgrades and Enhancements

VLBA Site Weather Station Upgrade: A replacement weather station system was successfully designed, integrated, and tested in the laboratory. COVID disruptions delayed the installation of the system at the Pie Town, NM site until mid-FY2021.

Complete Installation of Antenna E-rack: As part of a strategic development plan for VLBA antenna electronics, a new electronics rack is being installed in the VLBA antennas. Four installations had been completed before further work was disrupted by pandemic restrictions on travel. The remaining installations are now scheduled for FY2021.

E-Rack Production Power Supply Design: A design for an E-rack power supply passed an internal design review. This power supply will power the new synthesizers and other equipment that will eventually be housed in the E-rack. Production on a small number of these supplies began in FY2020 and will continue in the future as funding permits.

# SCIENCE SUPPORT & RESEARCH



*Credit: Sophia Dagnello, NRAO/AUI/NSF*

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. Multi-wavelength projects leading to a synergy with NRAO instruments are encouraged. Five new Jansky Fellows joined NRAO in 2020.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.

**Kimberly Emig** completed her Ph.D. at the Leiden Observatory with Alexander Tielens and Huub Rottgering. She explores the dynamical evolution of the interstellar medium (ISM) and its coupling with star formation largely through an expertise in radio recombination lines. Dr. Emig has demonstrated that radio recombination lines are viable pathways to probe the physical properties of the ISM out to cosmological distances. As a Jansky Fellow, she will use radio recombination line observations in large populations of galaxies and in the local ISM to investigate the characteristics of photo-ionized gas, its relationship to massive stars, and its role in the evolution of galaxies.

**Bang Nhan** received his Ph.D. from the University of Colorado at Boulder under the supervision of Prof. Jack Burns and Dr. Richard Bradley. His thesis work involved developing the Cosmic Twilight Polarimeter (CTP), a testbed system to constrain the foreground synchrotron spectrum for the spatially-averaged (global) cosmological 21-cm measurement using dynamical polarimetry. As a Jansky Fellow, Dr. Nhan will lead the development effort of the next generation CTP, which consists of an upgraded front end and antenna design for better instrumental calibration and stability.

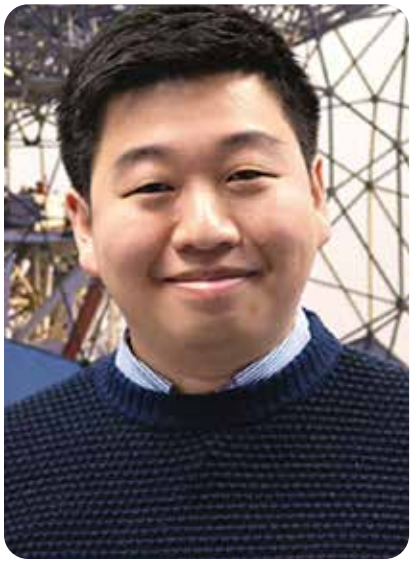
**Pallavi Patil** received her Ph.D. candidate at the University of Virginia. Her dissertation research focuses on understanding the nature of a rare sample of heavily obscured radio quasars with compact and newly-triggered jets, found at the epoch of cosmic noon. As a Jansky Fellow, Dr. Patil will continue to use NRAO radio facilities to investigate the role and impact of radio jets on their surrounding medium during early phases in the life cycles of luminous radio AGN.

**Dyas Utomo** received his Ph.D. from the University of California, Berkeley and went on to Ohio State University as a postdoc. His goal as a Jansky Fellow is to understand the physical processes that govern the conversion from atomic to molecular gas and from molecular clouds to star formation. To achieve that objective, Dr. Utomo will use multi-wavelength observations to measure the properties of gas, dust, and star formation at high physical resolution (~ 100 pc) in a large sample of nearby galaxies.

**Jacob White** received his Ph.D. from the University of British Columbia and was a Research Fellow at the Konkoly Observatory (Budapest, Hungary). He has extensive experience observing with ALMA and VLA to constrain the abundance, distribution, and morphological features of the gas and dust in the circumstellar disks, and is also leading an effort to build more comprehensive submillimeter to centimeter wavelength spectra of stars. Accurate stellar spectra at long wavelengths are required to study unresolved debris systems with ALMA and VLA and to constrain the impacts of space weather on habitability of planets orbiting ultracool dwarf stars. As a Jansky Fellow, Dr. White will continue to use NRAO facilities to study circumstellar debris and the radio emission of stars.

**During 2020, NRAO hosted the following Jansky Fellows:**

- Kazunori Akiyama, Massachusetts Institute of Technology (MIT)–Haystack (September 2017 to September 2020)
- Nithyanandan Thyagarajan, NRAO Socorro (September 2017 to September 2020)
- Ryan Loomis, NRAO Charlottesville (August 2018 to November 2019)
- Lisa Locke, NRAO CDL-Charlottesville (September 2018 to December 2019)
- Nolan Denman, NRAO CDL-Charlottesville (January 2019 to April 2020)
- Kunal Mooley, NRAO Socorro (January 2018 to current)
- Brian Svoboda, NRAO Socorro (June 2018 to current)
- Dary Ruiz-Rodriguez, NRAO Charlottesville (October 2019 to current)
- Craig Anderson, NRAO Socorro (November 2019 to current)
- Luis Henry Quiroga-Nuñez, NRAO Socorro/University of New Mexico (March 2020 to current)
- Jacob White, NRAO Charlottesville (September 2020 to current)
- Dyas Utomo, NRAO Charlottesville (September 2020 to current).



**Kazunori Akiyama**, a NRAO Jansky Fellow at MIT Haystack Observatory, received the Young Scientists' Prize, awarded by the Japanese Ministry of Education, Culture, Sports, Science, and Technology. The award annually recognizes scientists under 40 years old for their outstanding research. Kazunori received the prize for his significant contributions to the Event Horizon Telescope observations. He developed new imaging techniques and a software package named SMILI, one of the three software packages used to create the first images of the M87 black hole. Kazunori also received the 2020 Young Astronomer Award from the Astronomical Society of Japan.

At the conclusion of their fellowship: (a) Kazunori Akiyama moved to a MIT faculty position; (b) Nithyanandan Thyagarajan transitioned to a staff position at the Commonwealth Scientific and Industrial Research Organisation (CSIRO); (c) Ryan Loomis took on a NAASC scientific staff position; (d) Lisa Locke moved to a Jet Propulsion Lab–Deep Space Network staff position; and (e) Nolan Denman took a NRAO–Central Development Lab engineering position.

## Telescope Time Allocation: Semester 2020B

The NRAO completed the Semester 2020B proposal review and time allocation for the VLA and VLBA in 2020.

The VLA A-configuration will be available in the 2020B semester. A total of 201 new proposals were received by the 3 February submission deadline, including three large and 25 time critical (triggered) proposals. The oversubscription rate (by proposal number) was 2.9, and the proposal pressure (hours requested over hours available) was 2.8, both similar to recent semesters. For the VLBA, 38 new proposals were submitted. The oversubscription rate was 2.0 and the proposal pressure was 2.8, both similar to recent semesters.

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

Proposals submitted to the GBO were assessed through the same process. Sixty-five proposals for the Green Bank Telescope (GBT) were received for the 2020B Semester, including four large proposals. The oversubscription rate is 2.2 and the proposal pressure is 3.0. For information on proposals for GBT observations see the GBO website.

The 2020B Semester 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 and then considered by the Time Allocation Committee (TAC) during a remote meeting on 23-24 April. The TAC–comprising the 9 SRP chairs–was charged with recommending a science program for Semester 2020B to the Observatory Director. The recommended program was reviewed and approved on 6 May.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 15 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 was then posted to the NRAO science website. The authors, title, abstract, and scheduled hours for each approved proposal can be accessed from the Proposal Finder Tool.

## Telescope Time Allocation: Semester 2020A

The NRAO also completed the Semester 2021A proposal review and time allocation for the VLA and VLBA in 2020.

The VLA D- and C-configurations will be available in the 2021A Semester, and 194 new proposals were received by the 3 August submission deadline, including three large and nineteen time critical (triggered) proposals. The oversubscription rate

(by proposal number) was 2.5, and the proposal pressure (hours requested over hours available) was 2.0, both similar to recent semesters.

For the VLBA, 41 new proposals were submitted. The oversubscription rate was 2.7 and the proposal pressure was 3.6, both slightly higher than recent semesters.

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

Proposals submitted to the GBO were assessed through the same process. Seventy-four proposals for the GBT were received for the 2021A Semester. The oversubscription rate was 2.4, and the proposal pressure was 1.9. For information on proposals for GBT observations see the GBO website.

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 and then considered by the Time Allocation Committee (TAC) during a remote meeting on 19-20 October. The TAC–comprising the nine SRP chairs–was charged with recommending a science program for Semester 2021A to the Observatory Director. The recommended program was reviewed and approved on 4 November.

A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 9 November, 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 was then 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.

## New Assistant Director for Science Support & Research

Prof. Patricia (Trish) Henning arrived as the next NRAO Assistant Director for Science Support and Research in August.

Dr. Henning began her research career as a postdoctoral research associate in the Netherlands at Dwingeloo / Netherlands Foundation for Research in Astronomy, after gaining her Ph.D. in Astronomy at the University of Maryland. Later, she moved to the University of New Mexico (UNM) as an Assistant Professor (eventually full Professor), held the position of Director of the UNM Institute for Astrophysics for more than fifteen years, and most recently was the UNM Associate Vice President for Research. In these roles, Dr. Henning successfully continued her research career while taking on major administrative responsibilities, and has been highly active in public outreach and mentoring. She has held several senior committee roles throughout her career, including Head of User Programs for the Long Wavelength Array,

Chair of the U.S. Square Kilometre Array Consortium, and NRAO User Committee member. In recent years, she has personally contributed to several Diversity and Inclusion initiatives, and this area is a strong interest. Her time working in Europe, the U.S., China, South Africa, and Australia brings a wealth of experience in administration, understanding of radio astronomy research, experience with facilities, project management, and recruitment and mentoring of scientists and students.

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## Science Ready Data Products

The Science Ready Data Products (SRDP) program is increasing the impact of the NRAO telescopes by: (1) removing barriers to the use of NRAO telescopes, encouraging a broader user base; (2) curating a rich archive of science quality data images, and (3) performing automated calibration and imaging of NRAO telescope data. Three projects constitute the SRDP program: (1) Science Ready Archive and Operations, (2) the VLA Sky Survey (VLASS), and (3) a new suite of Telescope Time Allocation tools. The program has made significant progress in 2020, despite the global pandemic.

The Science Ready Archive and Operations (SRAO) project was the original SRDP initiative. NRAO began providing quality assured calibrations for the VLA as part of pilot SRAO operations in FY2019, and allowed user-specified imaging of ALMA data. While these services were fully implemented from the users' perspective, the supporting infrastructure was not yet at a production level. The transition to full operations of the initial capabilities suite was delayed until these issues were resolved.

The second project under the SRDP program is replacing the tools supporting the NRAO/GBO proposal and review process. The new tools decrease the required knowledge of instrumentation-specific details. This new generation of tools also support dual-anonymous review, alleviating bias in the review process. A Conceptual Design Review was delayed to allow for newly identified gaps to be addressed and the resulting requirements to be incorporated in architecture. Originally planned as an in-person review, the pandemic required a fully virtual review. The review committee recommended that the project advance to implementation. Due to competing resource demands, the kickoff for the implementation phase is scheduled for early 2021.

A joint deliverable with New Mexico Operations, the VLA Sky Survey is the third project managed by the SRDP program. The VLASS is the highest resolution all-sky survey ever undertaken at radio wavelengths. The VLA Sky Survey is synoptic, capturing the full sky visible from the VLA three times, with each of the three epochs split into two observing periods. Observation of the second epoch of VLASS began ~one month late due to delays in the VLA reconfiguration caused by COVID. Calibration and Quick Look images are being produced and are passing through the quality assurance process, prior to being released to the community. Several new data analysts were recruited and trained while respecting the limitations imposed by COVID.

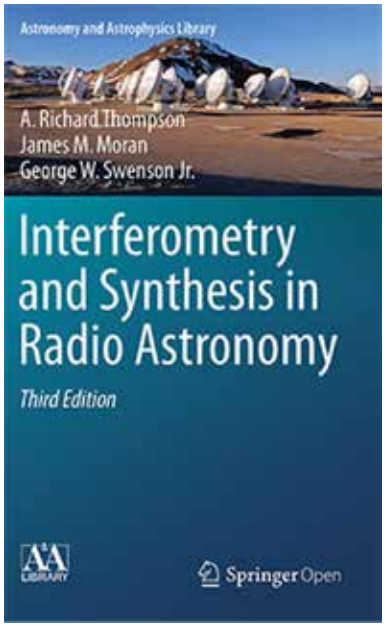
Production of higher fidelity Single Epoch VLASS images for the first epoch was delayed due to algorithmic and operational challenges, and the pipeline developed in FY2019 did not pass validation. In 2020, the VLASS Imaging Project was initiated, led by the Algorithm, Research, and Development Group (ARDG). The VLASS Imaging Project ran for ~12 weeks, providing a roadmap to an operational pipeline for producing high quality single epoch images.

The algorithms required for high-fidelity VLASS imaging are considerably more computationally expensive than expected, based on the original project estimates. The VLASS project is working closely with the Science Computing Group to develop and validate a scalable implementation of the imaging pipeline and identify external computing resources to augment NRAO's investment. Based on the preliminary results of this initiative, a revised production schedule is being developed and will be available in early 2021.

## Robert L. Brown Outstanding Doctoral Dissertation Award

NRAO is pleased to announce that **Dr. Jennifer Beth Bergner** is the winner of the 2019 NRAO/AUI Robert L. Brown Outstanding Doctoral Dissertation Award, for her Harvard Dissertation, Tracing Organic Complexity During Star and Planet Formation. Dr. Bergner's research impressively delineates how the properties of complex organic molecules can serve as a guide to the poorly understood chemical history of planetary systems and low-mass stars. Her innovative laboratory experiments have opened an exciting new path for understanding the complicated organic chemistry during the delivery of prebiotic material to future planets via a protoplanetary disk. The Award Committee was impressed by Dr. Bergner's thoughtful application of her laboratory results for interpreting spectral observations of low-mass stars obtained at ALMA.

The Robert L. Brown Outstanding Doctoral Dissertation Award is administered by AUI and NRAO on behalf of Bob Brown's friends and family to honor his life and career. The Award is given each year to a recent recipient of a doctoral degree from any recognized degree granting institution in the United States, and is substantially based on new observational data obtained at any NRAO/AUI facility and considered to be of an exceptionally high scientific standard. The Award is available to degree recipients of any nationality and consists of $1000 USD, a framed certificate, and an invitation to give a colloquium at the NRAO.




## Interferometry and Synthesis in Radio Astronomy: a New Edition

The third edition of the classic textbook Interferometry and Synthesis in Radio Astronomy by A. Richard (Dick) Thompson, James (Jim) M. Moran, and George Swenson, Jr. was published by Springer International in 2020.

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

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

## Jansky Lectureship Awarded to Dr. Martha P. Haynes

AUI and the NRAO awarded the 2020 Karl G. Jansky Lectureship to Dr. Martha P. Haynes, Goldwin Smith Professor of Astronomy at Cornell University. The Jansky Lectureship is an honor established by the AUI trustees to recognize outstanding contributions to the advancement of radio astronomy.

Professor Haynes is being honored for her influential impact to our understanding of galaxies. She has made important contributions to our knowledge of the atomic hydrogen (HI) content of galaxies, environmental effects on gas, and large-scale structure in the local Universe. She was responsible for the first three-dimensional view of remarkable large-scale filamentary structures, based on HI observations of the galaxies in the Pisces-Perseus supercluster.

Prof. Haynes's work showed that galaxies are clustered on scales of tens to almost 100 Megaparsecs, considerably more extensive than previously demonstrated. This completely altered our view of the scale of inhomogeneities in the universe, now recognized as a fundamental tenet of cosmology.

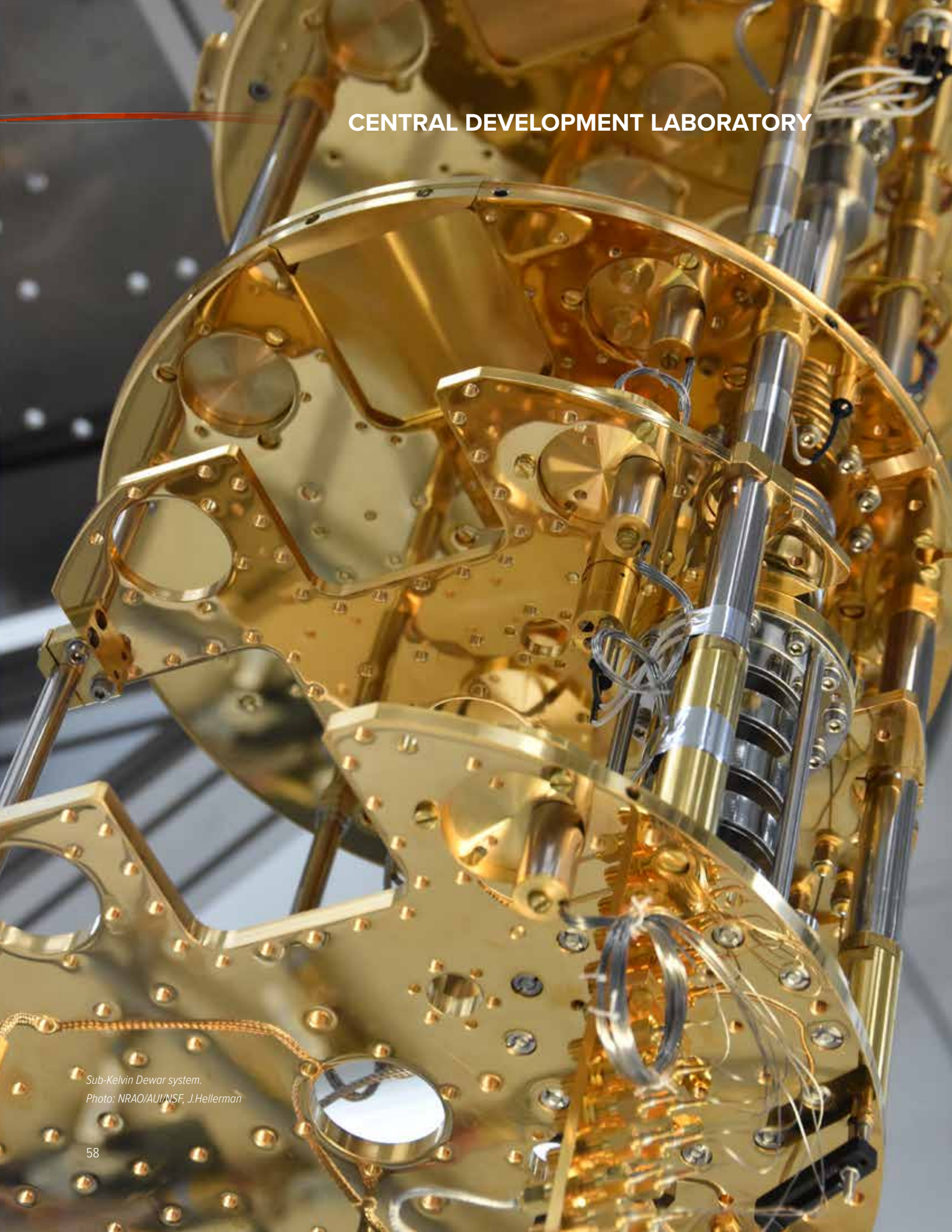
Prof. Haynes has also been a leader and advocate for the development of instruments to expand our ability to probe the radio Universe. She provided oversight and vision to the improvements made to the Arecibo Radio Telescope in Puerto Rico, culminating with the ALFALFA HI Survey, which covered one-sixth of the sky and detected an astonishing 31,000 galaxies. She is a leader of the collaboration building the CCAT-prime submillimeter telescope in Chile.

She has served as an advocate for radio astronomy at the highest national and international levels including vice chair of the 2010 Decadal Survey and vice president of the IAU (2006-2012). From 1981-1983 she was NRAO's Assistant Director for Green Bank, and from 1998-1999 she served as Interim President of AUI, where she gave broad oversight to the operation of NRAO and led the early negotiations leading to the establishment of the Atacama Large Millimeter/submillimeter Array (ALMA).

Haynes' achievements have been recognized through her election to the American Academy of Arts & Sciences in 1999, her election to the National Academy of Sciences in 2000, and through numerous highly-prestigious awards. Her professional activities have had a significant impact on astronomy policy and planning. In addition, she has been an inspiring teacher and mentor for her many students and a leader in bringing women into the field.

As Jansky Lecturer, Prof. Haynes will give (virtual) lectures at NRAO facilities in Charlottesville, Virginia, and Socorro, New Mexico. These lectures are open to the public.

# CENTRAL DEVELOPMENT LABORATORY



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

The NRAO 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 NRAO telescopes and to radio telescopes around the world. The laboratory also provides maintenance and upgrades to these instruments. The CDL staff of ~50 engineers and technicians is organized across crucial technologies, such as digital design and signal processing and low noise amplifiers. CDL is the world leader in the application of many of these technologies to radio astronomy.

CDL also supports the 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 engineering and astronomy students, and,
- Participating in student co-operative and internship engineering programs.

The greatest challenge facing the laboratory is the many late career employees in key leadership and technical positions. Over a five-year period, it will be necessary to backfill one-third to one-half of all laboratory personnel. This presents a significant challenge to talent development, knowledge transfer, and operations continuity, especially under COVID restrictions.

The NRAO, in collaboration with the U.S. radio astronomy community, continued to plan and develop an engineering design for a next generation Very Large Array (ngVLA). CDL proactively supported this process throughout 2020.

Additionally, CDL continued to engage in cross-observatory repair, maintenance, support, and in several programmatic and work-for-other construction projects. CDL continued investigating new and emerging technologies that have the potential to advance the state-of-the-art in instrumentation.

## Repair, Maintenance, Production & Support

The CDL core production and support activities for 2020 are described below.

**Low Noise Amplifiers (LNAs):** Production of ALMA Band 1 amplifiers for the National Astronomical Observatory of Japan (NAOJ) and ASIAA continued until the scheduled project completion in April 2020. The final 24 Band 1 amplifiers were built and accepted, concluding the contract to produce and supply 160 amplifiers. The CDL amplifier group continued to provide support for the ~1,000 VLA, GBT, and VLBA receivers in the field. Support for the refurbishment of ALMA Band 6 IF preamplifiers was continued.

**Millimeter and Submillimeter Receivers (MSMRx)**

During 2020, CDL continued to support offsite maintenance of the ALMA Band 6 receivers, and maintained quantities of spare mixers and preamplifiers. CDL also supported the Arizona Radio Observatory, the South Pole Telescope, the Taiwanese Greenland Telescope, and in the outfitting of millimeter/submillimeter telescopes for VLBI. Other than ALMA support, these activities were outside the scope of the Observatory's NSF award and were undertaken only when they did not interfere with the NSF award tasks.

Maintenance and production of Band 6 (211–275 GHz) mixer-preamps was delayed the past several years by the inability to reproduce mixer-preamps with the stringent gain flatness of those used in the original receiver production run. During 2020, additional mixer-preamplifiers were built and tested using the chip-and-wire amplifier design, employing the commercial Diramics devices and qualified for use in Band 6 cartridge repair work in FY2019. Though the pandemic slowed progress, the test set was thoroughly checked out and qualified, and has enabled acceptance verification of repaired Band 6 cold cartridge assemblies.

### Integrated Receiver Development

The Integrated Receiver Development (IRD) group supported the VLA and VLBA by providing construction and repair services on their multi-chip modules. The IRD group is uniquely qualified to carry out the specialized design and micro-fabrication tasks for such instruments.

### ALMA Offsite Hardware Support

The CDL offsite hardware team supported ALMA operations during 2020, and continued to work on repairing broken Line Replaceable Units (LRUs), though telescope operations were shut down for several months. Support included diagnosis consultancy, onsite visits to the OSF by support teams, software and firmware support, and repair of malfunctioning LRU hardware. In all, 16 Front-end LRUs, 35 Warm Cartridge Assembly LRUs, and 28 Back-end Local Oscillator and Photonics LRUs were returned to the ALMA site after repairs. A few notable LRUs that were repaired included Band 6 cold cartridge assemblies, FE bias modules, FE IF switch assemblies, warm cartridge/local oscillator assemblies, line-length correctors, sub-array switches, and LO photonic receivers.

The production of ALMA Band 1 LO assemblies for ASIAA continued and 30 articles were built, accepted, and shipped. The final quantity of 15 Band 1 LO assemblies have also been built and are in acceptance reviews, concluding the contract to produce and supply 65 Band 1 LO assemblies.

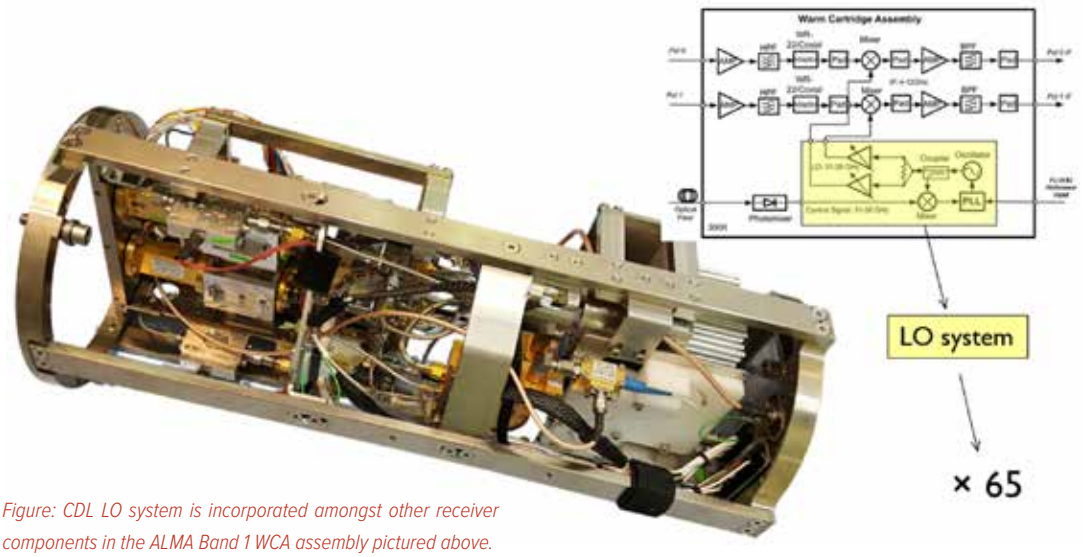



*Figure: CDL LO system is incorporated amongst other receiver components in the ALMA Band 1 WCA assembly pictured above.*

## Development Plan

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

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

### Millimeter and Submillimeter Detectors (MSMRx)

In 2020, CDL and the University of Virginia Microfabrication Laboratory (UVML) continued to develop the technology for next generation ALMA receivers, including SIS mixers and the development of ALMA-compatible TKIP amplifiers.

Under an ongoing ALMA development study, noise and S-parameter measurements were made at 4 K on a 4–20 GHz ferrite isolator and low-noise amplifier for possible use in the Band 6 receiver upgrade.

A wafer of small chip (1 x 3 mm) 4–12 GHz superconducting quadrature hybrids was completed at UVML and S-parameter measurements were made at 4 K. The performance was deemed acceptable up to 8 GHz but the return loss was excessive at higher frequencies. This project is being continued to develop a 4–16 GHz and/or 4–20 GHz hybrid for use in a future Band 6v2 receiver upgrade. Samples of these superconducting quadrature hybrids were provided to the University of Massachusetts for evaluation for use in the IF stage of their 1.3-mm multi-beam SIS receiver.

A goal for the ALMA Band 6v2 (211–280 GHz) design effort is to develop wideband SIS mixers with Nb/AlN/Nb and Nb/AlOx/Nb junctions and compare the performance and fabrication yield. A new ALMA Band 6 mixer was designed and mask sets manufactured. Fabrication of this design at UVML was hampered by pandemic delays in refurbishing the UVML cleanroom.

A Microwave Office program for millimeter-wave receiver analysis and design was completed, and will be useful for the emerging generation of millimeter receiver designers. It replaces older CDL software which has been rendered obsolete. For the planned Band 6 upgrade, the new software will allow the mixer and amplifier designers to work together to optimize the wideband IF circuit of the mixer-preamp.

### Optics and Electromagnetic Components

In support of the ngVLA, axially corrugated feed-horn designs were analyzed as radiators for 1.2-12.3 GHz. The reference design antenna efficiency was analyzed, and its sensitivity to horn positioning was computed. Beam-pointing and efficiencies were calculated for translations and rotations of the ngVLA antenna optical elements.

Work on the design, fabrication, and testing of a 310 MHz short-backfire antenna for the synchrotron radiation measurement on the GBT continued. After the initial design was completed, tests with a mechanical wooden mockup were carried out. A decision was made to modify the design for safe stowing under high wind conditions, prior to fabricating a prototype. This revised design was completed, but fabrication and testing remains.

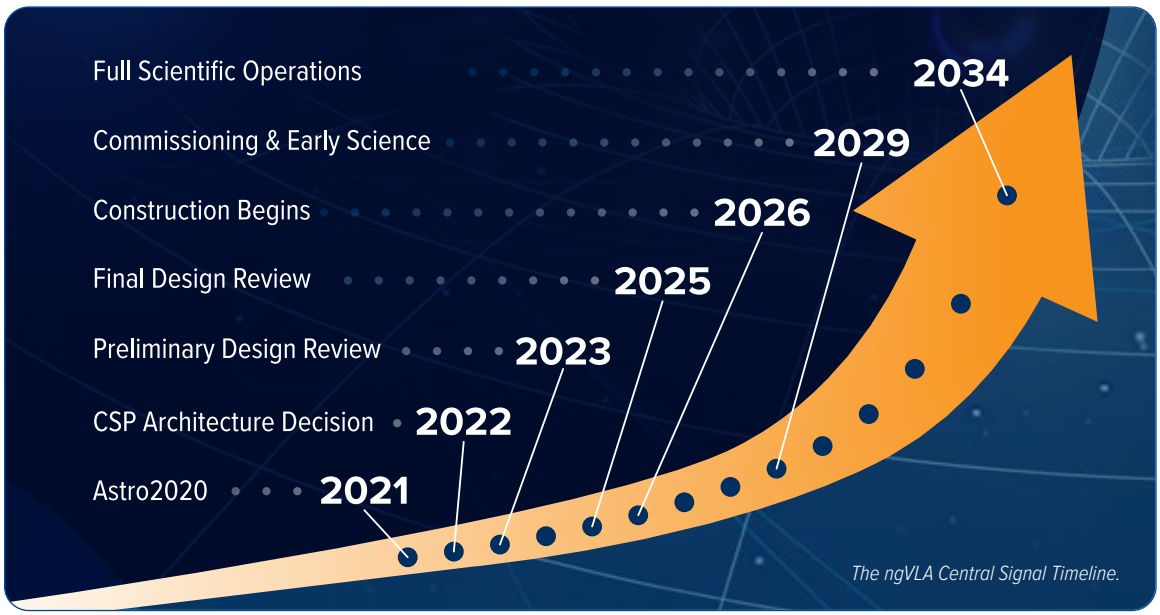
To monitor the progress of additive manufacturing technology (3D printing) and to determine if any advances might be useful in manufacturing EM components, the CDL has collaborated with selected vendors to produce 3D printed parts for test and evaluation, including a K-Band waveguide manufactured at Optisys, Inc., and a dielectric block printed at Lincoln Laboratory.

Preliminary measurements of the K-band waveguide have revealed that its loss is ~0.42 dB/ft (at room temperature), compared to 0.152–0.207 dB/ft loss of a standard aluminum waveguide. No change in loss characteristics was noted after temperature cycling the printed waveguide to 20 K. Measurements of the cryogenic loss of this waveguide are ongoing.

**Digital Signal Processing and Correlators**

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

- Is relatively low risk as it is based on SKA design.
- Is designed for efficiency under ngVLA requirements.
- Is scalable to any observatory size and needs.
- Is most efficient for the interferometric mode of operation.




*The ngVLA Central Signal Timeline.*

During 2020, hardware/tools for FPGA development were procured for continued development of the SCREAM technology.

The SCREAM prototype under development will consist of two beamforming and channelizing (B&C) nodes with basic functionality and a control/gateway node. These nodes will be implemented on the iWave SoM boards, which have been received and verified, and are on-hand. The DSP blocks for the gateway node were completed, while work is ongoing for the B&C nodes. Interlaken transceivers (up to 150 Gbps) will be used for data I/O from the B&C and the gateway nodes. Python based GUI was implemented and finalized for the monitor and control functionality, while work continued on adding the display functionality to the interface code.

The ngVLA Central Signal Processor (CSP) effort continued to mature towards the compilation of a SCREAM-based alternative proposal. The reference design was further optimized, potentially saving ~50% of the hardware over the original ngVLA reference design.

*Figure: The small size and cost of the iW-RainboW-G35D board is suitable for continued SCREAM development under work-from-home conditions.*

An ALMA correlator sustainability effort was initiated during 2020. Future spares requirements were reviewed and procurement initiated for boards and parts to support the baseline correlator for at least another decade. As this hardware is received, work will continue in FY2021 to consolidate and build spare hardware, some of which is already obsolete. For hardware/articles which are no longer available, obsolescence mitigation projects were initiated for a redesign effort.

**LO Reference and Timing**

Local Oscillator (LO) reference and timing work was executed in the context of the continuing development of ngVLA designs and concepts, and was carried out extensively with external collaborators (NRC-Penticton, NAOJ-Mitaka, Raytheon Technologies). This work included:

- Detailed design concepts for the antenna station based LO and timing so that size, weight, and power envelopes could move forward in concert with antenna design and station electronic design.
- Developing an ngVLA-specific implementation of a NRC scheme called "incoherent clocking," in which the antenna station clocks and digitizers are themselves free-running and all phase and timing corrections are applied centrally.
- Collaborating with Raytheon on clock requirements and feasibility of coherent distribution for ~500 km and ~5000 km order of antenna station separations. This effort started in 2020 and will continue in FY2021.
- Collaborating with NAOJ on distribution of nanosecond timing for ~1000 km antenna station separation. This effort, initiated in 2020, will also continue in FY2021.

**LO Group**

InP HBT and GaN device based RF power amplifier technology has made significant advances since the FE LO was first designed. Commercial devices are available up to 100 GHz and these were evaluated in 2020 to move away from custom power amplifier MMICs to alleviate the problem of unrepeatable wafers/processes.

In the ALMA LO system, GaN did not seem a suitable technology match given its power and heat dissipation requirements. InP HBTs were evaluated and the output power was found to be suitable for LO application up to the desired frequency of 120 GHz and could serve as alternate technology to the existing GaAs custom-MMICs. The sideband noise performance remains to be quantitatively qualified for the InP HBT solution. Further development of amplifier packages is required to comply with the shape, form, and function required to fit into the existing systems. This work is ongoing and will continue.

Via the ALMA Cycle 7 study, investigations were initiated to improve the sideband amplitude noise of the existing ALMA Band 6 Local Oscillator during 2020, and this work is expected to continue in 2021 under an approved no-cost schedule extension.

**Integrated Receiver Development (IRD)**

The Integrated Receiver Development (IRD) program aims to develop compact, mass-producible, and field-replaceable front-end hardware for the next generation of radio telescope facilities. 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, achieving unmatched precision and stability.

Recent years saw the demonstration of an end-to-end W-band dual-polarization receiver system utilizing a wide variety of novel IRD concepts, with 32 Gbps of data being transmitted over 10 km of fiber while performing calibrated sideband-separation in real-time. This year, the goal was to design and implement an SADC Application Specific Integrated Circuit (ASIC) drop-in module for the W-band front-end. Problems with the SADC chip prevented this from being accomplished.

While the SADC concept has been proven in FPGA architecture, there were errors on the part of the ASIC contractor. The vendor made efforts to correct the on-chip hardware errors, however post-editing evaluation did not yield favorable results.

**IRD ngVLA Work**

Design of the ngVLA Band 3 IRD-style module was started in FY2019. The plan was to build the module as the first to incorporate the new SADC ASIC. Since that has not materialized, the team is now building a prototype of the analog signal path only.

During 2020, a Teledyne amplifier was evaluated for use in the ngVLA Band 6 (70–116 GHz) and yielded very good small signal performance/results.

In close coordination with the ngVLA management and the Program Management Department, significant effort was expended in preparing for the second attempt at the SADC ASIC development. The plan is to purchase available silicon-proven IP blocks and work with a physical design contractor to integrate them on to a single chip. The next step is to identify the available IP and obtain budgetary quotes for the same. This effort will continue in 2021.

**Hydrogen Epoch of Reionization Array (HERA)**

HERA is an on-going multi-year CDL development project. The goals addressed in 2020 included:

- Developing a portable antenna beam mapping system based on receiving downlink signals from the OrbComm satellite constellation. The system is to be deployed at the HERA site in South Africa.

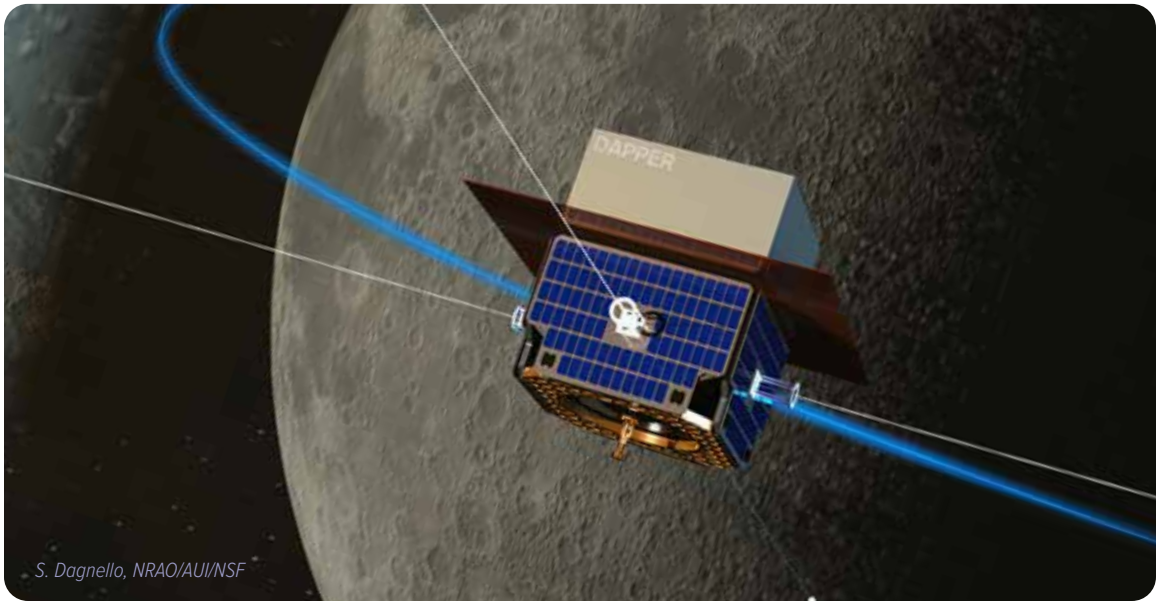
- Development of a novel precision Unmanned Aerial Vehicle (UAV)-based antenna beam mapping system. This system was evaluated at the University of Virginia test flight facility. Strategies for phase measurements, RFI suppression, and multipath signal mitigation were investigated. Future operational tests will be conducted at the HERA site in South Africa.

**Network for Exploration and Space Science (NESS)**

This research continued in 2020 towards the development of the next generation Cosmic Twilight Polarimeter (CTP), a ground-based instrument that will help refine the polarimetry technique for hydrogen cosmology studies. Upgrades included a correlation receiver, a high-speed digital Back End platform with improved Digital Signal Processing, noise and pilot tone-based calibration, and improved temperature stability of the Front End electronics. This instrument will be deployed in Green Bank for detailed evaluation and sky measurements leading to the prototype for the Dark Ages Polarimeter Pathfinder (DAPPER). The test data will also serve to aid the development of multi-signal pattern recognition algorithms.

**Dark Ages Polarimeter Pathfinder (DAPPER) SmallSat Mission Concept**

Last year, the DAPPER concept study report was completed and the spacecraft proposed as a NASA Discovery-class mission. The mission was selected for Technology Readiness Level 6 technology maturation, and the CDL started to develop the radio frequency portion of the science instrument under the auspices of the new Space Electronics Division. This effort is a collaboration with the University of Colorado at Boulder, NASA Ames Research Center, and the Berkeley Space Sciences Laboratory, and incorporates significant early career participation. A detailed Integration & Test flow and schedule was completed. A next generation Cosmic Twilight Polarimeter, the DAPPER engineering prototype, is under development.



*S. Dagnello, NRAO/AUI/NSF*


Virtual Tour
Saturday, December 5
1-2 PM MST
Mountain Standard Time
Karl G. Jansky
Very Large Array
National Radio
Astronomy
Observatory

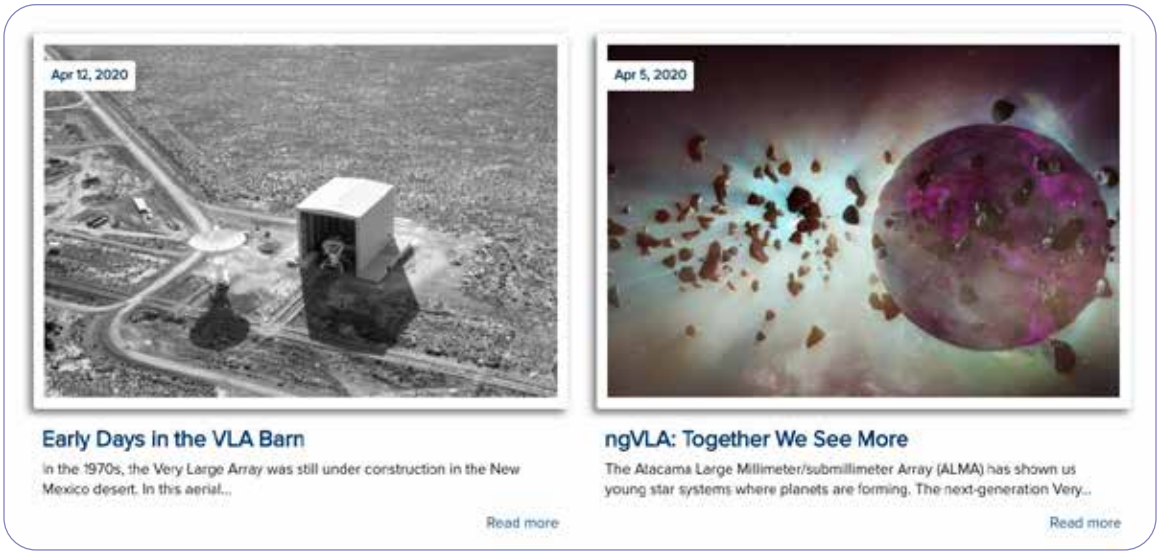
The NRAO Education and Public Outreach (EPO) department serves the strategic Observatory goal of broadening public appreciation of and participation in Science, Technology, Engineering, Arts, and Mathematics (STEAM). EPO's four divisions had a busy year highlighting the discoveries, technologies, and careers pioneered and exemplified by the NRAO. There were disruptions caused by the change in work from home due to the COVID pandemic, but EPO was able to adjust and continue.

## News and Public Information

**Press and Image Releases:** The news division had a banner year in 2020 with 40+ press products. The variety of press releases on ALMA discoveries, VLA discoveries, joint VLA and ALMA observation results, VLBA discoveries, and NRAO milestones. In addition to press releases, EPO distributed announcements highlighting milestones of the Observatory.

**Feature Stories and Images of the Week:** For the last two years, the news group has committed to publishing quarterly stories not driven by individual press releases, but an opportunity to explore a topic in more depth. This year, four Feature Stories were published.

With the redesign of the public website home page, there is an additional opportunity to feature the facilities and the discoveries they make possible with the Image of the Week. This was consistently kept dated.




**Media Outreach:** In 2020, the Public Information Officers (PIOs) committed to several major media events with two audiences in mind: the researchers who use NRAO data to make discoveries, and the reporters and science writers who bring those discoveries to the public. Two major science meetings were at the heart of these efforts, the winter American Astronomical Society (AAS) meeting and the annual meeting of the American Association for the Advancement of Science (AAAS).

EPO PIOs sponsored a meet-and-greet at the winter AAS meeting in Hawaii. Reporters and writers were welcomed to the reception by the Observatory Director and the audience included representatives from ALMA, VLA, ngVLA, and VLASS.

The AAAS Annual Meeting is the primary gathering of U.S. science journalists. Since the 2020 meeting was in Seattle, NRAO reached out to the Northwest Science Writers Association to co-sponsor the event. Signage and credit was given and NRAO representatives were on-hand to mingle with the media.


*Virtual ngVLA walkthroughs at the winter AAS meeting in Honolulu HI.*

The NRAO Users Committee has noted that many users do not realize the media relations support available through NRAO. EPO has included notices in eNews about these services, and also featured them in the exhibit halls of the AAS and AAAS, using the video wall in the exhibit and print materials to introduce press officers and how they could work with the scientists to publicize their discoveries.

**Communications Training:** Dave Finley is a regular guest speaker at the technical communications course at NM Tech. In addition to PIO work with all NRAO presenters at press conferences at the AAS and AAAS meeting, there were three additional training efforts:

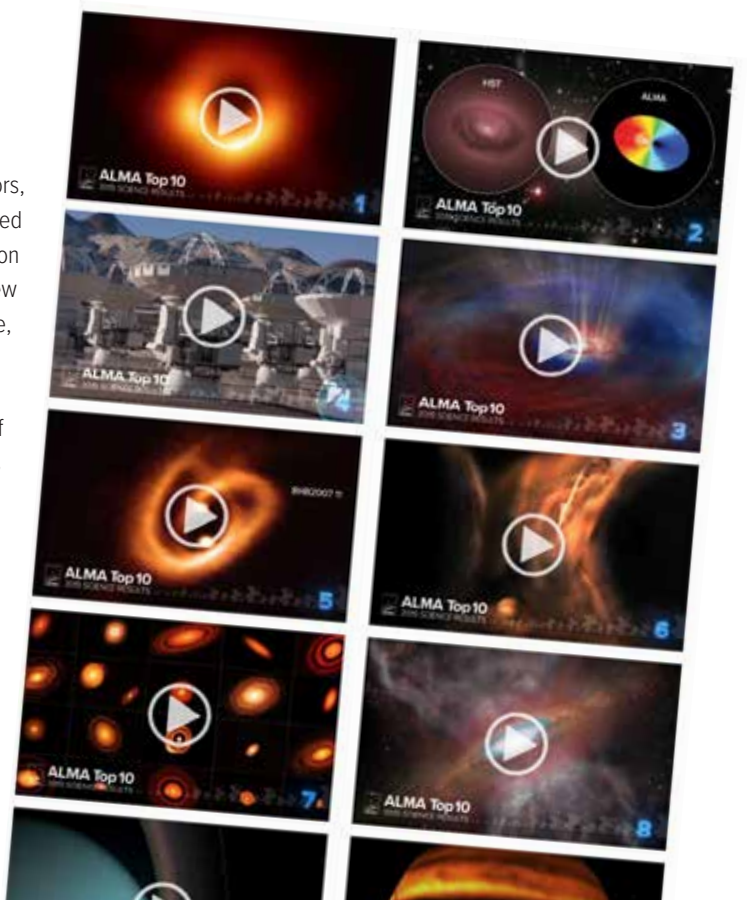
- EPO presented a workshop to ALMA Ambassadors in February that covered the basics of storytelling and poster design and presentations for professional conferences.
- EPO worked with the Observatory Director to develop talking points around the increasing number of satellites orbiting the Earth and their impact on our ability to observe. He then conducted a short training for the tour guides and STEAM Ed educators who are fielding these questions in their virtual outreach and tours.

**Liaison with ALMA Partners:** The ALMA PIO participated in the monthly meetings of the ALMA partners to discuss upcoming news releases and possible collaborations.

## Multimedia Engagement

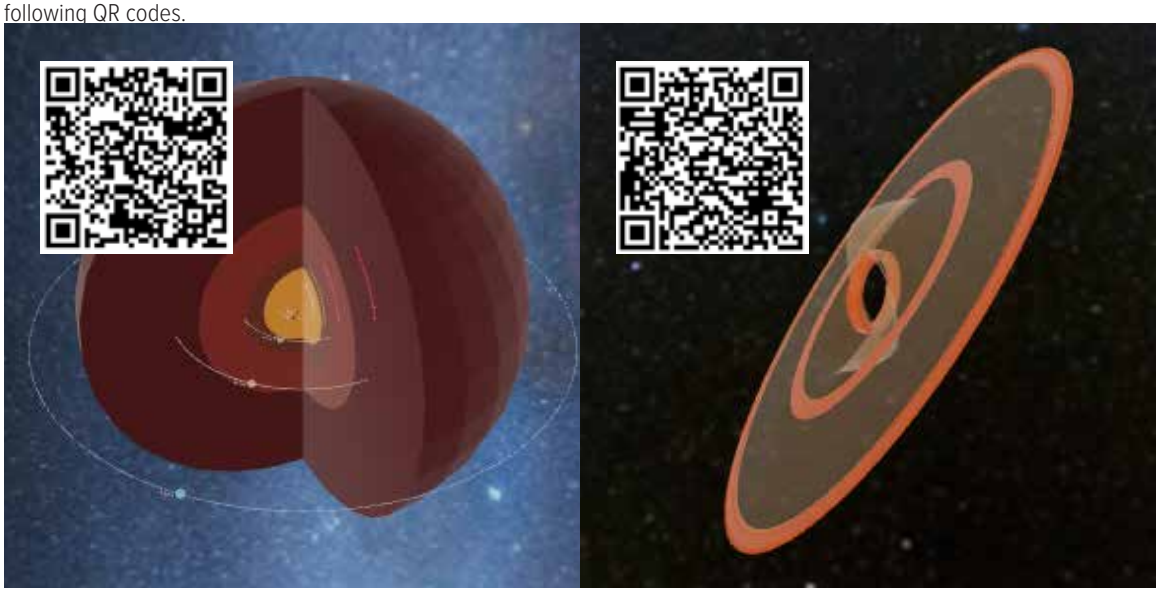
A dedicated, creative team of animators, artists, illustrators, designers, writers, and web developers designed and developed unique multimedia materials, in support of the news and information page, social media, and STEAM efforts, as well as creating new products that were distributed through the public-facing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

**Press Products:** The multimedia group created a series of posters and videos to celebrate a banner year of discoveries made possible by ALMA. Phil Plait, the popular Bad Astronomer blogger, was contracted to write 60–90 second scripts and do the voiceover for 10 ALMA videos based on press releases from the calendar year. These videos were then created based on available press release images and B-roll of ALMA and released via social media and can be found archived in the public gallery.



In addition to the usual creation of science images and artist impressions created to support press releases, the multimedia group started providing 3D Augmented Reality models for select press releases. Of note are: the 3D model of the extent of the atmosphere of Antares as observed by both the VLA and ALMA; the misaligned protoplanetary rings of a triple star system; and the detection of an exoplanet through astrometric measurements of its star.

These are best explored on a mobile device, and can be found easily using the camera on a smartphone with each of the following QR codes.



**Revised/Improved Image Gallery:** New workflows have been developed to keep the public-facing gallery populated with the latest images from press releases and other multimedia group projects. The overall gallery was still a challenge to search for particular images, so the organization and tagging of images was revised in late 2020.

**Investigate Podcasts Development:** With the increased development of videos, Augmented Reality and Virtual Reality, this was beyond the time capabilities of staff for this year. While it was investigated, it was decided that the Feature Stories, Baseline Videos, and Blogs are the limit of regular features that can be supported.

**Baseline Hosted Videos:** Bill Saxton has taken the lead on the production of these videos. The opening credits were developed by Sophia Dagnello and the scripts are written quarterly by Brian Koberlein. The three created in 2020 are:

- Viewing Active Galaxies
- Measuring the Expanding Universe
- The VLA at 40
- VLASS Mapping the Radio Sky

Now that the workflow is ironed out, these will continue as a regular quarterly feature for the foreseeable future.

# EDUCATION & PUBLIC OUTREACH

**NRAO Brand and Style Guide:** This is a work in progress. As new projects are developed, like Augmented Reality, they are being added to the scope of the style guide.

**Augmented Reality:** Augmented reality was developed for press releases, but the first applications of it were for our telescope pages on the public website. Along with the fast facts for each facility, a 3D model of the ALMA 18m dish and the VLA 25m dish were placed on the website. The public can interact with the 3D model, on the computer with a mouse or through the camera of their mobile device, they can bring the model into their room or space with them.

**Virtual Reality:** As an additional activity, the multimedia group lead by Sophia Dagnello developed a virtual reality tour of the ngVLA for the NRAO exhibit booth at the winter AAS meeting. Oculus Rift headsets were purchased and a plan was in place to enhance the straightforward landscape tour with additional interactive information so that it could be used at instrumentation and supercomputer conferences. This project moved to the back burner while travel is suspended.

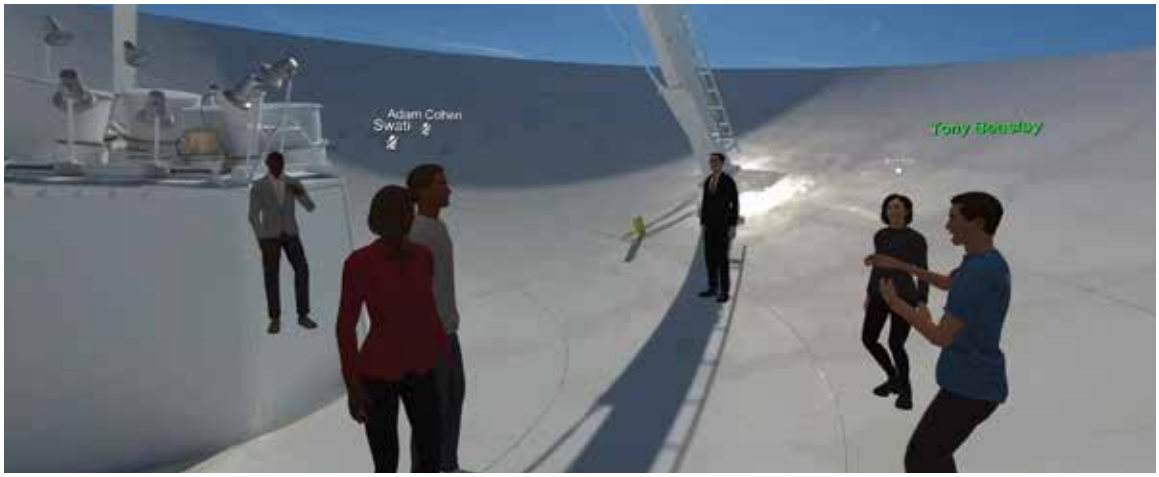
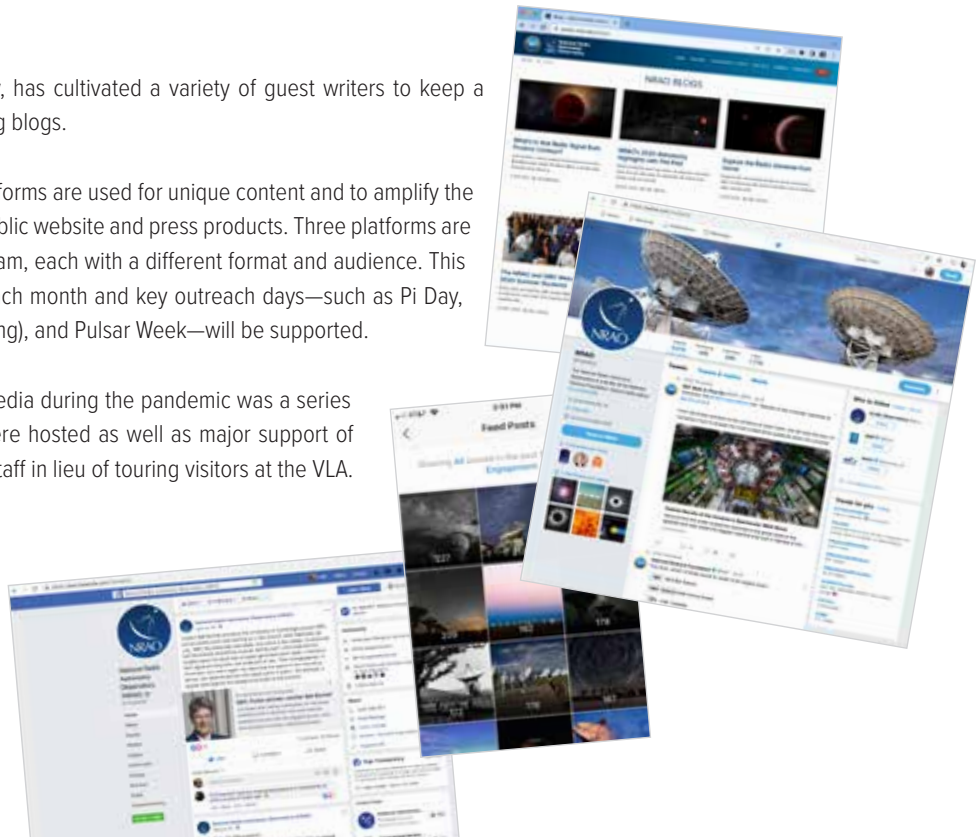



Figure: Oculus Rift and ngVLA walkthrough

**Blog:** Social media specialist, Nan Janney, has cultivated a variety of guest writers to keep a steady flow of blogs, as well as contributing blogs.

**Social Media Programs:** Social media platforms are used for unique content and to amplify the distribution of new content on the NRAO public website and press products. Three platforms are maintained: Facebook, Twitter, and Instagram, each with a different format and audience. This year, a different theme will be explored each month and key outreach days—such as Pi Day, Black Hole Friday (the day after Thanksgiving), and Pulsar Week—will be supported.

A major pivot that happened with social media during the pandemic was a series of Facebook live events. Seven events were hosted as well as major support of the virtual tours offered by the STEAM Ed staff in lieu of touring visitors at the VLA.



**Website Maintenance:** EPO has maintained the public website through consistent software updates to enhance front end and back end efficiency and security. Industry standards have been deployed for search engine optimization to ensure web outreach efforts are effective and as broad as possible. At the end of the fiscal year, IT transferred the public website to new servers.

## STEAM Education and Outreach

**Lesson Plan Development:** The NRAO public website is rich with new and sometimes interactive content (e.g., colorizing app and interferometry app). The STEAM team worked with the African American Teaching Fellows (AATF) STEAM Education Think Tank in Virginia to create a suite of lesson plans that are available for testing. The testing was derailed by the pandemic but will be picked up in the next academic year.

**Sister Cities and Observatories:** This NRAO-funded program partners two high school students and a teacher near the VLA in New Mexico with two high school students and a teacher near the ALMA site in northern Chile in a joint cultural/learning exchange, using a scientific experiment as a connecting thread of inquiry. This 10-day exchange seeks to reinforce the school curriculum through STEAM education activities. The emphasis this year will be to expand the shared experiences of the two cohorts leveraging the packaged STEAM Education lesson plans. A commitment and involvement will be required by students and school teachers from New Mexico and the Likan Antai C-30 School in Toconao, Chile. The students and teachers will be responsible for participating in shared research experiences and for being ambassadors in local schools. EPO staff will work with teachers and students to refine their proposed curriculum projects. Travel for the New Mexico cohort was cancelled because of the pandemic.

**Outreach Events:** Most outreach events have been postponed during the pandemic. Before the shutdown, the STEAM Ed team participated in community events in local Socorro schools including Sarracino STEAM Night, Enchanted Skies Star Party, Festival of the Cranes, and San Antonio Elementary Science Day. The one virtual outreach event was for Project Rousseau, which hosted EPO educators in a classroom Zoom visit.

**VLA Visitor Experiences:** As a team, the STEAM Ed group completed certified interpretive guide training. This is a shift in mindset from specific content-learning goals to creating interpretive experiences at the VLA that are audience centered and mission driven focused. These skills will be applied to the revised virtual tours.

## Visitor Center Operations

NRAO operates a visitor center at the VLA, west of Magdalena, NM. The site has indoor and outdoor public exhibits, a small auditorium, a gift shop, and monthly tour program. The VLA site was closed to the public from mid-March through 2020. The VLA served 10,279 visitors, plus 3,756 local and international students and tour groups receive special tours. Of those served, 1390 of those participated in virtual tours during the shutdown.

**Marketing:** A special 40th Anniversary marketing plan was underway when operations were shut down.

**Retail operations:** Gift shop sales in FY2020 were on track with $132,114 in total sales before the shutdown EPO is working on a sustainable model for an online shop to open in 2021 that can be maintained when the visitor center is open to the public again.

# 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

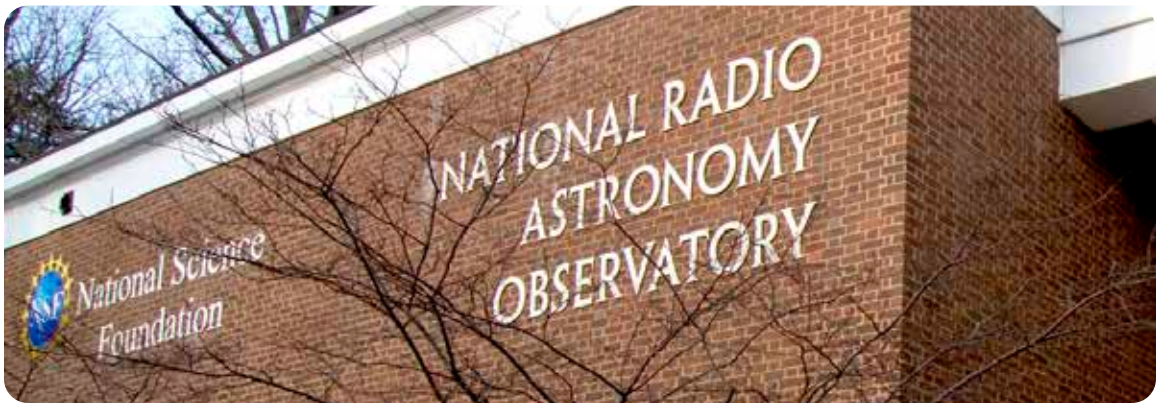
The Central Development Laboratory (CDL) led by Assistant Director **Bert Hawkins** supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to build the next generation of radio astronomy instruments. CDL accomplishes this through development of the enabling 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. **Laura Lockledge** is the Charlottesville-based Assistant Director for the NRAO Budget Department.

Assistant Director **Patricia Henning** 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 NRAO Office of Diversity and Inclusion (ODI) was established in FY2015 to support NRAO in achieving its core mission goals by increasing staff diversity and inclusion across the Observatory, developing and implementing programs to improve the recruitment, retention, and success of under-represented and under-served students and staff members, and fostering a work environment that is inclusive of all individuals. In 2020, the ODI Director worked closely with HR, EPO, and SSR to develop and maintain programs that affect the NRAO workforce, broader impact efforts, new and ongoing pipeline initiatives, and the internal NRAO culture and climate.

**Diversity Council:** ODI is staffed by the Director of Diversity and Inclusion, and the Radio Astronomy Data Imaging and Analysis (RADIAL) Project Director. ODI is advised by the NRAO Diversity Council, comprised of the Assistant Directors of Human Resources (HR), Science Support and Research (SSR), Education and Public Outreach (EPO), Program Management, New Mexico Operations (NM Ops), the Central Development Lab (CDL), and the Office of Chilean Affairs (OCA). The Council met quarterly, provided advice, and assisted the ODI by supporting and coordinating Observatory-wide efforts to improve and enhance diversity in all aspects of Observatory operations, and facilitating communications between NRAO departments.

**Employee Diversity Group:** In acknowledgement that NRAO employees have an important role in advocating for, and supporting, Diversity and Inclusion initiatives and efforts, the ODI supports an Employee Diversity Group (EDG). In 2020, EDG members met regularly to identify ways to build and support an inclusive culture at the Observatories. In March, when COVID sent the workforce home, the EDG developed and hosted a series of virtual meetings, Employee Connections, designed to provide employees with a place to gather and brainstorm ways to maintain connections, build remote working relationships, and manage sudden changes and challenges to work/life balance. EDG members represent all NRAO locations: CDL and Headquarters in Virginia, Socorro and the VLA in New Mexico, and the Office of Chilean Affairs in Santiago, Chile.

Examples of Employee Connections conversations include:

- Parenting challenges during the pandemic
- Being alone during quarantine
- Inviting colleagues into your home via Zoom
- Transitioning between different pandemic states
- A discussion on anti-racism
- COVID-19 and racial disparities
- Use of “master/slave” terminology in tech
- Back to school, or not?
- News polarization impact on public discourse about race
- It’s OK to not be OK.

*Employee Diversity Group members*

**Diversity, Cultural, and Community Awareness:** A culturally diverse and aware workforce can create an environment of mutual respect and dignity, garnering a reputation as a fair employer in the job market. In 2020, diversity awareness opportunities were offered across the Observatory utilizing a mixture of outside speakers, online training, discussions focused on diversity issues, and the WeSpeak series, which offers NRAO staff the opportunity to share their interests with others in the Observatory. Diversity and Inclusion awareness is incorporated in supervisor and management training, the NRAO’s on-boarding program, and the Observatory Leadership Cohort. In 2020, diversity speakers were scheduled as a part of the summer internship experiences for undergraduates.

In 2020, education and training related to diversity and inclusion were made available to all members of NRAO staff on a volunteer basis, and included:

- Anti-racism conversations
- News Polarization
- Stress Management in Challenging Times
- Introduction to the Office of Diversity and Inclusion
- Overview of RADIAL
- Overview of Broader Impacts at NRAO
- Tips and Tricks for Student Independence
- Courage, Vulnerability, and Connection in the Workplace.

NRAO continues to focus on education and training related to the importance of a diverse workforce and inclusive environment. In 2020, ODI and HR introduced a fresh set of online training modules that address current and emerging diversity and inclusion, and HR-related topics. Examples of courses and workshops that have been, and continue to be, offered include:

- Diversity and Inclusion
- Preventing Harassment and Discrimination
- Tools for an Ethical Workplace.

**Broader Impacts:** In 2020, ODI collaborated with department and division heads across the Observatory to develop a Broader Impacts (BI) plan that takes advantage of the many opportunities, across a number of disciplines, for broadening the impact of Observatory activities to a wide range of stakeholders. The ngVLA Broader Impacts plan focused on identifying, developing, and tracking the many BI activities available through the ngVLA project.

In 2020, activities included efforts to better educate and inform Observatory staff about BI efforts, including the development of a:

- BI Strategy Framework
- BI Toolkit (to include a reporting mechanism)
- Definition of Community for Stakeholder Engagement
- New Mexico Outreach Database.

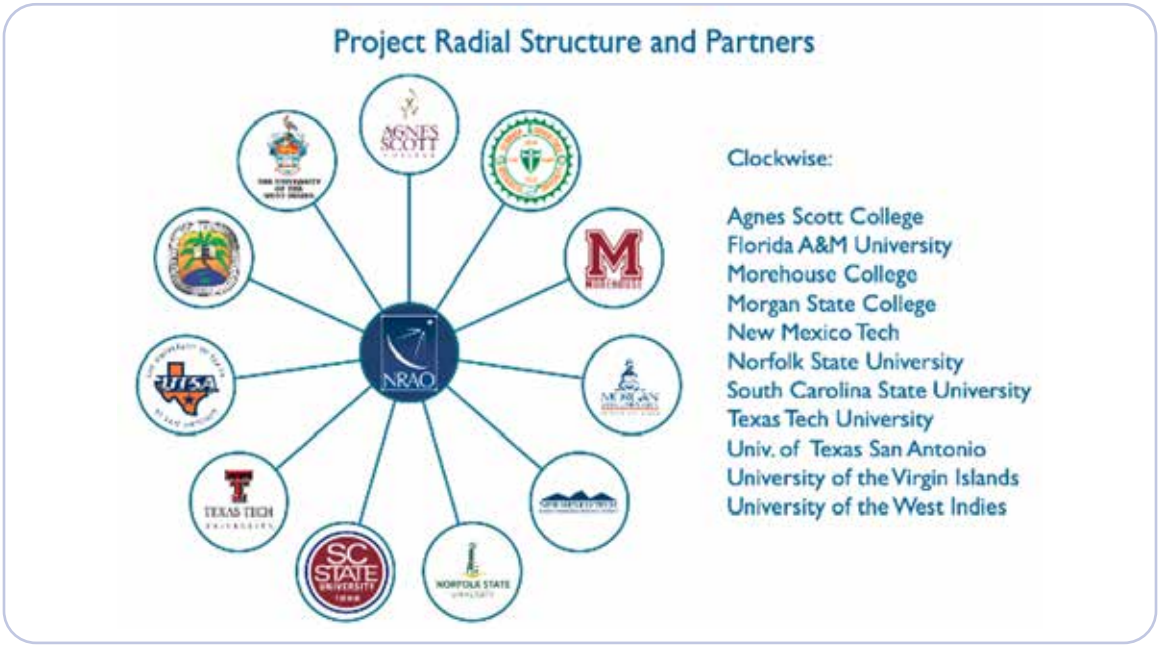
## Local and National Programs

ODI operates programs that serve national and international constituents and strive to increase the numbers of underrepresented populations in STEM fields that support radio astronomy.

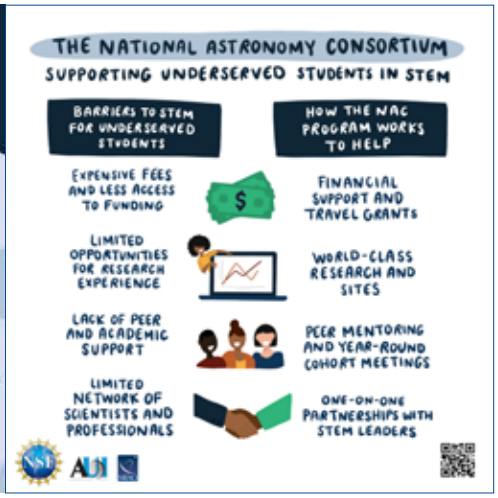
**Project RADIAL:** The Radio Astronomy Data Imaging and Analysis Labs (RADIAL) project was initiated by the NRAO to address current and future astronomy big data challenges and to cultivate a diverse and globally competitive STEM workforce while doing so. The project is a partnership between NRAO, Minority-Serving Institutions (MSIs) in the USA and abroad, and the private sector.

RADIAL uses 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 minority-serving institutions (MSIs) in the U.S., industry, non-governmental organizations, and international partners in Costa Rica, Honduras, South Africa, and Trinidad and Tobago. RADIAL's objective is to provide MSIs with computer hardware and data sets 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.

In 2020, the initial project design for Project RADIAL was completed via workshops with RADIAL partner MSIs. Proposals were also developed to raise funding and support for RADIAL from the private sector. An NSF Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES) planning grant was awarded for 2021 to establish a project office, develop required strategies and plans, and conduct front-end evaluation. By the end of 2020, 11 partners were committed to Project RADIAL.




**National Astronomy Consortium:** The National Astronomy Consortium (NAC) is led by NRAO in collaboration with the National Society of Black Physicists (NSBP) and several minority- and majority-serving universities and observatories. The NAC program goal is to build a pipeline of students from under-represented and under-served groups to STEM fields that support full-spectrum astronomy (e.g., science, data management and analysis, and engineering). The NAC uses a cohort model, multiple mentors, professional development, and lifelong career mentoring to increase participation of under-represented groups in astronomy-related careers.


***Far Left:*** *The National Astronomy Consortium (NAC) program path.*

***Left:*** *Barriers to STEM for Underrepresented Students.*

# MANAGEMENT & ADMINISTRATION

In 2020, the NAC placed 15 undergraduate students, from community colleges and universities across the country, with trained NRAO mentors, and four additional partner sites: Space Telescope Science Institute, the University of Wisconsin-Madison, Michigan State University, and Princeton University. Five students were returning NAC alums. Students were recruited from partner MSIs and HBCUs, and through targeted outreach to Hispanic-Serving Institutions (HSIs).

In response to COVID, NRAO and the partner sites converted from the typical in-person internship to a virtual summer research and professional development experience.

This virtual summer program replicated many of the NAC program components that have characterized previous summers: research with mentors, (virtual) interaction with other summer students from each research site, and professional development activities. The NAC program took advantage of the opportunities provided by a virtual environment to bring all 15 of the 2020 NAC students together, twice a week, for professional development and cohort-building activities. For the first time, the NAC summer program was led by a NAC alum, Tierra Candelaria, a Ph.D. candidate at New Mexico Tech.

Examples of events and activities offered to the NAC students over the summer include:

- Informal mentoring
- Workshops on mental health issues (e.g., imposter syndrome), technical skills (e.g., python), and professional development (e.g., writing a CV and personal statement)
- A career panel
- Science communication
- Broader Impacts
- Education and Public Outreach (e.g., social media connection)
- Cohort-building activities (e.g., "Riddle Night")

In 2020, the NAC program offered a ten-week Project Management course, led by a Green Bank Observatory Project Manager, designed to prepare students to take the Project Management Institute (PMI) Certified Associate in Project Management exam.



***Above:*** *NAC Alums meet with 2020 Cohort.*
***Left:*** *The 2020 NAC Student Cohort.*

**NAC Alums:** The year 2020 marked the eighth year of NAC programming, resulting in 74 active NAC alums. Twenty-eight alums are in graduate school; most of the remaining alums are undergraduates. This year, the NAC program continued to facilitate opportunities for alums to build and maintain peer-mentoring relationships across cohorts. In 2020, NAC alums organized and facilitated a webinar series 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.


**Annual NAC Meeting:** The NAC Annual meeting, typically held in September, was moved to October 2020 in response to student feedback. Owing to COVID, the decision was made to convene a virtual meeting to span 11 October–12 November. New this year was an Organizing Committee composed of NAC alums, making the 2020 NAC Annual Meeting entirely organized and facilitated by NAC graduate and undergraduate alums. From August through September, a team of nine graduate student alums planned the meeting and prepared to facilitate the scheduled Zoom sessions.

**VA-NC Louis Stokes Alliance for Minority Participation:** In 2020, NRAO participation in the NSF-awarded Louis Stoke Alliance for Minority Participation (LSAMP) Virginia-North Carolina Alliance resulted in participation by four Alliance students in Project Management training internships. Students completed a Program Management Institute (PMI) online training course, supplemented by weekly tutorials and mentoring by Green Bank Observatory and NRAO mentors, to prepare for the PMI examination for Project Management certification.

**NSBP and SACNAS:** In 2020, ODI continued to support the NSBP and SACNAS by participating in their respective annual meetings, and recruiting students from both organizations for the NAC program.

ODI continued planning to host the 2021 NSBP Annual Meeting (postponed to 2022) in Charlottesville, Virginia. The first NSBP/ National Society of Hispanic Physicists (NSHP) Student Summit was also planned for Summer 2020, but was postponed due to COVID.

*NSBP Board, NSBP students, NRAO representatives, City representatives during site visit for 2021 NSBP Annual Meeting.*

**URM Student Network Partnership:** In 2020, at the 235th Annual AAS meeting, ODI met with leaders of student programs focused on serving underrepresented minority students with the goal of identifying opportunities for improving Under Represented Minority-focused programs to better serve undergraduate and graduate students of color in STEM.

## International Partnerships

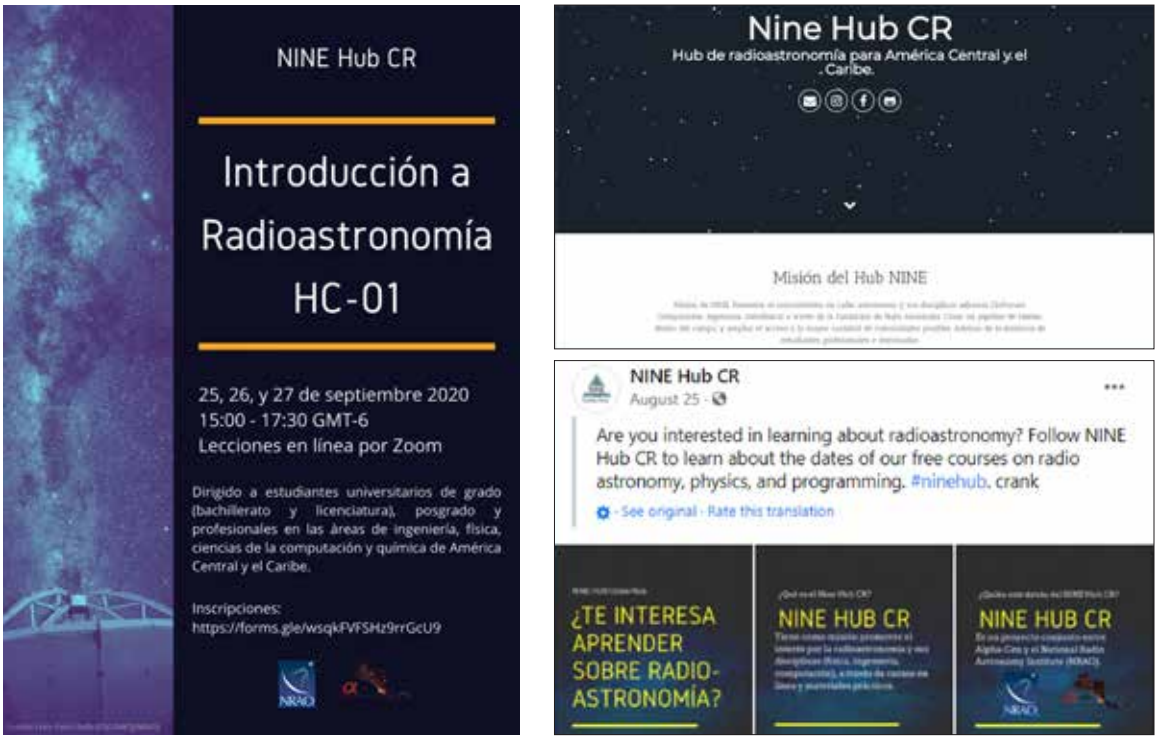
**National and International Non-Traditional Exchange (NINE):** NINE provides practical skills development opportunities for participants from under-represented minorities or developing countries. Participants complete an intense summer training

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 required, upon returning to their home location, to establish a NINE Hub and take on the role of a NINE trainer in the specific skill/s learned. The anticipated program outcome will be worldwide partnerships with fast-growing radio astronomy communities designed to facilitate the exchange of NINE trainers.

In 2020, the Universidad Latina de Costa Rica joined the NINE network owing to the continued collaboration with Astrofisica CentroAmericana y del Caribe (Alpha-Cen).

The NINE training program focused on Machine Learning techniques in the northern hemisphere summer 2020, using an image dataset from the VLA Sky Survey. The NINE participants successfully completed the Certified Associate in Project Management exam through the PMI and designed a Broader Impacts project and a plan for the development of the Alpha-Cen/Universidad Latina de Costa Rica Hub.

The Costa Rica Hub developed and delivered a Spanish-language Introduction to Radio Astronomy course, a Hub website and training repository, and translated the course to English for use by the RADIAL partners and NINE hubs.




***Above Left:*** *Introduction to Radio Astronomy course announcement;* ***Top Right:*** *Costa Rica Hub Resource Portal;* ***Bottom Right:*** *Costa Rica Hub Facebook page.*

**OCA Collaboration:** The ODI supports the efforts of the Office of Chilean Affairs (OCA) in Santiago in the area of diversity and inclusion, and coordinates with the OCA Director and Outreach and Diversity Officer where possible to share resources and expertise.

**Chile Research Experience for Undergrads program:** In 2020, ODI supported the Chile REU program, with three undergraduate participants, from areas of Chile typically underrepresented in the Chilean astronomy community, undertaking research mentored by ALMA scientists. ODI sponsored a short science visit to NRAO by a 2019 Chile REU alum to continue research with an NRAO mentor.

*Photo: Bettymaya Foott, NRAO/AUI/NSF*

## Spectrum Management

### VLA and VLBA Radio Frequency Interference Mitigation

The NM Operations Interference Protection Office coordinates spectrum usage for the VLA site by:

(1) Responding to requests for Special Temporary Authority submitted through the NSF from the National Telecommunications and Information Administration (NTIA). The requests are analyzed for their potential impact to radio astronomy observing by performing propagation simulations and mapping terrain profiles, calculating the expected power flux density at the array 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.

(2) Informing 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 Arecibo Observatory 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.

(3) Monitoring VLA site spectrum conditions using array observations and external monitoring equipment, and reviewing the resulting spectral plots and observer reports to detect new, unknown RF emissions. Detections in spectrum allocated to radio astronomy trigger source identification and technical discussions with the responsible spectrum user. Particularly detrimental emissions in non-radio astronomy spectrum allocations lead to goodwill discussions with the responsible spectrum user with the goal of interference reduction or elimination via technical means.

(4) Performing RF emissions tests on incoming commercial or NRAO-designed equipment and reviewing the results to determine interference potential. Equipment found to exceed the detrimental limits is either rejected, modified, shielded, or submitted for re-design.

### National Spectrum Management

Satellite Coordination: Satellite coordination with SpaceX was handled by NSF's Electromagnetic Spectrum Management Unit that earlier concluded a private 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 will have to be renegotiated concurrent with SpaceX's more recent updates to the planned operation of their constellation. A teleconference was hosted by NSF at which SpaceX claimed, using simulations, with no clear technical justification and without answering the technical questions posed by NRAO, that the unwanted emissions of their constellation into the protected radio astronomy band had improved by about a factor ten. The necessity for such a claim becomes clear when it is realized that the previous simulation barely met the required protection criteria with a constellation 3–10 times smaller than those that SpaceX has applied to operate.

OneWeb went bankrupt in March 2020, fired 95% of their staff and disappeared from the coordination effort that NRAO had provoked in FY2019 with a letter to the Federal Communications Commission (FCC). Despite being a U.K. company, OneWeb was brought out of bankruptcy in the U.S. courts and vowed to renew coordination with radio astronomy and to protect optical-infrared astronomy from optical reflection by its satellites. The proposed OneWeb orbit at 1200 km presents a much smaller problem for naked eye astronomy and a much more profound problem for research astronomy because of the prolonged visibility after twilight of satellites at 1200 km.

**Non-satellite Issues:** Notable FCC activity occurred when a Notice of Proposed Rulemaking was released in June 2020 regarding a petition to allow use of 71–76, 81–86, and 92–96 GHz to create an airborne mesh network to promote wireless broadband

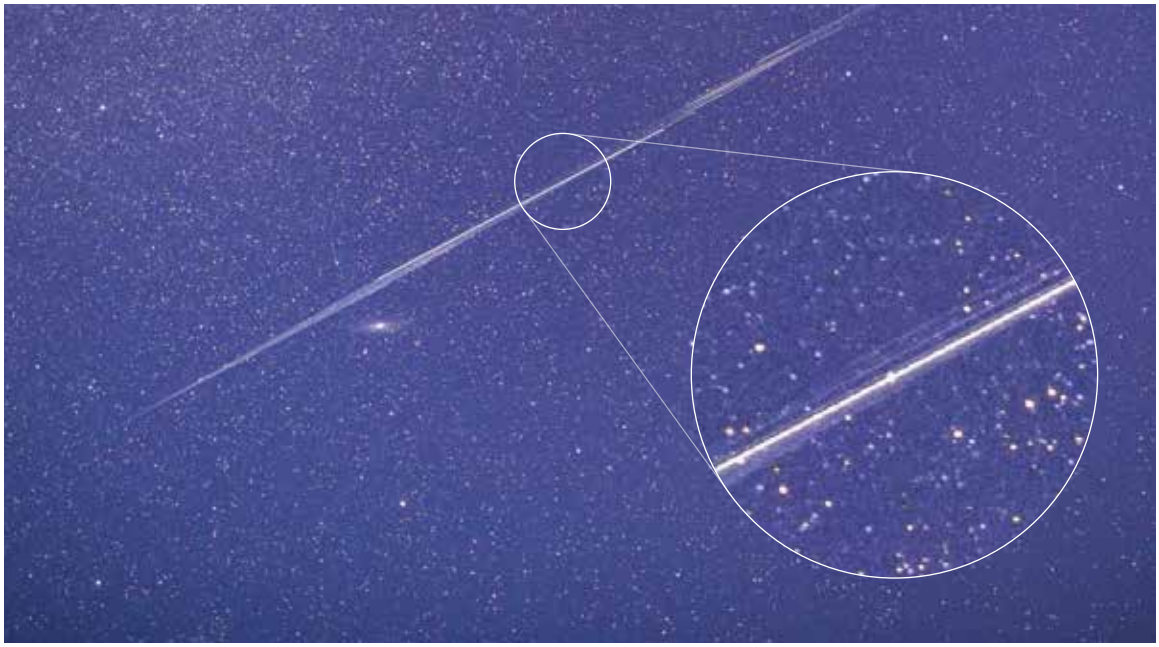


Photo: Bettymaya Foott

***Above:*** *Long-exposure photograph of Starlink satellites as viewed from Molas Lake outside of Silverton, Colorado.*

connectivity on aircraft. The proposed application would perform air-air and air-ground communication using ½-MegaWatt Effective Isotropic Radiated Power on planes, in bands that previously were used for only fixed microwave point-point links on the ground. This is a highly unfavorable scenario for radio astronomy: airborne transmissions visible from vast distances, readily apparent over telescopes, and in quiet zones previously insulated by geographic separation at those frequencies, in bands adjacent and threatening to the passive band allocation at 86–92 GHz that is a workhorse of millimeter-wave radio astronomy. Yet, the only prior consideration given to protection of radio astronomy was the statement by the prospective operator that all Federal radio astronomy installations would be protected by removing the ground stations from urban areas.

NRAO showed calculations demonstrating the long reach of potential interference from the proposed operations and filed reply comments when a third party suggested that interference was a minor matter that could be signed away by creating Memoranda of Understanding with the NSF to allow radio astronomy to notify the operator whenever it wished to observe in its own bands. The Committee on Radio Frequencies (CORF) also filed and one of its members felt the matter was serious enough to warrant a filing from the AAS, which commented, a rare occurrence.

**Spectrum Outreach:** The NRAO spectrum manager spoke at Haystack Radio Observatory in December 2019, at the winter American Astronomical Society meeting in Honolulu in January 2020, and to the Astronomy and Astrophysics Advisory Committee and the Astro2020 Decadal Survey Panel on radio astronomy in March 2020. Four lectures were delivered at the IUCAF Spectrum Management School (see below) in March 2020. That activity was followed by the usual presentation to the spring open meeting of CORF in May 2020.

## International Activities

The World Radio Communication (WRC) Conference-19 took place 28 October–22 November 2019 in Sharm El- Sheik, Egypt. The NRAO spectrum manager conveyed radio astronomy's views on the WRC-19 Agenda Items through the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF). The positive outcomes for radio astronomy at WRC-19 were largely those that IUCAF managed to have adopted at the Conference Preparatory Meeting where delegates crafted the default methods to satisfy the WRC 19 Agenda Items. High Altitude Platform Stations (HAPS) will have to coordinate with and protect

previously-registered radio astronomy operations, at 15 dB better levels than would otherwise have been the case. The harmonics of maritime mobile operations at 160 MHz were required not to interfere with radio astronomy operations at 327 MHz. This is the first instance where the International Telecommunications Union–Radio Sector (ITU-R) put hard limits at radio astronomy's preferred levels on the harmonic unwanted emissions of an active service operation. With a boost from Japan, the particularly troublesome Article 4.6 in the Radio Regulations was re-worded in the English version to coincide with the French and so remove troublesome semantics that allowed active services to argue that radio astronomy was not entitled to define its own interference thresholds. A satisfactory outcome was gained regarding the nominal protection of radio astronomy operations at 275–450 GHz from land mobile and fixed service operations.

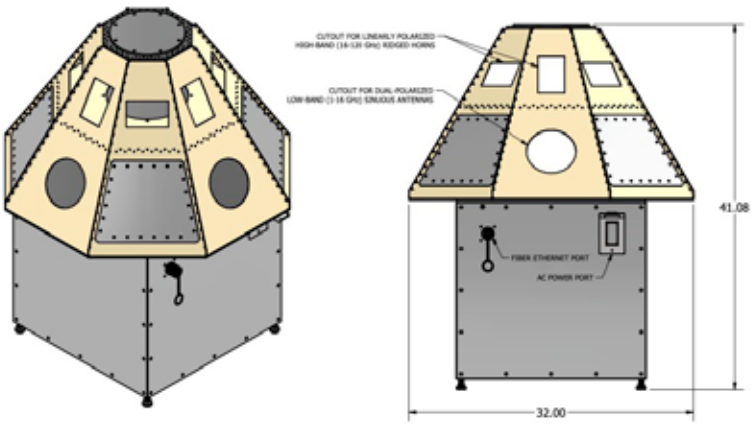
The trend in commercial use of radio spectrum is increasingly unfavorable to radio astronomy. Despite IUCAF opposition, European radio astronomers favored the granting of new privileges and primary allocation status to the notoriously interfering Iridium mobile satellite constellation, in return for unenforceable limits in a footnote to the Table of Frequency Allocations. Within one month after the WRC, Iridium, presented with German evidence that its interference had increased, announced its abandonment of the measures needed to protect radio astronomy and Germany formally protested once more to the FCC.

IUCAF, with strong CRAF and South African Radio Astronomy Observatory (SARAO) support, held its Fifth International Spectrum Management School in Stellenbosch, South Africa 2–6 March 2020 before COVID-19 closed in. This was the best-attended such school ever with 55 attendees. To encourage attendance, all fees associated with the meeting were waived and travel costs were heavily subsidized for students and older nascent spectrum managers.

ITU-R meetings were much abbreviated in spring 2020 and are being held online through February 2021.

As Chair of IUCAF, the NRAO spectrum manager arranges IUCAF's affairs, writing the annual report for URSI Radio Science Bulletin and procuring the annual operating budget from IAU, URSI, and COSPAR.

The NRAO spectrum manager participated in a workshop (5-9 October 2020) and meeting (early April 2021) on *Dark and Quiet Skies for Science and Society.* NRAO participated on the Scientific Organizing Committee and led the radio astronomy working group. This effort has produced a report covering all aspects of research astronomy and the enjoyment of the dark night sky, for presentation to the UN Office of Outer Space Affairs' (UNOOSA) Committee on Peaceful Uses of Outer Space (COPUOS) in February, April, and June 2021. This report makes recommendations to constrain light pollution, bio-hazards of over-lighting, optical reflection from non-geostationary satellites and interference to radio astronomy.  It will also make recommendations regarding radio frequency satellite operations that transcend the narrow concerns of radio spectrum regulators.




*Engineering drawing of the Advanced Spectrum Monitor (ASM) Prototype currently under development at the CDL.*

## 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.

In 2020, SciCom organized an effective Observatory presence at major science community meetings, such as the semi-annual American Astronomical Society (AAS) meetings.


*Photo: Brian Kent, NRAO/AUI/NSF*

The winter AAS meeting was held 4–8 January in Honolulu. Three NRAO event proposals were scheduled: (1) an NRAO Town Hall; (2) a Special Session titled Breakthrough Science with the Atacama Large Millimeter/submillimeter Array; and (3) a Special Session titled The Scientific Quest for High Angular Resolution. 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.

Originally scheduled to be held in Madison, Wisconsin with in-person attendance, the COVID pandemic led to the summer AAS meeting being transitioned to a wholly virtual meeting that took place 1–3 June. SciCom organized and led NRAO participation at the summer 2020 AAS including re-invention of the NRAO physical exhibit set in the virtual world; and representing the NRAO at the Observatory's virtual exhibit space at the three-day virtual Exhibition. Some long-standing AAS meeting events, such as EPO participation in hands-on demonstrations with large numbers of local students, were necessarily cancelled by the AAS.

A science symposium proposal was organized by the Director's Office and submitted by SciCom in April 2019 for the 2020 American Association for the Advancement of Science (AAAS) Annual Meeting (13–17 February, Seattle, Washington). The proposal was accepted and scheduled into the AAAS science program for 15 February, 10:00–11:30 am PST. Titled Detecting Extraterrestrial Technologies and Life, this symposium featured a diverse set of speakers who described 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 also examined how technosignature research and development is rapidly advancing and influencing the astronomy community's exoplanet research strategies and tactics.

SciCom wrote and designed the 2019 NRAO Annual Report in 2020. This report features calendar year 2019 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 will be published and distributed online and in hardcopy.

In 2020, 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 9,500+ subscribers in North America and around the world. SciCom also updated the NRAO Research Facilities brochure prior to the winter 2020 AAS meeeting.

# 2020 PERFORMANCE METRICS

## Observing Hours

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

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

### Observing hours for each NRAO telescope are divided into the following categories:

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

Scheduled = [ Astronomy + Downtime ]

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

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

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

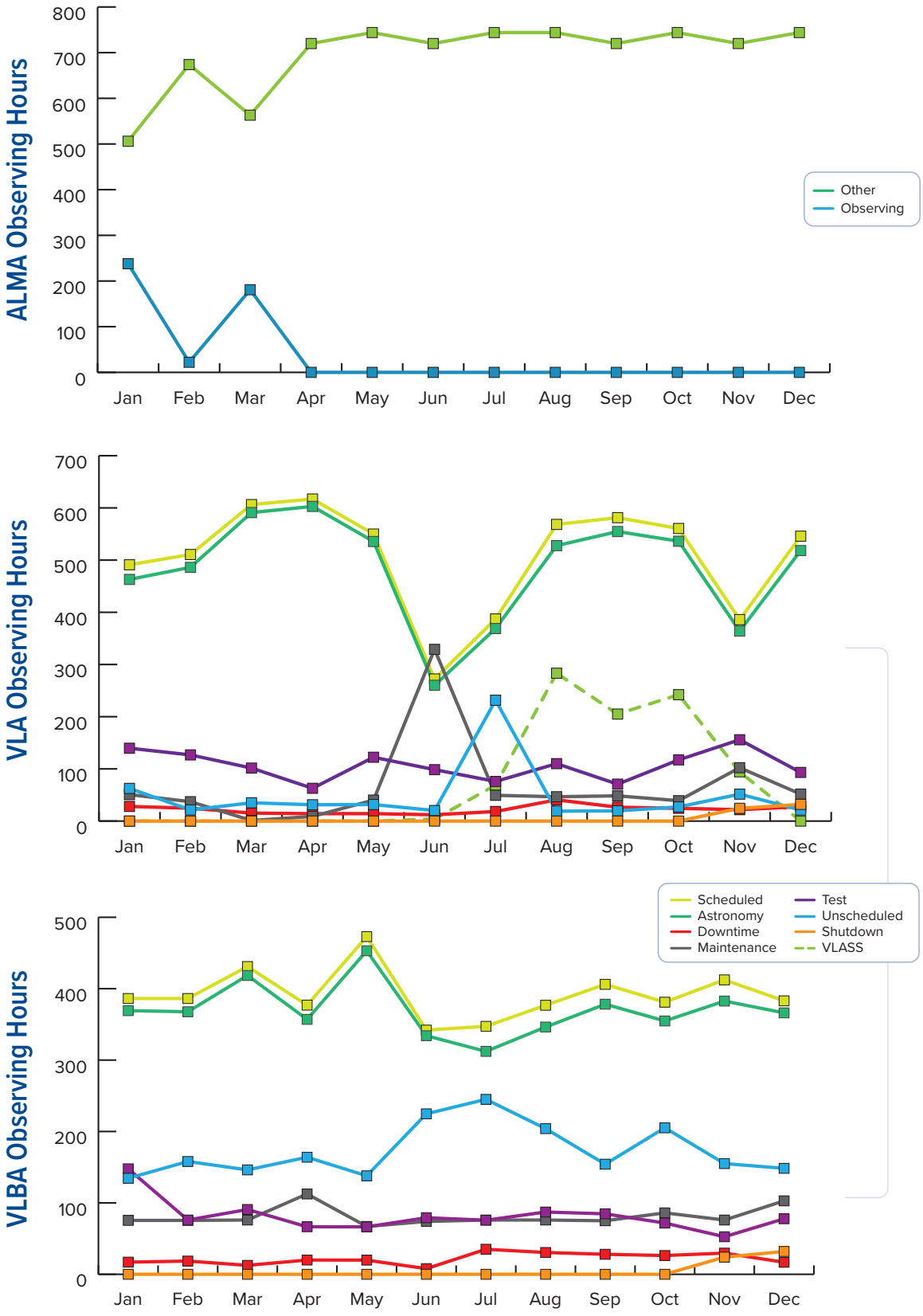
**Test:** Actual hours for test observations rather than peer-reviewed science proposals.

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

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



Photo by Jeff Hellerman, NRAO/AUI/NSF


ALMA Observing Hours
800
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
VLASS
VLBA Observing Hours
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
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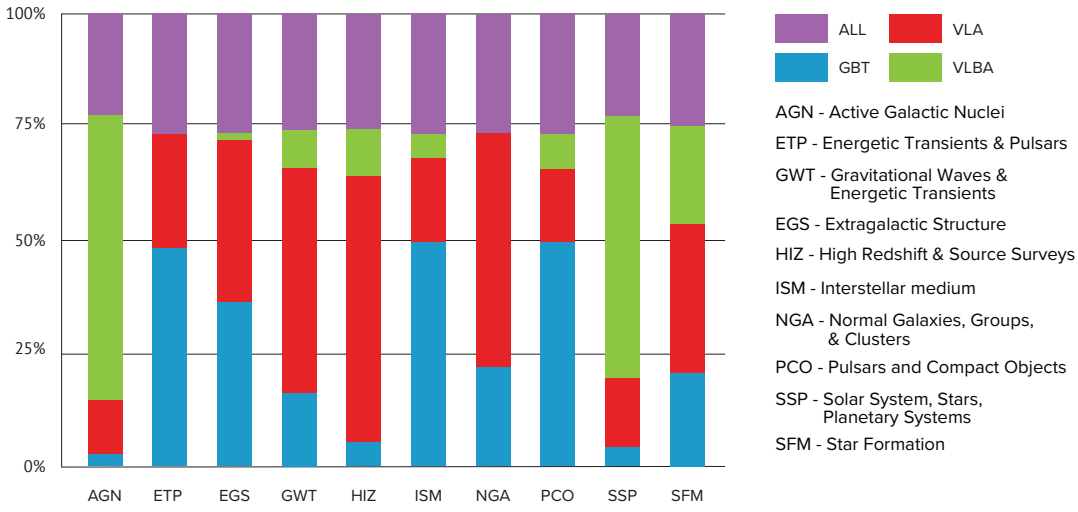
# 2020 PERFORMANCE METRICS

## Observing Hours by Science Category

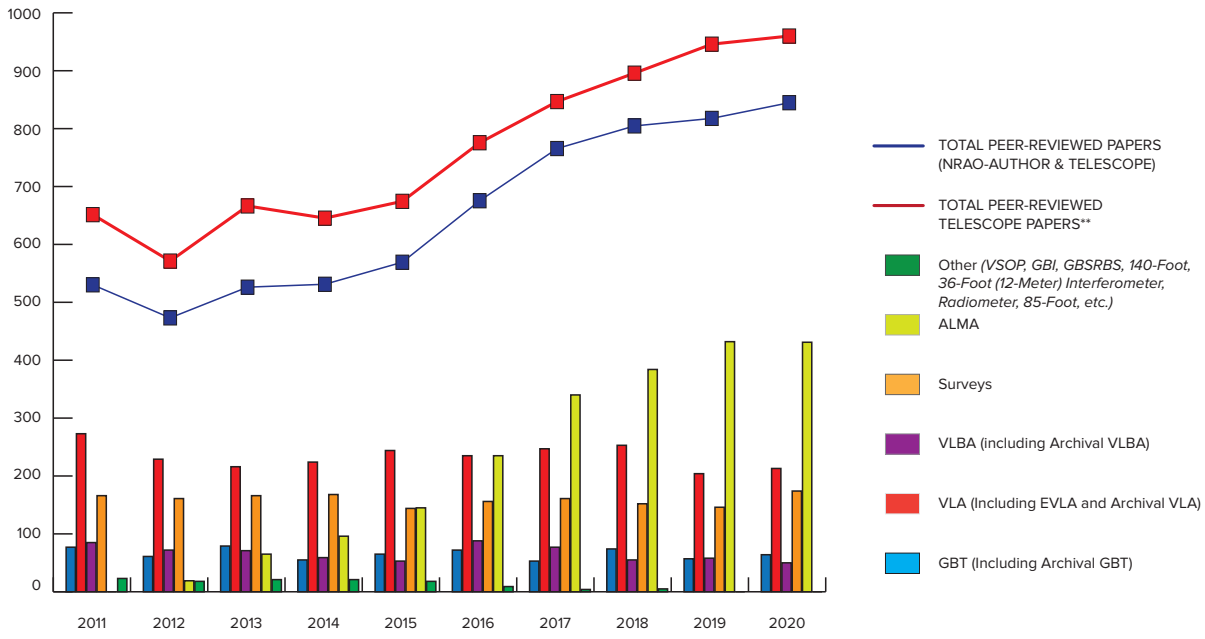



Observing hours for each of the GBT, VLA, and VLBA are tracked in the ten science categories defined in the NRAO-GBO proposal evaluation and time allocation process.



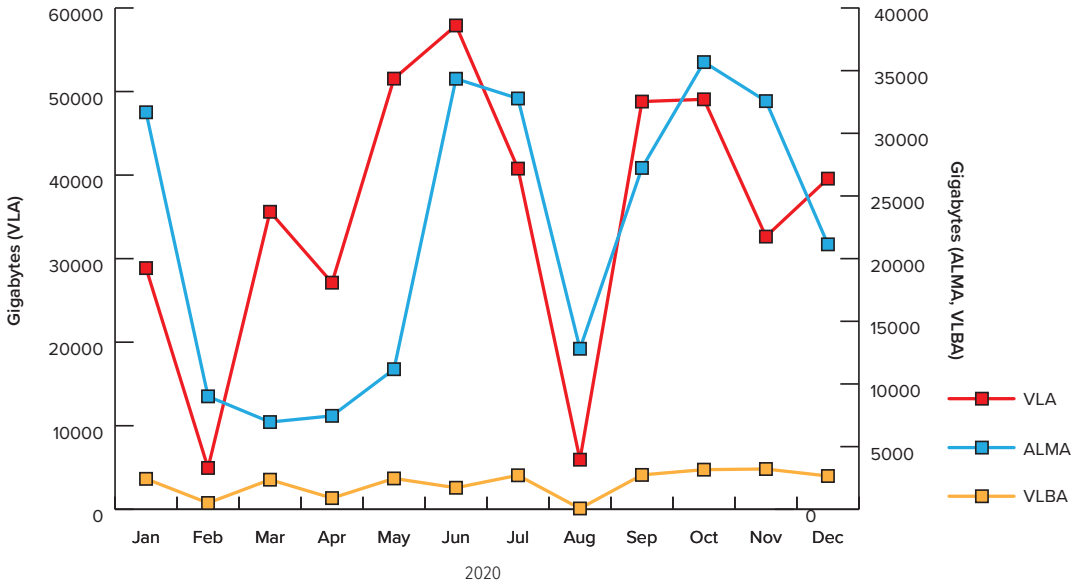
Photo by Jeff Hellerman, NRAO/AUI/NSF

## 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

## 2020 NRAO REFEREED PUBLICATIONS


Aalto, S.; Falstad, N.; Muller, S.; Wada, K.; Gallagher, J. S.; König, S.; Sakamoto, K.; Vlemmings, W.; Ceccobello, C.; Dasyra, K.; Combes, F.; García-Burillo, S.; Oya, Y.; Martín, S.; Van Der Werf, P.; Evans, A. S.; Kotilainen, J., "ALMA resolves the remarkable molecular jet and rotating wind in the extremely radio-quiet galaxy NGC 1377," Astronomy and Astrophysics, 640: A104, 2020.

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# APPENDIX A: PUBLICATIONS


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# APPENDIX A: PUBLICATIONS


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# APPENDIX A: PUBLICATIONS


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# APPENDIX A: PUBLICATIONS


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# APPENDIX B: EVENTS & MILESTONES

**2 January**
NRAO Semester 2020B Call for Proposals opens

**4-8 January**
*235th AAS meeting*
Honolulu, Hawaii
NRAO Town Hall
NRAO Exhibit
Special Session: Breakthrough Science with the Atacama Large Millimeter/submillimeter Array
Special Session: The Scientific Quest for High Angular Resolution
Summer Student Presentations
Student Reception / Orientation
Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

**28-30 January**
Space VLBI 2020: Science and Technology Futures
Charlottesville, Virginia

**3 February**
NRAO Semester 2020B Call for Proposals submission deadline

**11-13 February**
The ALMA2030 Vision: Design Considerations for the Next ALMA Correlator
Charlottesville, Virginia

**15 February**
American Association for the Advancement of Science Annual Meeting
Detecting Extraterrestrial Technologies & Life
Seattle, Washington

**21 February**
35th New Mexico Symposium
Socorro, New Mexico

**21 February**
Jansky Lecture: Dr. Anneila Sargent
Socorro, New Mexico

**21 February**
AUI Executive Committee Meeting (Hybrid)
6 March–3 April
ALMA Ambassadors Cycle 8 Proposal Preparation Workshops (Virtual)

**17 March**
ALMA Cycle 8 Call for Proposals opens

**20 March+**
ALMA Cycle 7 Science Operations & ALMA Cycle 8 Call for Proposals suspended due to COVID
Joint ALMA Observatory, Chile

**22 April**
ALMA Board Meeting (Virtual)

**1 May**
Cycle 8 Call for North American ALMA Development Study proposals deadline

**12 May**
AUI Executive Committee Meeting (Hybrid)

**25-28 May**
Canadian Astronomical Society (CASCA) Meeting 2020
York University: Toronto, Ontario, Canada

**26-28 May**
NRAO Users Committee/ANASAC Meeting (Virtual)

**1–3 June**
236th American Astronomical Society meeting (Virtual)
NRAO Town Hall
NRAO Exhibit

**18-19 June**
AUI Board Meeting (Virtual)

**25 June–10 September**
ngVLA Summer Short Talk Series (Virtual)

**29 June–17 July**
17th Synthesis Imaging Workshop (Virtual)

*Giannandrea Inchingolo of the University of Bologna, Italy, won first prize in an image contest sponsored by NRAO for a video combining VLA radio observations and computer simulations of the collisions of clusters of galaxies. The contest was part of the VLA 40th anniversary celebration.*

**6 July**
NRAO Semester 2021A Call for Proposals opens

**14-15 July**
Compact Objects and Energetic Phenomena in the Multi-messenger Universe (Virtual)

**15 July**
Call for Proposals for ALMA Development Projects opens

**3 August**
NRAO Semester 2021A Call for Proposals deadline

**27 August**
AUI Executive Committee Meeting (Virtual)

**18 September**
VLA 40th Anniversary Image Contest submission deadline

**2 October**
ALMA Town Hall (Virtual)

**14-16 October**
The ALMA 2030 Vision: Design Considerations for Digitizers, Backend and Data Transmission Systems (Virtual)

**15 October**
Call for Proposals for ALMA Development Projects submission deadline

**20-23 October**
CASA Users Committee Meeting (Virtual)

**23 October**
2020 ALMA Ambassadors Postdoctoral Program application deadline

**29-30 October**
AUI Board Meeting (Virtual)

**2 November**
2021 Jansky Fellowship Program application deadline

**13 November**
35th New Mexico Symposium (Virtual)
Socorro, New Mexico

**13 November**
Jansky Lecture: Prof. Martha Haynes (Virtual, eastern U.S.)

**17 November**
Jansky Lecture: Prof. Martha Haynes (Virtual, western U.S.)

**18-19 November**
ALMA Board Meeting (Virtual)

**7-11 December**
HL Tau at Five Years (Virtual)

**15 December**
NRAO Community Day (Virtual)

**16 December**
ngVLA Town Hall (Virtual)

**17 December**
AUI Executive Committee Meeting (Virtual)

**18 December**
AUI Visiting Committee Meeting (Virtual)

**31 December**
2020 Robert L. Brown Outstanding Doctoral Dissertation Award application deadline

# 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.

- **Edo Berger**, Harvard University, 2021
- **Casey Law**, California Institute of Technology, 2022
- **Rachel Osten** (ANASAC), Space Telescope Science Institute, 2020
- **Ilse Cleeves**, Vice-Chair, University of Virginia, 2021
- **Laurent Loinard**, UNAM, 2021
- **Kate Su** (ANASAC), University of Arizona, 2021
- **Alessandra Corsi**, Texas Tech University, 2024
- **Thomas Maccarone**, Texas Tech University, 2023
- **Stephen White** (ANASAC/ASAC), Kirtland AFB, 2020
- **Christopher DePree** (CASA UC), Agnes Scott College, 2021
- **Dan Marrone** (ANASAC/ASAC), University of Arizona, 2020
- **Christine Wilson** (ANASAC/ASAC), McMaster University, 2020
- **Jin Koda**, Chair (ANASAC), Stony Brook University, 2021
- **Susan Neff**, NASA/GSFC, 2022
- **Shih-Ping Lai** (ANASAC), National Tsing-Hua University, 2020
- **Giles Novak** (ANASAC), Northwestern University, 2020



Photo by Jeff Hellerman

## 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 listed.

- **Jin Koda**, Chair (ANASAC), Stony Brook University, 2021
- **Rachel Osten** (ANASAC), Space Telescope Science Institute, 2020
- **Shih-Ping Lai** (ANASAC), National Tsing-Hua University, 2020
- **Kate Su** (ANASAC), University of Arizona, 2021
- **Dan Marrone** (ANASAC/ASAC), University of Arizona, 2020
- **Stephen White** (ANASAC/ASAC), Kirtland AFB, 2020
- **Giles Novak** (ANASAC), Northwestern University, 2020
- **Christine Wilson** (ANASAC/ASAC), McMaster University, 2020

# 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 Committee membership 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**, Univ. Nacional Autónoma de México (2020)
**Greg Taylor**, University of New Mexico (2022)
**Belinda Wilkes**, Chandra X-ray Center (2021)

## NRAO Time Allocation Committee

The persons listed below served on the NRAO Time Allocation Committee (TAC) for Semesters 2020B and 2021A. The scientific purview of each TAC member is indicated.

**Semester 2020B**

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

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

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

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

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

**Alexander van der Horst**
Gravitational Waves and Energetic Transients (GWT)
George Washington University

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

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

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

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**Semester 2021A**

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

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

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

**Lynn Matthews**
Solar System, Stars, and Planetary Systems (SSP)
MIT Haystack Observatory

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

**Alexander van der Horst**
Gravitational Waves and Energetic Transients (GWT)
George Washington University

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

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

**Adam Avison** (EU, Deputy Chair), University of Manchester
**Chris DePree** (NA), Agnes Scott College
**D.J. Pisano** (NA), West Virginia University
**Michael Bietenholz** (NA, Chair), Hartebeesthoek Radio Astronomy Observatory, York University
**Hauyu Baobab Liu** (NA), Academia Sinica Institute of Astronomy and Astrophysics
**Shigehisa Takakuwa** (EA), Kagoshima University
**Alessandra Corsi** (NA), Texas Tech University
**A-Ran Lyo** (EA), Korea Astronomy and Space Science Institute
**Ilse van Bemmel** (EU), Joint Institute for VLBI ERIC

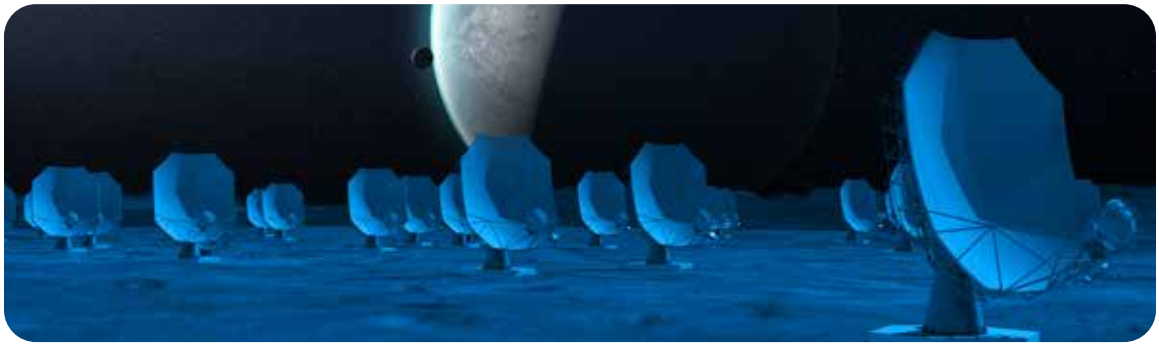
*NA: North America, EU: Europe, EA: East Asia*

Photo: Bettymaya Foott

# APPENDIX C: ADVISORY COMMITTEES

## ngVLA Science Advisory Council

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



## ngVLA Technical Advisory Council

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

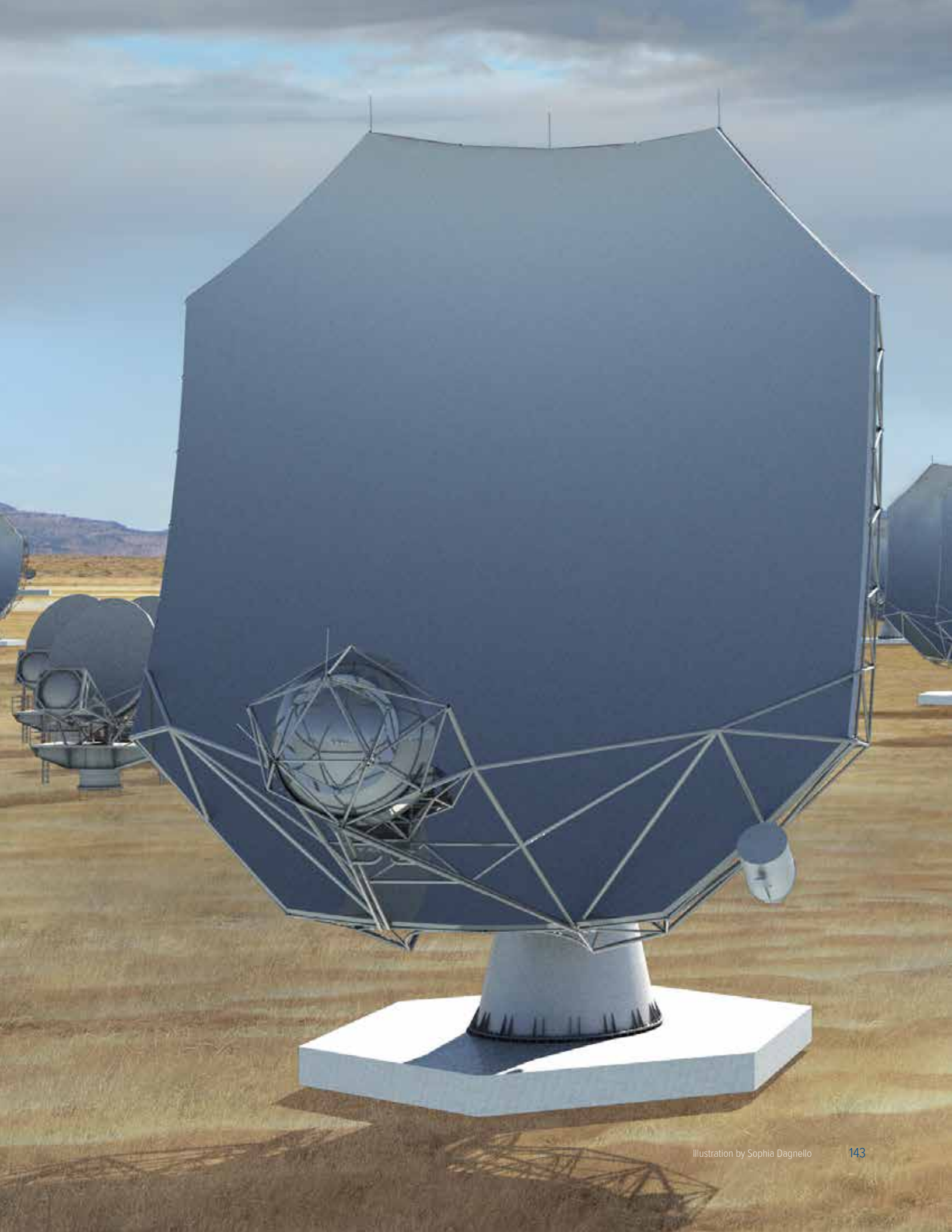


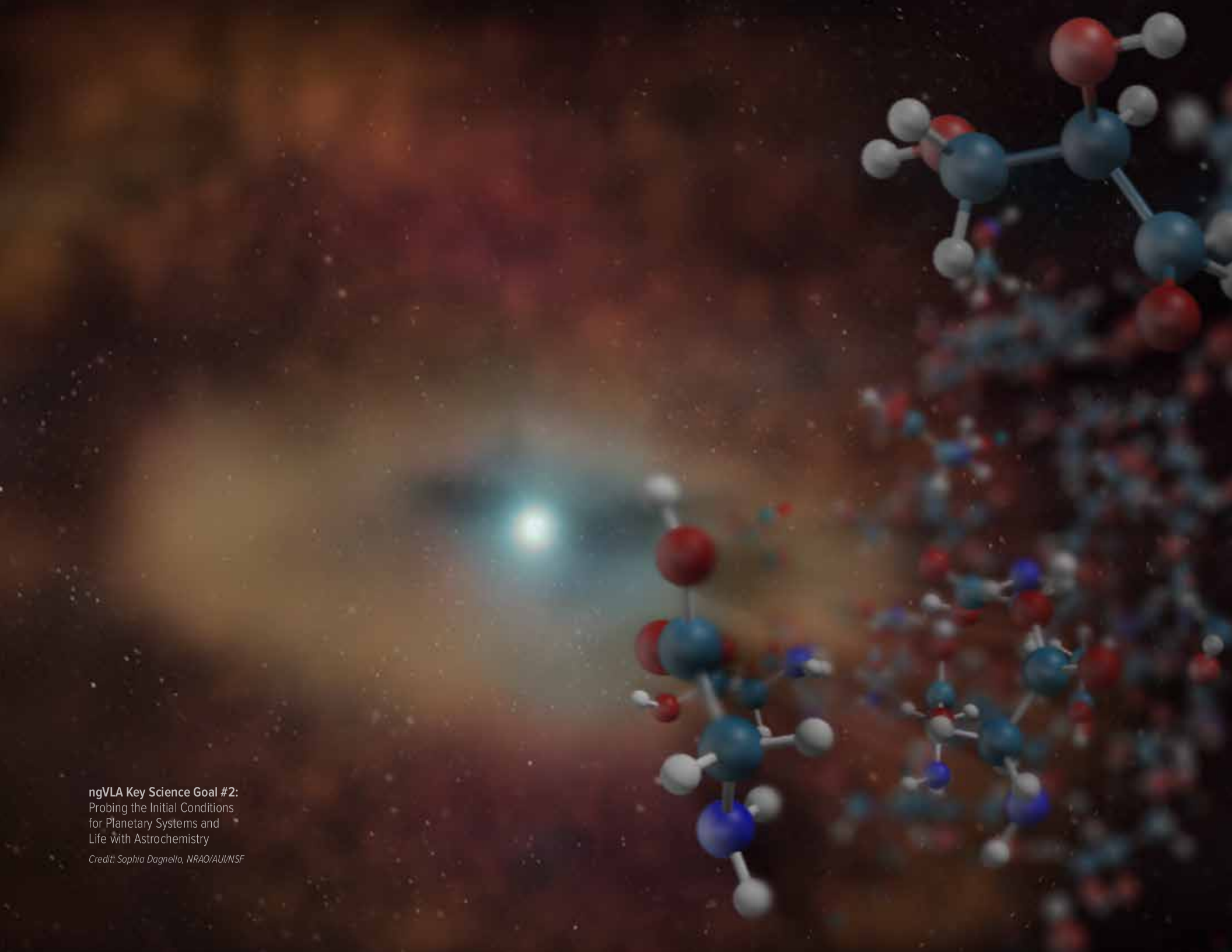
Illustration by Sophia Dagnello

# APPENDIX D: FISCAL YEAR 2020 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 | $3,359.7 | $2,380.8 | $2,978.2 | $8,068.0 | $497.5 | $2,518.7 | ($452.0) | $0.0 | $0.0 | $19,351.0 |
| Development Programs | $0.0 | $6,600.7 | $0.0 | $1,142.9 | $0.0 | $0.0 | $204.1 | $2,933.6 | $0.0 | $10,881.3 |
| Director's Office | $765.9 | $0.0 | $544.7 | $6,204.1 | $0.0 | $1.2 | $4,276.1 | $0.0 | $0.0 | $11,792.1 |
| Education & Public Outreach | $458.0 | $0.0 | $0.0 | $697.3 | $60.7 | $0.0 | $775.8 | $0.0 | $0.0 | $1,991.8 |
| Science Operations | $645.3 | $19.9 | $0.0 | $9,758.3 | $0.0 | $0.0 | $10,658.4 | $32.3 | $0.0 | $21,114.2 |
| Telescope Operations | $5,478.5 | $10,014.0 | $5,650.4 | $11,721.6 | $283.9 | $0.8 | $837.3 | $16.2 | $0.0 | $34,002.7 |
| External Grants | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $4,382.3 | $4,382.3 |
| **Grand Total** | **$10,707.4** | **$19,015.4** | **$9,173.4** | **$37,592.2** | **$842.1** | **$2,520.8** | **$16,299.8** | **$2,982.1** | **$4,382.3** | **$103,515.4** |

Fiscal Year 2020 = 1 October 2019 – 30 September 2020



**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 |
| AAB | Antenna Assembly Building |
| 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 |
| AoD | Astronomer on Duty |
| 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 |
| ASPECS | ALMA Spectroscopic Survey in the Hubble Ultra Deep Field |
| AST | NSF Division of Astronomical Sciences |
| AU | Astronomical Unit |
| AUI | Associated Universities, Incorporated |
| B&C | beamforming and channelizing |
| BI | Broader Impacts |
| BLC | Baseline Correlator |
| 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 |
| CBE | Correlator Back End |
| CDL | Central Development Laboratory |
| CDR | Critical Design Review |
| CHILES | Cosmos HI Large Extragalactic Survey |
| CHIME | Canadian Hydrogen Intensity Mapping Experiment |
| 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 |
| CORE | Council of Representative for Engagement |
| 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
DDT . . . . . Director's Discretionary Time
DMS. . . . . Data Management & Software
DOMT . . . . . Digital Orthomode Transducers
DSACore . . . . . Dynamic Scheduling Algorithm
DSN . . . . . Deep Space Network
DSOC. . . . . Domenici Science Operations Center
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
ERIC. . . . . European Research Infrastructure Consortium
ESO . . . . . European Organisation for Astronomical Research in the Southern Hemisphere
ETP . . . . . Energetic Transients and Pulsars
EVLA . . . . . Expanded Very Large Array
f2f . . . . . face-to-face
FBOT . . . . . Fast Blue Optical Transient
FCC . . . . . Federal Communications Commission
FE . . . . . Front End
FEHV . . . . . Front End Handling Vehicles
FIRST . . . . . Faint Images of the Radio Sky at Twenty Centimeters
FPGA . . . . . Field Programmable Gate Array
FRB . . . . . Fast Radio Bursts
FRM . . . . . Focus Rotation Mount
FSA . . . . . Frequency Site Architecture
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
GWT. . . . . Gravitational Waves & Energetic Transients
HBCU. . . . . Historically Black Colleges and Universities
HEMT. . . . . High Electron Moblity Transistor
HERA . . . . . Hydrogen Epoch of Reinonization Array

# APPENDIX E: ACRONYMS

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
ICRF . . . . . International Celestial Reference Frame
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
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

Photo by Jeff Hellerman, NRAO/AUI/NSF

# APPENDIX E: ACRONYMS

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 Canada-Herzberg Astronomy and Astrophysics
NRL . . . . . Naval Research Laboratory
NRQZ . . . . . National Radio Quiet Zone
NSF . . . . . National Science Foundation
NSBP . . . . . National Society of Black Physicists
NVSS . . . . . NRAO VLA Sky Survey
OCA . . . . . Office of Chilean Affairs
ODI . . . . . Office of Diversity and Inclusion
OMT . . . . . OrthoMode Transducer
OPT . . . . . Observation Preparation Tool
OSF . . . . . Operations Support Facility
OT . . . . . Observing Tool
pc . . . . . parsec
PCO . . . . . Pulsars and Compact Objects
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
SB . . . . . Scheduling Blocks
SciCom . . . . . Science Communications Office
SC . . . . . Saint Croix
SCG . . . . . Science Computing Group

SCO . . . . . Santiago Central Office
SCR . . . . . Silicon Controlled Rectifiers
SCREAM . . . . . Scalable Reconfigurable Modular
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
SRAO . . . . . Science Ready Archive and Operations
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
UAV . . . . . Unmanned Aerial Vehicle
UC . . . . . Users Committee
UNM . . . . . University of New Mexico
URSI. . . . . International Union of Radio Science; Union Radio Scientifique Internationale
UVA . . . . . University of Virginia
UVML. . . . . University of Virginia Microfabrication Laboratory
VA . . . . . Virginia
VANDAM. . . . . VLA/ALMA Nascent Disk and Multiplicity
VFD . . . . . Variable Frequency Drive
VLA . . . . . Very Large Array
VLASS . . . . . Very Large Array Sky Survey
VLBA . . . . . Very Long Baseline Array
VLBI . . . . . Very Long Baseline Interferometry
VLT. . . . . Very Large Telescope
VME . . . . . VLBA Versa Model Eurocard
VNDA . . . . . VLBA New Digital Architecture
WFO. . . . . Work for Others
WIDAR . . . . . Wideband Interferometric Digital Architecture
WISE . . . . . Widefield Infrared Survey Explorer
WRC. . . . . World Radio Conference
WVR. . . . . Water Vapor Radiometer
YUPPI. . . . . Y Ultimate Pulsar Processing Instrument
ZTF . . . . . Zwicky Transient Facility

science.nrao.edu
public.nrao.edu

**NRAO Headquarters and North American ALMA Science Center**

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

**NRAO - Central Development Laboratory**

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

**NRAO - Pete V. Domenici Science Operations Center**

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

**NRAO/AUI - Chile**

NRAO/AUI
Av. Alonso de Córdova 2860
Office 702
Vitacura, Santiago Chile, 7630440
+56-2-2210-9600

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