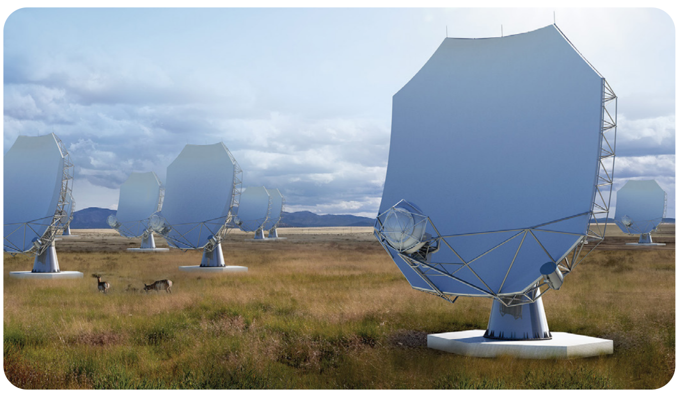
NATIONAL RADIO ASTRONOMY OBSERVATORY

RESEARCH. **EXPLORE.** DISCOVER.

2024

CONTENTS

RESEARCH FACILITIES 2024



(above)

The **next-generation VLA (ngVLA)** is an interferometric array that improves by more than an order of magnitude the sensitivity and spatial resolution of the Jansky VLA and ALMA at the same wavelengths. The ngVLA operates at frequencies of 1.2 GHz (21 cm) to 116 GHz (2.6 mm), building on the legacy of the Jansky VLA, ALMA and the VLBA as the next major national facility in ground-based radio astronomy. The ngVLA opens a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, while also delivering unprecedented broadband continuum imaging and polarimetry of non-thermal emission.

Credit: NRAO/AUI/NSF, Sophia Dagnello

(front cover)

Karl G. Jansky Very Large Array, New Mexico, USA

Credit: NRAO/AUI/NSF, Bettymaya Foott

(back cover)

Atacama Large Millimeter/submillimeter Array, Chile

Credit: Pablo Carrillo

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A diverse staff is critical to NRAO mission success: enabling world-class science, training the next generation of scientists and engineers, and fostering a scientifically literate society. NRAO is committed to a diverse and inclusive work place culture that accepts and appreciates all individuals.

go.nrao.edu/ODI

NRAO Overview

ALMA: Pablo Carrillo; VLA: Bettymaya Foott

The National Radio Astronomy Observatory (NRAO) delivers transformational scientific capabilities and operates world-class telescope facilities that enable the astronomy community to address its highest priority science objectives.

The NRAO telescope suite includes the Atacama Large Millimeter/submillimeter Array (ALMA), the Karl G. Jansky Very Large Array (VLA), and the Very Long Baseline Array (VLBA). Each is the world leader in its observing domain. Collectively, these telescopes enable scientists to observe from submillimeter to meter wavelengths with excellent resolution, sensitivity, and frequency coverage. Used individually or in combination, the NRAO telescopes provide the capabilities required to enable science for the 2020s and beyond, such as placing constraints on the nature of dark energy, imaging the first galaxies, and directly observing planet formation in proto-planetary disks.

ALMA continues to open new windows into the cold Universe via a major increase in sensitivity and resolution at millimeter and submillimeter wavelengths and is providing, for the first time, detailed images of stars and planets in formation, young galaxies being assembled throughout cosmic history, and much more. The highest priority for development of ALMA will be the Wideband Sensitivity Upgrade (WSU), a partnership-wide initiative that will increase the system bandwidth by at least a factor of two, with a goal of a factor of four.

At the adjacent centimeter-wavelength range, the Jansky VLA has scientific capabilities that are comparable to ALMA and exceed the original VLA capabilities by one to four orders of magnitude. These Jansky VLA capabilities were delivered on schedule and on budget, and are meeting all of the project's technical specifications and scientific objectives. The Jansky VLA is the world's most capable and versatile centimeter-wave imaging array. The on-going Very Large Array Sky Survey (VLASS) is the highest resolution all-sky radio wavelength survey ever undertaken.

The VLBA is the premier dedicated Very Long Baseline Interferometry (VLBI) array in the world. Astrometry with the VLBA has reached a precision of a few micro-arcseconds, enabling distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and into the Hubble flow. When the VLBA is used in conjunction with the phased VLA and the Green Bank Telescope (GBT), the resultant High Sensitivity Array greatly enhances VLBI sensitivity and significantly broadens the discovery space that can be addressed.

To maximize the usage and science impact of the NRAO facilities, NRAO aims to broaden their access to all astronomers, through uniform and enhanced user support services, student programs, science ready data products (SRDP), and development opportunities. These services are coordinated Observatory-wide by the Science Support and Research Department and are provided by the North American ALMA Science Center in Charlottesville, Virginia and the Pete V. Domenici Science Operations Center for the VLA, and VLBA in Socorro, New Mexico.

The NRAO is also developing forefront technology to continuously improve our facilities and to realize next generation facilities. Taking advantage of the outstanding technical expertise across NRAO, the Central Development Lab oversees a science-driven research and development program that will help realize key science goals, such as the detection of gravitational waves via pulsar timing and the study of the epoch of reionization. The community and the NRAO have initiated the design of a future large area radio telescope, a next generation VLA (ngVLA). This ngVLA will be optimized for imaging thermal emission to milli-arcsecond scales, will address a range of ambitious, high priority science goals, and will open new discovery space from protoplanetary disks to distant galaxies.

After leading pioneering science, research and engineering for over six decades, the NRAO continues to lead in radio astronomy, an invaluable resource for the astronomy community in the United States and around the world.

science.nrao.edu

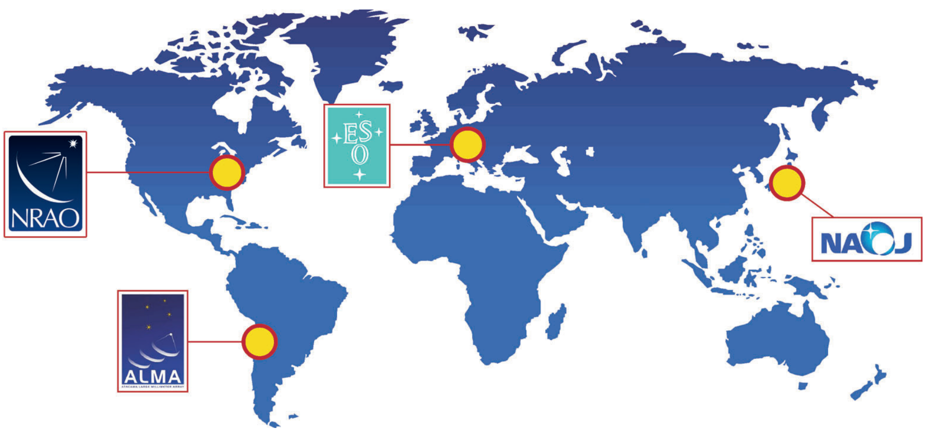
Atacama Large Millimeter/ submillimeter Array (ALMA)

Altiplano de Chajnantor, Chile

The Atacama Large Millimeter/submillimeter Array (ALMA) enables transformational research into the physics of the cold Universe, regions where the sky is dark in the visible part of the spectrum but shines brightly at millimeter wavelengths.

ALMA can probe the origin of the first heavy elements and image interstellar gas in the process of forming new planets, thus providing a window on cosmic origins. The telescope is situated on the Chajnantor plain of the Chilean Andes at an altitude 5000 m above sea level, where the Earth's atmosphere is largely transparent at millimeter wavelengths. ALMA provides unprecedented sensitivity and imaging fidelity in the (sub) millimeter observing window. ALMA has 66 high-precision antennas and is capable of imaging the sky at resolutions as fine as 0.005 arcsec, a factor of ten better than the Hubble Space Telescope. ALMA is the most sensitive and capable millimeter interferometer in the world.

The Call for Proposals for Cycle 11 is expected to be available in Spring 2024 for observations beginning in October 2024. See the documentation available on the ALMA Science Portal (**almascience.nrao.edu**).



The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Republic of Chile. ALMA is funded by ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. ALMA construction and operations are led by ESO on behalf of its Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA..

The North American ALMA Science Center (NAASC)

The North American ALMA Science Center, based at the NRAO headquarters in Charlottesville, Virginia, supports the use of ALMA by the North American scientific community, and conducts research and development for future ALMA upgrades. Users can visit the NAASC in Charlottesville to process and analyze their ALMA data with assistance from the scientific and technical staff, and remote support is available as well. The NAASC provides a number of additional key services, including calibrating, imaging, and distributing ALMA data, supporting and hosting conferences, training sessions, and workshops, financial support to early-career researchers, and assisting users during the preparation and submission of ALMA proposals and observations. The NAASC also prepares and maintains ALMA user documentation and web sites, and runs the ALMA Helpdesk. The NAASC is operated by NRAO in Charlottesville Virginia, in collaboration with Canada's NRC Herzberg, and the National Science Council of Taiwan. Users may request assistance from the NAASC through the ALMA Helpdesk at **help.almascience.org**.

science.nrao.edu/facilities/alma

KEY SCIENCE

Origins of Galaxies

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

Origins of Chemical Complexity

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

Origins of Planets

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

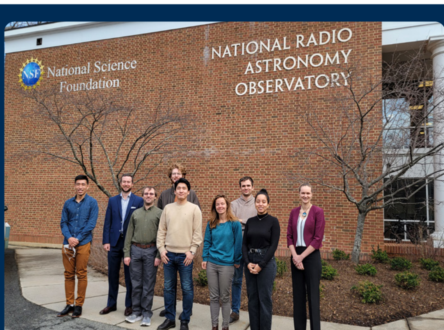
ALMA is a general-purpose research instrument. In addition to accomplishing the specific design goals, ALMA can image spectral line and dust continuum emission from galaxies out to z = 10, showing how galaxies assemble during their earliest stage of formation. ALMA supports blind surveys of molecular gas nearby and at high redshift, thus revealing the star-formation history of the Universe. ALMA can image molecular gas in the nuclei of nearby active galaxies with spatial resolutions of 10-100 pc, revealing the structure of the dusty torus in active galactic nuclei. ALMA also enables detailed studies of the full life cycle of stars and can detect heavy, prebiotic molecules in newly forming solar systems. ALMA can probe the gas dynamics in young stellar systems as the disk, jet, and central star themselves form. And in the spectacular supernova explosions that mark the end of the stellar life cycle, ALMA can image heavy elements and chemicals as they re-seed the interstellar medium with new material that will form the next generation of stars.

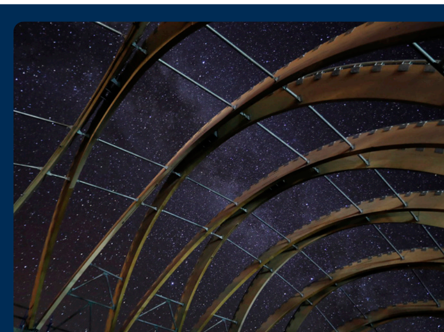
RECEIVER BANDS

Band #	1	3	4	5	6	7	8	9	10
Frequency Range (GHz)	35 - 50	84 - 116	125 - 163	158 - 211	211 - 275	275 - 373	385 - 500	602 - 720	787 - 950
Wavelength Range (mm)	8.5 - 6	3.6 - 2.6	2.4 - 1.8	1.9 - 1.4	1.4 - 1.1	1.1 - 0.8	0.78 - 0.60	0.50 - 0.42	0.38 - 0.32

	Cycle 10
Antennas	>43 x 12 m; 10 x 7 m; 3 x 12 m TP
Bands	Bands* 1, 3, 4, 5, 6, 7, 8, 9, 10
Continuum Bandwidth	7.5 GHz x 2 pol
Finest spectral resolution at 100 GHz	0.01 km/s
Angular Resolution	~0.2" × (300/ ν GHz) x (1 km / maximum baseline)
Maximum Baseline	Cycle 10 : 8.5 km (16.2 km in alternate cycles)
Continuum Sensitivity (60 sec, Bands 1 & 3 - 10)	~0.058 – 3.3 mJy/beam (43 antennas)
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 1 & 3 - 10)	~ 12 – 292 mJy/beam

** Band 2 will become operational in future Cycles. Refer to the ALMA Primer and Sensitivity Calculator for further information.*





***Left:** The ALMA Ambassadors meet for training at the NAASC Headquarters in Charlottesville, VA, February 2023. Their innovative workshops will help ALMA users with the entire gamut of the scientific process - from proposal writing to data reduction. **Center:** An ALMA Transporter moves an antenna into position (Image: Pablo Carrillo). **Right:** ALMA North America has recently completed a covered multi-court indoor sports facility, the Multicancha, providing activity space for employees at the site.*

almaobservatory.org

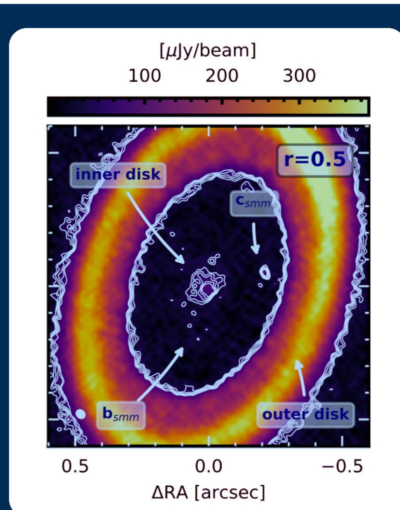
ALMA SCIENCE SUSTAINABILITY

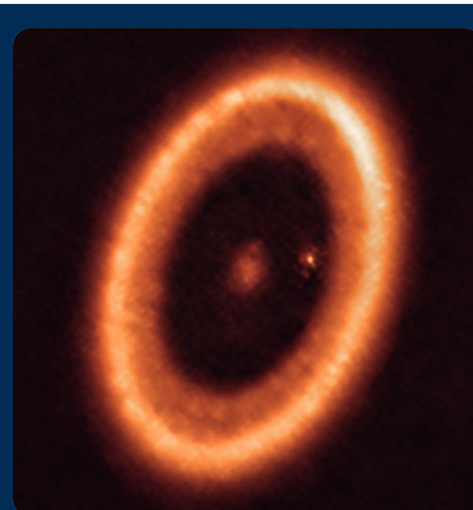
ALMA began transforming astronomical paradigms when science operations began in 2011. Sustaining the pace of that transformation requires upgrading ALMA to maintain and expand its capabilities. The ALMA Operations Plan envisaged an ongoing program of development and upgrade. That science sustainability program, shared by the international ALMA partners, has resulted in new capabilities and was ramped up to full funding in 2015. With a modest investment of less than 1% of the ALMA capital cost per year, divided among the three funding entities, ALMA will lead astronomical research into the 2020 decade and beyond. With over 10,000 users and oversubscription greater than 6 to 1, future development must increase science throughput to accommodate scientific demand. The ALMA Development Roadmap (ALMA Memo 612; https://go.nrao.edu/ALMA_Roadmap), based on inputs from the ALMA Science Advisory Committee (ASAC) and the community, outlines a roadmap for future developments that will significantly expand ALMA's capabilities. The highest priority for ALMA's development is a transformative increase of its instantaneous processed bandwidth, by a factor of 2 at least (and a goal of a factor 4). The ALMA Wideband Sensitivity Upgrade (WSU) is a partnership-wide initiative that will realize this development across the entire ALMA's wavelength range through a series of major hardware upgrades of the telescope's components.

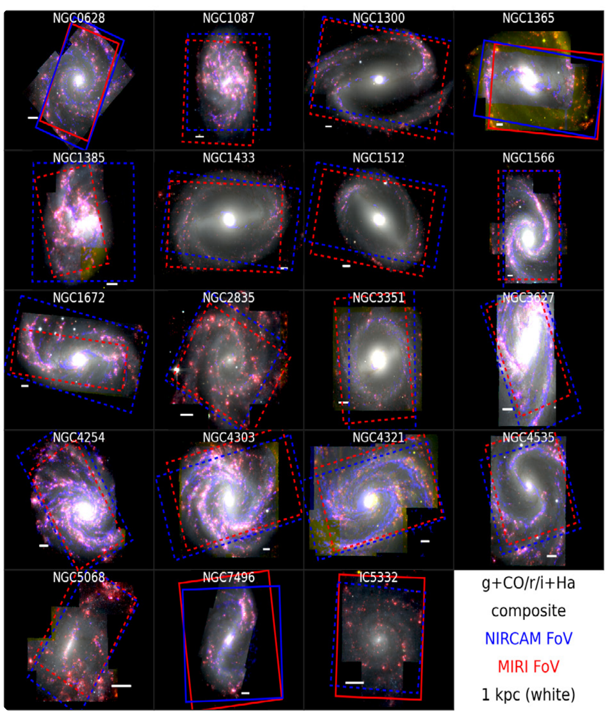
A Moon-forming Disk

ALMA has imaged a circumplanetary (Moon-forming) disk at high angular resolution (~20 milli-arcsecond, 2.3 AU) via its dust emission at 855μm. A compact source of emission is co-located with PDS 70c, spatially separated from the circumstellar disk and less extended than ~1.2 AU in radius.

Figure: The PDS 70 system at a resolution of 0.036 arcsec x 0.030 arcsec. Contours are 3 to 7σ, spaced by 1σ. (Benisty at al. arXiv:2108.07123)
Image credit: ALMA / ESO / NAOJ / NRAO / Benisty et al.







Star Formation, Feedback, and Dust Physics in Nearby Galaxies

PHANGS-JWST is a 112.6 hour program to image 19 nearby galaxies (D < 20 Mpc) in eight filters from 2 microns to 21 microns using NIRCam (F200W, F300M, F335M, F360M) and MIRI (F770W, F1000W, F1130W, and F2100W).

The PHANGS-JWST nearby spiral galaxy sample features overlapping coverage from ALMA, HST, and VLT-MUSE and other facilities presenting our NIRCam and MIRI observing strategy.

Left: Composite gri+H+CO images for the 19 galaxies in the PHANGS-JWST Treasury program. The gri+H images are constructed from VLT MUSE full-eld spectral mapping (Emsellem et al. 2022), with H line emission in red, and combined with ALMA CO(2-1) (Leroy et al. 2021) maps, with CO(2-1) flux in blue. JWST NIRCam and MIRI footprints are shown to overlap existing MUSE, ALMA, and HST data. Footprints shown with dashed lines represent observations that have not been executed at time of writing (October 2022), and may rotate slightly due to the range of allowed orient angles specified for the target. The JWST sample spans a factor of ~50 in stellar mass and SFR, and a factor of ~100 in CO surface density. It includes galaxies with prominent dust lanes, a full range of stellar bar, bulge, spiral arm morphologies, as well as nuclear starbursts and AGN activity.

almascience.nrao.edu

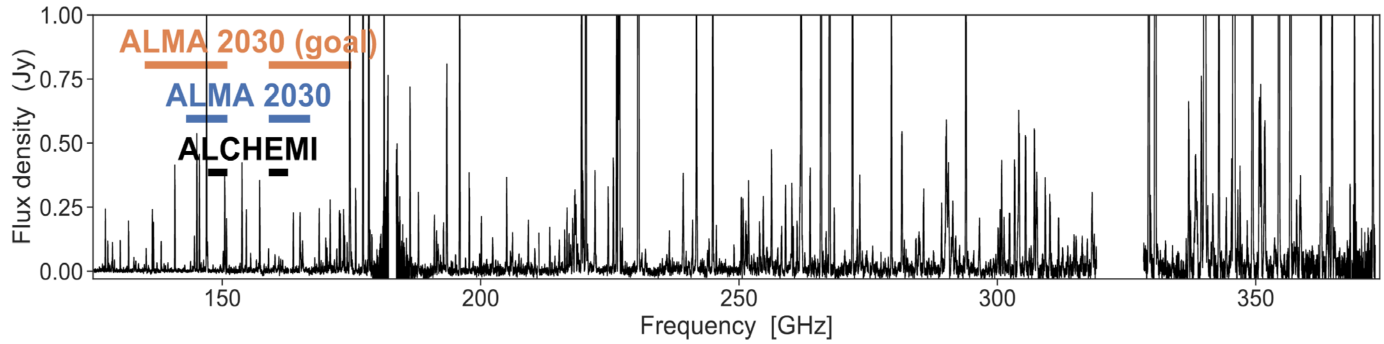
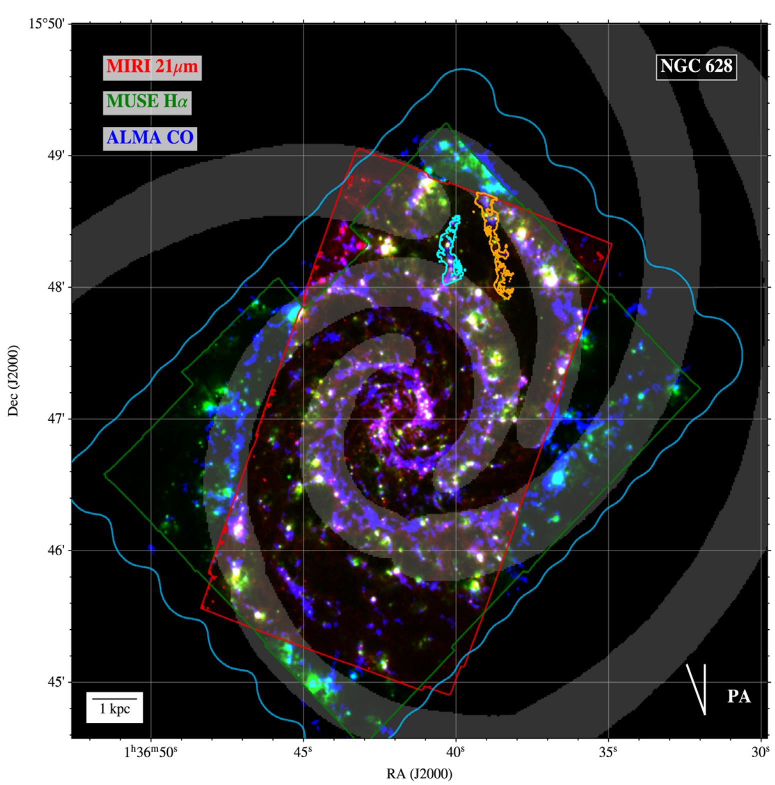


Illustration of the improvement that the Wideband Sensitivity Upgrade (WSU) will provide for spectral scan observations. The plot shows the spectral scans across multiple bands obtained for NGC 253 (Martín et al. 2021). The instantaneous spectral coverage of the actual observation is shown in black, while that of the ALMA2030 upgrade is shown in blue for the minimum requirements and in orange for the goal. The ALMA2030 upgrade will improve the instantaneous coverage by a factor of 2-4 for coarse spectral resolution scans such as NGC 253. Figure from Carpenter et al. 2022, ALMA Memo 621: ***https://arxiv.org/pdf/2211.00195.pdf***



Spurring on Star Formation - Localized Star Formation in a Spiral Arm Spur of NGC 628

Three-color image of NGC 628, with ALMA CO in blue, MUSE H-alpha in green, and JWST 21 micron in red. The blue, red, and green boxes show the extent of each corresponding observation. The two focus spurs are shown as cyan (CO-rich), and orange (CO-poor) contours. (Williams et al., arXiv:2212.00032)

ALMA/NAASC INITIATIVES

- The **ALMA Ambassadors** program trains early-career scientists (including graduate students, postdocs, and junior faculty/staff) in ALMA technical capabilities and data processing techniques. Ambassadors then return to their home institutes and run workshops to train the community in preparing and submitting ALMA proposals and in reducing data obtained from PI'ed or archival ALMA programs.

- As part of WSU, an upgrade to ALMA's workhorse Band 6 (1.3mm), Band 6 v2 is under way to realize all three ALMA2030 science goals. This 1.3mm upgrade will provide greater tuning flexibility and improved noise performance across a bandwidth of at least 4-16 GHz (with correlator upgrade).

- In 2023, ALMA's Board approved the construction of the 2nd generation correlator: the Advanced Technology ALMA Correlator (ATAC), laying the foundation for the rest of the Wideband Sensitivity Upgrade.

science.nrao.edu/ facilities/alma/alma-develop

Very Long Baseline Array (VLBA)

St. Croix, VI • Hancock, NH • North Liberty, IA
Fort Davis, TX • Los Alamos, NM •
Pie Town, NM • Kitt Peak, AZ • Brewster, WA
Owens Valley, CA • Mauna Kea, HI

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

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

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

The VLBA recently celebrated 30 years of science, transforming high-resolution interferometry and science for the astronomical community.

KEY SCIENCE

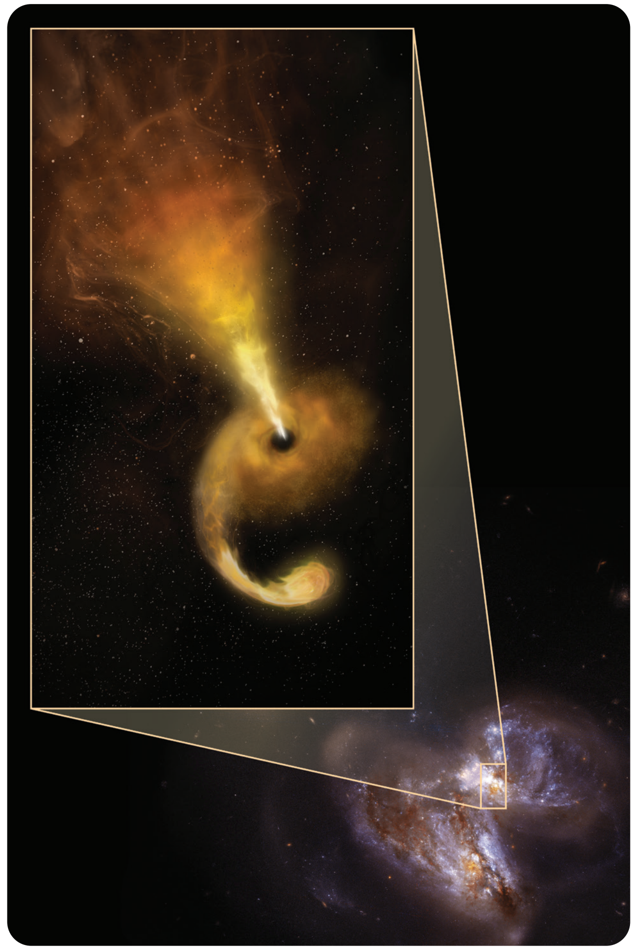
Accurate measurement of distances to objects throughout the Milky Way Galaxy has become a VLBA scientific centerpiece. With the VLBA, the classical astronomical parallax technique, originally limited to a small number of nearby stars, can be extended to measure distances across most of the Galactic disk, seeing through intervening dust.

Distance measurements to ~400 high-mass star-forming regions will substantially improve our understanding of the three-dimensional structure of the Milky Way. This program is also measuring the fundamental parameters of Galactic rotation, helping to quantify the distribution of luminous and dark matter in our Galaxy.

Similar measurements recently determined the distance from the Sun to young stars of the Pleiades cluster, to an unprecedented accuracy of 1%. These results resolved a 17-year controversy over the actual distance, which is a crucial parameter in interpretation of stellar physics and evolution.

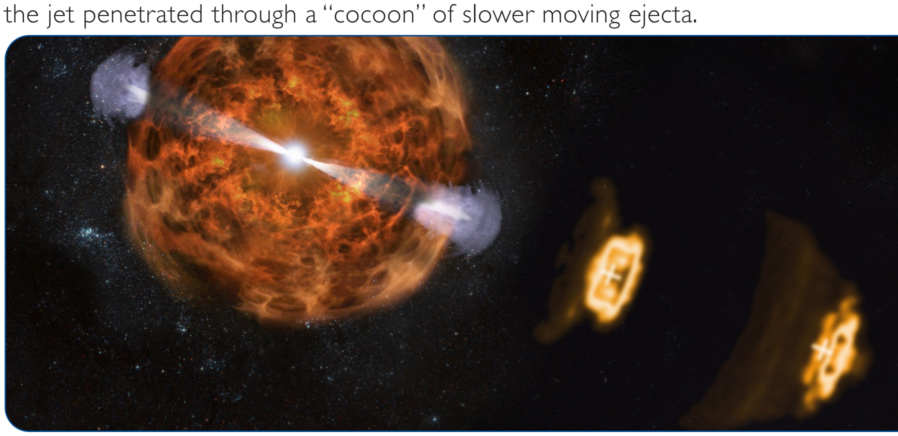
The VLBA is able to discover exoplanets using a technique that requires extremely precise measurements of a star's position in the sky. This involves detection of a miniscule "wobble" in a star's motion in space caused by the gravitational effect of a planet. Using this technique, a Saturn-sized planet was discovered recently, orbiting a small, cool star 35 light years from Earth.

The VLBA can be used to image the consequences of a star traveling too close to a supermassive black hole. The result, a "tidal disruption event", is caused when the star is pulled apart and approximately half of the star's matter is funneled into an accretion disk surrounding the black hole. This fuels a relativistic jet which can be imaged over time with the VLBA.



Artist's concept (upper left) of a Tidal Disruption Event in the colliding galaxies Arp 299 (HST image, lower right). The powerful gravity of a supermassive black hole shreds a passing star, pulling material into the disk rotating around the black hole, and launching a jet of particles. Credit: Sophia Dagnello, NRAO/AUI/NSF; NASA, STScI

The VLBA played a significant role in understanding the physics behind the neutron star merger event detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) on August 17, 2017. A relativistic jet was launched from the merger site. HSA astrometry and imaging over eight months allowed astronomers to deduce that the jet penetrated through a "cocoon" of slower moving ejecta.



As the jet from the neutron-star merger event emerged into space, simulated radio images in this artist's conception illustrate its extremely fast motion. In the 155 days between two observations, the jet appeared to move two light-years, a distance that would require it to travel four times faster than light. This "superluminal motion" is an illusion created as the jet is pointed nearly toward the Earth and it is actually moving more than 97 percent of light speed. (Not to Scale.) Credit: D.Berry,O.Gottlieb,K.Mooley,G.Hallinan,NRAO/AUI/NSF

science.nrao.edu/facilities/vlba

Karl G. Jansky Very Large Array (VLA)

Socorro, New Mexico

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

- Operation at any frequency between 1 and 50 GHz, in addition to 58 to 84 MHz and 220 to 500 MHz.
- Unprecedented continuum sensitivity with up to 8 GHz of instantaneous bandwidth per polarization, 64 independently tunable sub-band pairs, each providing full polarization capabilities.
- Up to 65,536 spectral channels, adjustable frequency resolution from 2 MHz to sub-kHz, and extensive capabilities to allocate correlator resources with a planned increase to up to 4,194,304 spectral channels.
- VLA phased array mode for pulsar observations or Very Long Baseline Interferometry with the Very Long Baseline Array (VLBA), the Long Wavelength Array stations in New Mexico, or as an element in the High Sensitivity Array (HSA).
- Dynamic scheduling based on weather, array configuration, and science requirements. Calibrated visibilities and reference images of calibrators for quality assurance automatically produced, with all data products archived.
- Calibration of all data acquired on the telescope through a dedicated pipeline currently optimized for Stokes I continuum science, with planned expansions to include polarization and spectral line science projects, as well as imaging.

KEY SCIENCE

The Magnetic Universe

The sensitivity, frequency agility, and spectral capability of the modernized VLA allows astronomers to trace the magnetic fields in X-ray emitting galaxy clusters, image the polarized emission in thousands of spiral galaxies, and map the 3D structure of magnetic fields on the Sun. The instantaneous wide-bandwidth capabilities provided by the WIDAR correlator and new digital electronics enable tomographic scanning of magnetized regions of the Universe using the Faraday Rotation effect.

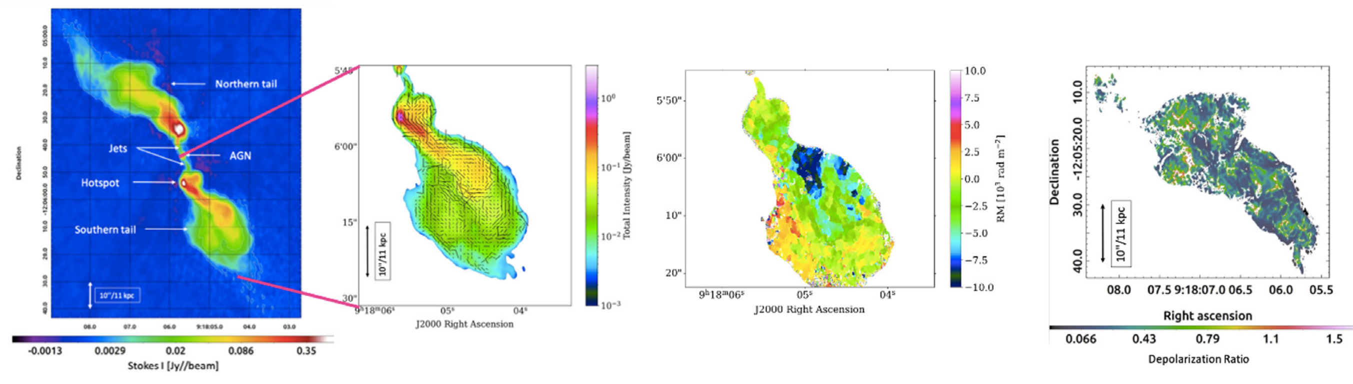
The Obscured Universe

Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The VLA observes through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young stellar objects, and image the densest regions in nearby starburst galaxies. The Jansky VLA is the ideal instrument to carry out many aspects of ALMA science in the highly obscured Universe.

The Transient Universe

Astronomical transient sources tend to be compact objects that emit synchrotron radiation from high-energy particles, radiation best observed at radio wavelengths. The VLA is ideal for studies of variable sources because of its high sensitivity, ability to observe day and night under most weather conditions, and the rapid response enabled by dynamic scheduling. The VLA is able to image novae and relativistic jets anywhere in the Milky Way, and measure the sizes of many tens of gamma-ray bursts each year. Newly deployed capabilities for fast mosaicking enable a new generation of wide-area synoptic surveys of the radio sky, allowing the capture of the emergence and long-duration evolution of explosive and energetic events anywhere in the visible sky. The Jansky VLA is poised to be a powerful radio counterpart to surveys at other wavebands (such as Pan-STARRS and Rubin-LSST), as well as providing an electromagnetic perspective on events discovered using other messengers (such as gravity waves from Advanced LIGO).

science.nrao.edu/facilities/vla



Above: VLA polarimetric imaging of Hydra A, from left to right: total intensity at 2 GHz, 1" resolution; magnetic field vectors; rotation measures; depolarization at 6 GHz from 3" to 0.5" resolution (Baidoo et al. 2023, ApJ, 955, 16).

Multifrequency VLA observations of the prototype FRI radio galaxy, Hydra A, reveal extreme Faraday rotation measures (RMs), with magnitudes as large as -12300 rad m^{-2}, the majority of which arises in the magnetized thermal Cluster gas. The radio emission also depolarizes systematically with decreasing frequency and decreasing resolution. These results can be modeled by a Faraday screen of magnetized cluster gas, external to the radio lobes, with field strengths of a few micro-Gauss, and with both large scale ordered fields on tens of kpc scales, plus turbulent field structures down to scales of 1 kpc, or less. Such fields have important implications on cluster thermal conductivity and turbulence.

The Evolving Universe

Radio telescopes can trace the evolution of neutral hydrogen and molecular gas, and provide extinction-free measurements of synchrotron, thermal free-free, and dust emission. The VLA is able to distinguish dust from free-free emission in disks and jets within local star-forming regions, thus obtaining a measure of the star-formation rate irrespective of dust extinction, in high-z galaxies. For the most distant known objects, the millimeter and sub-millimeter wave rest-frame spectrum is redshifted down into the frequency range accessible to the VLA. Thus, the Jansky VLA is the counterpart to ALMA in the distant Universe.

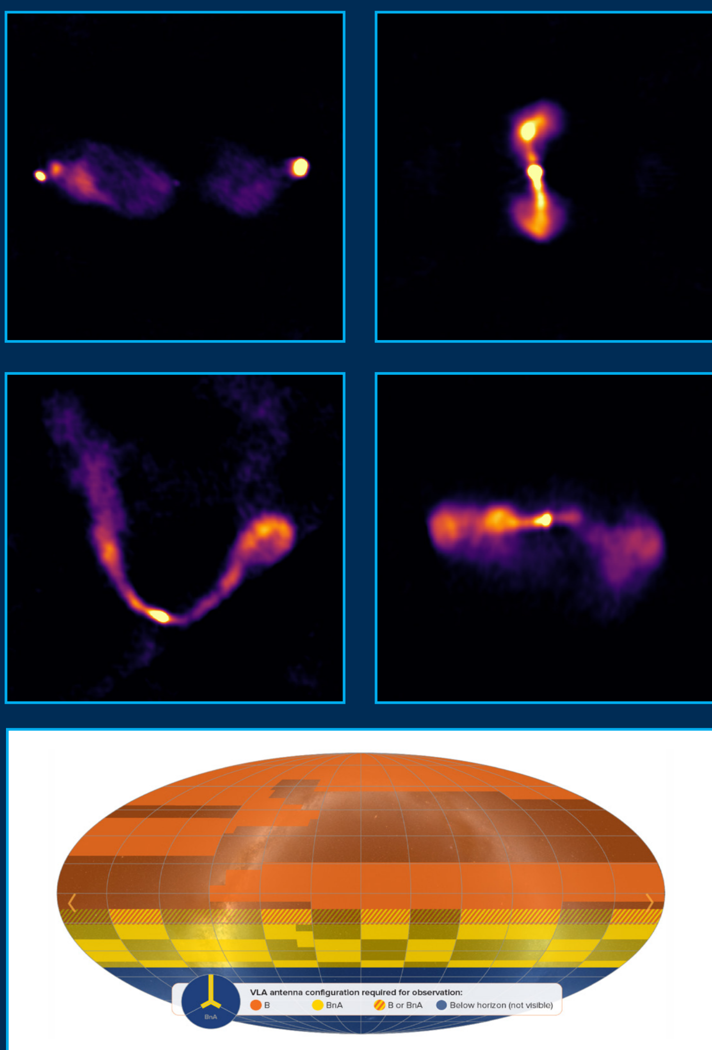
RECEIVER BANDS

Band Name	4m	P	L	S	C	X	Ku	K	Ka	Q
Frequency Range (GHz)	0.058 - 0.084	0.22 - 0.50	1.0 - 2.0	2.0 - 4.0	4.0 - 8.0	8.0 - 12.0	12.0 - 18.0	18.0 - 26.5	26.5 - 40.0	40.0 - 50.0

Parameter	Description/Capability
Antennas (diameter)	27 (25m)
Array Configuration (maximum baseline)	A (36.4km), B (11.1 km), C (3.4 km), D (1.03 km)
Angular Resolution at 74 MHz in arcsec (array configuration)	24 (A), 80 (B), 260 (C), 850 (D)
Angular Resolution at 45 GHz in arcsec (array configuration)	0.043 (A), 0.14 (B), 0.47 (C), 1.5 (D)
Maximum Bandwidth	2 GHz (8-bit samplers), 8 GHz (3-bit samplers)
Number of frequency channels without recirculation	16,384
Maximum frequency channels	4,194,304
Frequency Resolution	2 MHz (coarsest), 0.12 Hz (finest)
Continuum Sensitivity in 60 min, 1 GHz bandwidth at L-band	~8 microJy/beam
Continuum Sensitivity in 60 min, 8 GHz bandwidth at Q-band	~10 microJy/beam
Spectral Line Sensitivity in 60 min, 1km/s (5 kHz) at 1.5 GHz	~3 mJy/beam
Spectral Line Sensitivity in 60 min, 1km/s (150 kHz) at 45 GHz	~2 mJy/beam

VLA SKY SURVEY (VLASS)

NRAO is undertaking the highest resolution all-sky radio survey ever made. The survey, developed in collaboration and consultation with the astronomy community, will observe the entire sky visible to the VLA in multiple epochs. The first epoch was observed from 2017-2019, the second from 2020-2022, and the third epoch began observations in 2023. Plans for a fourth epoch are currently being considered. The unique ability of the VLA to collect data over an entire octave in frequency (2–4 GHz) in a single observation with polarization information allows both the radio colors of hundreds of thousands of radio sources and the properties of the intervening plasma between the radio sources and the observer to be characterized in a way that has not been possible until now. By carrying out the survey in three passes over the whole sky, transient radio sources that appear or disappear during the survey period are being revealed. In total, the VLASS will detect 5–10 million radio sources, considerably more than currently cataloged. The key science areas for this survey are described below.



Above: A sample of radio galaxies from VLASS and sky coverage with observing array configurations. Credit: VLASS Survey Collaboration, NRAO/AUI/NSF

Hidden Explosions: The VLASS will open up new parameter space for finding supernovae, tidal disruption events, gamma-ray bursts and mergers of compact objects (e.g. two neutron stars).

Peering through our Dusty Galaxy: Dust is transparent to radio waves, allowing us to see structures in the Galaxy hidden at other wavelengths. Additionally, the survey will reveal extreme pulsars and cool stars with active coronae that are likely to be variable in the optical and radio.

The Magnetic Sky: Our understanding of how and when magnetic fields arose in the Universe is poor. The VLASS will be able to measure the Faraday Rotation of the plane of polarization of radio waves that occurs when they pass through a magnetized plasma. Faraday Rotation is one of the few techniques for finding magnetic fields in space, from the surroundings of radio sources in dense galaxy clusters, to the magnetic field of our own Milky Way.

Galaxies through Cosmic Time: Jets of radio-emitting plasma can heat the gas within and around galaxies, slowing the formation of stars. The VLASS will help obtain a full census of these radio jets and AGN, needed to determine whether this heating is sufficient to restrict the growth of galaxies via this feedback mechanism.

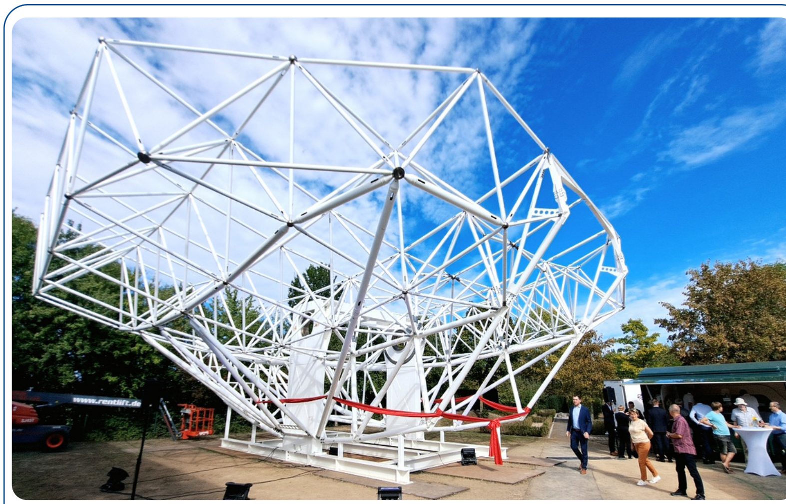
Missing Physics: Whenever a survey breaks new ground in parameter space there will be discoveries unanticipated by the survey team. The radio part of the spectrum, in particular, provides unique diagnostics for a whole range of physical processes. Combining the VLASS data with ambitious new optical and infrared surveys will inevitably lead to significant discoveries..

Quick look images from the 34,000 square degrees covered by the survey are available for the first, second and first half of the third epoch, with higher quality "Single Epoch" images starting to be produced using epoch 2 data. Observations of the third epoch will complete in October 2024. Above is a sample of radio galaxies from VLASS epoch 1 Quick Look images, where all the images are 2 arcminutes on a side. Further information can be found at the website below.

science.nrao.edu/vlass

NEXT GENERATION VERY LARGE ARRAY (ngVLA)

Inspired by the dramatic discoveries from the Jansky VLA, VLBA, GBT, and ALMA, NRAO and the international science community are currently designing a large collecting area radio telescope array that will open new discovery space from protoplanetary disks to distant galaxies. Building on the superb centimeter observing conditions and existing VLA and VLBA site infrastructure, the ngVLA is an interferometric array with more than an order of magnitude improvement in sensitivity and spatial resolution of the Jansky VLA and ALMA, operating at 1.2 - 116 GHz.



Above: The ngVLA antenna structure prototype was unveiled by mtex antenna technology in Leipzig, Germany, with attendees from the scientific and engineering communities, government, and industrial manufacturing. A new state-of-the-art facility will open in Albuquerque, New Mexico for the manufacturing of the ngVLA antennas. This expansion into New Mexico will bring job, scientific, engineering, and economic development, spearheaded by mtex and the NRAO. Photo by Brian R. Kent (NRAO/AUI/NSF)

The ngVLA is optimized for observations at wavelengths between the exquisite performance of ALMA at submillimeter wavelengths, and the future SKA1 at decimeter to meter wavelengths, and will be highly complementary with these facilities. The ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, and deliver unprecedented broadband continuum polarimetric imaging of non-thermal processes.

To ensure strong community engagement during the development of the ngVLA design concept, NRAO has spearheaded a number of initiatives, including the creation of an external Science Advisory Council (SAC). The ngVLA SAC is the interface between the scientific community and NRAO, providing feedback and guidance directly to the ngVLA Project Office on issues that affect the scientific design. The SAC participated in the creation of the ngVLA Science Book, which contains 88 chapters (850+ pages) by over 285 unique authors that highlight key areas of astrophysics ripe for major breakthroughs and underscores the broad U.S. and international support for pursuing the ngVLA. In addition to the SAC, the ngVLA Technical Advisory Council (TAC) works in parallel advising NRAO on technical design issues. This collaboration has aided in the recent publication of the ngVLA reference design, which is a low-technical-risk, costed concept that supports the Key Science Goals for the facility, and forms the technical and cost basis of the ngVLA Astro2020 Decadal Survey proposal. The compendium includes 56 technical documents (1400+ pages) and represents the work of more than 54 engineers and scientists contributing to the project. The ngVLA project was identified by the Astro2020 Decadal Survey as a high-priority, large ground-based facility whose construction should begin this decade.

NRAO strongly encourages the community to get involved with the ngVLA effort by signing up for the mailing list or joining a science working group as the observatory aims to continue the strong legacy New Mexico interferometry well into the next decade and beyond.

In July 2023 the U.S. National Science Foundation approved the ngVLA project for entry into the Major Research Equipment & Facilities Construction (MREFC) review process. Entry into the MREFC queue entry signals strong scientific and technical promise, and growing project readiness. Three MREFC reviews (Conceptual, Preliminary, Final) will be completed over the next three or so years. Those reviews will provide the Foundation with the critical information needed to consider adding ngVLA construction to a budget request later this decade.

Left: The joint ngVLA-SKA conference held May 2023 in Vancouver, British Columbia, Canada. Participants in this meeting shared the cutting-edge science opportunities enabled by the unprecedented SKA-ngVLA coverage across three decades of radio frequency (50 MHz to 116 GHz). Photo by Brian R. Kent (NRAO)

ngvla.nrao.edu

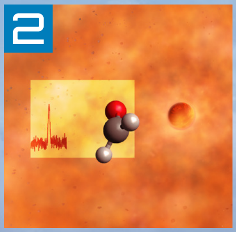
ngvla

Next Generation Very Large Array

KEY SCIENCE GOALS

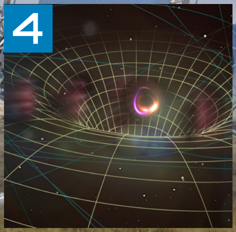
The ngVLA will have broad impact on many of the high priority goals of modern astrophysics

1 Terrestrial Planet Formation



2 Astrochemistry & Life

3 Galaxies Across Cosmic Time



4 Fundamental Physics

5 Multi-messenger Astrophysics

ngvla.nrao.edu

Image by Sophia Dagnello, NRAO/AUI/NSF

Central Development Laboratory (CDL)

Charlottesville, Virginia

The CDL mission is to support the evolution of NRAO facilities by developing the technologies and expertise critical for the next-generation of radio astronomy instrumentation. CDL-developed technology is integral to all NRAO-operated telescopes and to other radio telescopes around the world. CDL maintains a staff of approximately fifty personnel organized into teams of engineers and technicians working across crucial radio telescope technologies, including: digital design and signal processing; low noise amplifiers; millimeter and submillimeter detectors; optics and electromagnetic components; and new receiver architectures. The lab is the world leader in the application of many of these technologies to radio astronomy.

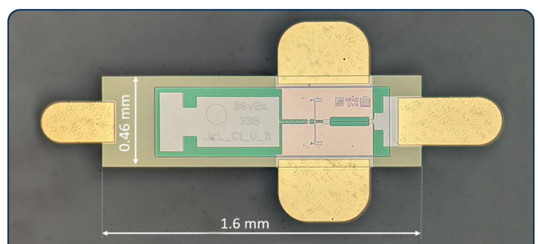
Local Oscillators (LO) and Low Noise Amplifiers

This CDL group specializes in precision LO phase and timing reference distribution and generation of local oscillator signals up to 950 GHz for down-converters used in millimeter and submillimeter receivers. The designs incorporate advanced photonics as well as millimeter and submillimeter techniques to achieve phase-noise and phase-drifts down to tens of femtoseconds, ensuring phase coherence between antennas separated over baselines as long as 15 km. Current research supports the ALMA 2030 Roadmap and ngVLA, including efforts to improve the noise performance of the ALMA Band 6 LO, investigating the requirements for the ALMA LO to support longer baselines, and investigating technologies to support LO and timing distribution for ngVLA and its extremely large baseline lengths and numerous receivers.

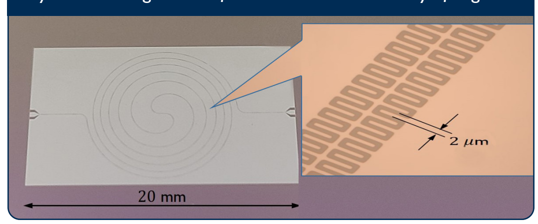
CDL produces the low noise amplifiers from 0.1-115 GHz for its facilities and for the international astronomical community. These amplifiers are the enabling technology behind the high sensitivity and success of the VLA, GBT, VLBA, and ALMA, and have been key to the success of nearly every other astronomical instrument requiring cm-wave and mm-wave low-noise amplifiers over the last 30 years. The CDL continues to explore the limits of low noise amplification, investigating ultra-short gate length Monolithic Millimeter-wave Integrated Circuits (MMICs) for mm-wave devices and SiGe Hetero-structure Bipolar Transistors (HBTs) for broadband cm-wave amplifiers. Current research of the group focuses on developing new broadband IF amplifiers based on commercially available devices that can improve performance of the current and future ALMA Band 6 receivers and developing MMIC-based amplifiers for ngVLA and other future projects.

Millimeter and Submillimeter Receivers

The current generation of NRAO millimeter and submillimeter Superconductor-Insulator-Superconductor (SIS) mixer-based receivers, which are some of the most sensitive in the world, are the result of lengthy development at the CDL in collaboration with the University of Virginia Innovations in Fabrication (IFAB). This pioneering collaboration produced the first-ever niobium-based superconducting circuits for radio astronomy, and resulted in the development of wideband SIS mixer MMICs and their use in implementing sideband separating SIS mixers. The CDL and IFAB collaboration continues to pursue device materials and fabrication technology to develop improved quantum-limited receivers, and extend their frequency coverage up to and beyond 1 THz. Current research focuses on improved device technology to enable development of an ALMA Band 6 upgrade in support of the ALMA 2030 roadmap.



Above: Photograph of a Band 6v2 SIS mixer chip designed at NRAO/CDL and fabricated at The IFAB Innovations in Fabrication Lab at the The University of Virginia. Below: An early Traveling-Wave Kinetic Inductance Parametric (TKIP) layout also designed and fabricated at the University of Virginia.



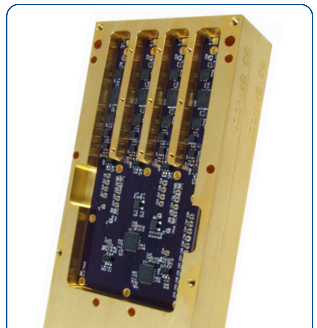
CDL is working with UVa and the Jet Propulsion Laboratory on a breakthrough superconducting amplifier technology called Traveling-Wave Kinetic Inductance Parametric (TKIP) amplifiers. These devices hold the potential to provide near quantum-limited performance over more than an octave of instantaneous bandwidth for all ALMA bands. The laboratory has installed a milli-Kelvin dilution refrigerator to test these devices at RF frequencies and work with fabrication facilities to make design changes that will allow them to work at higher temperatures.

Electromagnetic Components and Optics

Receiver optics and electromagnetic components – including feeds, orthomode transducers, polarizers, and phase shifters – are crucial to the sensitivity, beam quality, and polarization purity of radio telescopes. The CDL designs and builds these critical passive components, including broadband feeds, to maximize the sensitivity of mm- and cm-wavelength radio astronomy instruments. Current research includes improving the optics for the ALMA Band 6 upgrade, and investigating electromagnetic components produced by additive manufacturing.

Digital Signal Processing

All new radio astronomy instrumentation development requires advanced digital hardware and signal processing (DSP), and in many cases, digitization and subsequent processing are dominant parts of the project. DSP-driven subsystems will continue to grow in importance in radio astronomy because of the advantages digital implementation has over analog in data transport and processing. CDL's digital design team is working on the next generation correlators in radio astronomy, concentrating on modularity, reconfigurability, and the flexibility such an architecture provides. The team is also working on implementing an ASIC-based design of a novel analog-to-digital convertor developed in our advanced integrated receiver team and on designs that perform receiver functions now implemented in hardware, such as sideband separation, in software.



The ngVLA Band 3 IRD analog front-end receiver prototype.

Advanced Integrated Receivers

The extreme demands of future instrumentation and facilities, such as large-format focal plane arrays and next generation interferometers, will require innovative receiver architectures. These new designs must realize substantial improvements in cost, compactness, power dissipation, and maintainability, while expanding the bandwidth or field-of-view, with little or no compromise in system noise temperature. The CDL has embarked on the development of a highly integrated receiver starting at the antenna feed terminals or waveguide, and ending in a digital data stream that may be delivered to numerical signal processors. The signal will be digitized very close to the antenna output and sent via optical fiber to the central processing facility. This receiver design will likely be used on ngVLA receivers. Further in the future, conventional electromagnetic polarization splitters will be largely replaced by more accurate digital signal processing based polarization splitters, and multiple frequency conversions will be replaced by a single mixer followed by high-isolation digital sideband separation. The precision of digital signal manipulation will be complemented by the stability of end-to-end electronic integration that breaks down the traditional barriers between analog, digital, and fiber optic subsystems. The long-term result will be a high-performance, compact, radio astronomy receiver with unusually smooth spectral baselines and low systematic errors after calibration.

Space Electronics

CDL pioneers advanced instrumentation and techniques to address key scientific goals: an experiment to understand the cosmology of the early Universe; a high dynamic range spectrometer to study solar flares and coronal mass ejections; and a search for Dark Matter. CDL is also working with NASA and other partners on the Lunar Radio Science & Exploration Laboratory (LunaRLab), in which a diverse group of leading scientists, engineers, and technologists will pursue a comprehensive program of research and science centered on the design, deployment, operation, and analysis of low frequency radio instrumentation on the Moon's surface.

Mechanical Design, Precision Machining, and Finishing

CDL's mechanical design team, precision machine shop, and electroplating lab operate on a research and development footing, working as part of an integrated development team along with CDL's engineers and technicians. High precision design, machining, and finishing of microwave and millimeter wave components to tolerances of 0.0002" (5 microns) is typical; however, a recently acquired five-axis precision milling machine is capable of holding tolerances to 0.5 micron.

Developing The Next Generation Radio Astronomy Engineer

Thanks to a generous grant from the Heising-Simons Foundation, and as part of NRAO's ongoing commitment to women in engineering, a new "Women in Engineering" fellowship program at CDL supports outstanding postdoctoral women engineers whose research is related to our mission. These fellows, who will be granted two-year appointments, will spend up to 75 percent of their time on self-directed research. The "WiE" program also provides opportunities for women undergraduate and graduate co-op students to work at CDL. This program is in addition to CDL's existing Engineering Jansky Post-doctoral Fellowship and co-op program.

science.nrao.edu/facilities/cdl

Student & Visitor Programs

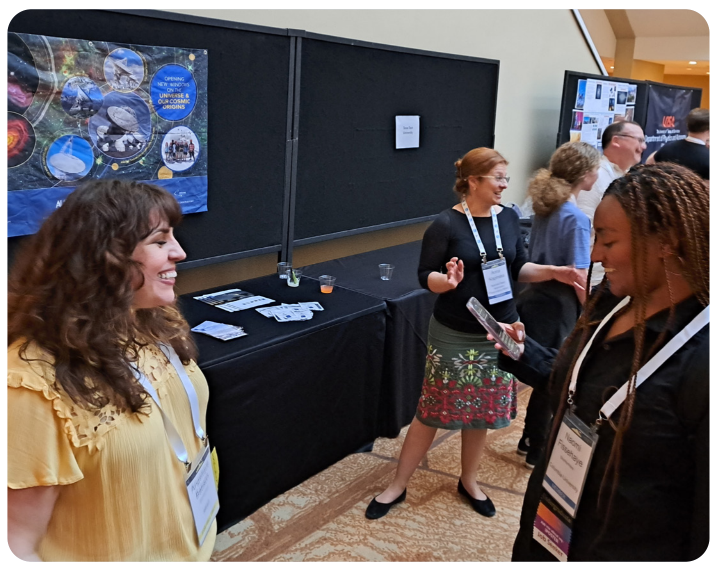
Summer Student Programs

Summer students conduct research under the supervision of scientific and engineering staff members on site at the NRAO in Socorro, NM or Charlottesville, VA, or at the Green Bank Observatory (GBO) in Green Bank, WV. Projects may involve radio astronomy research, instrumentation, or software development. Students receive relocation support and a monthly stipend, and partial support may be available to present summer research at a scientific conference such as a meeting of the American Astronomical Society. All undergraduates in the NRAO and GBO program also have the opportunity to participate in a summer school in Green Bank with hands-on observing, a lecture series, and other career development opportunities. NRAO and GBO host several summer student programs, including the Research Experiences for Undergraduates (REU), Undergraduate Summer Student Research Assistantships, the National Astronomy Consortium (NAC), and Physicists Inspiring the Next Generation (PING). In addition, graduate students may apply for Graduate Summer Student Research Assistantships. Information on summer programs is available at **https://science.nrao.edu/opportunities/student-programs**. **All summer programs use the same application form, and applications are due on February 1, 2024.**

Co-op Program

Each semester the NRAO sponsors one or more paid undergraduate students in co-op programs hosted on site either at Socorro or at the Central Development Lab in Charlottesville. These co-op students, normally juniors and seniors, spend one or more semesters working with an NRAO mentor. Typical assignments include engineering tasks related to the design, prototyping, testing, or production of radio astronomical instrumentation or programming tasks related to radio telescope monitor and control.

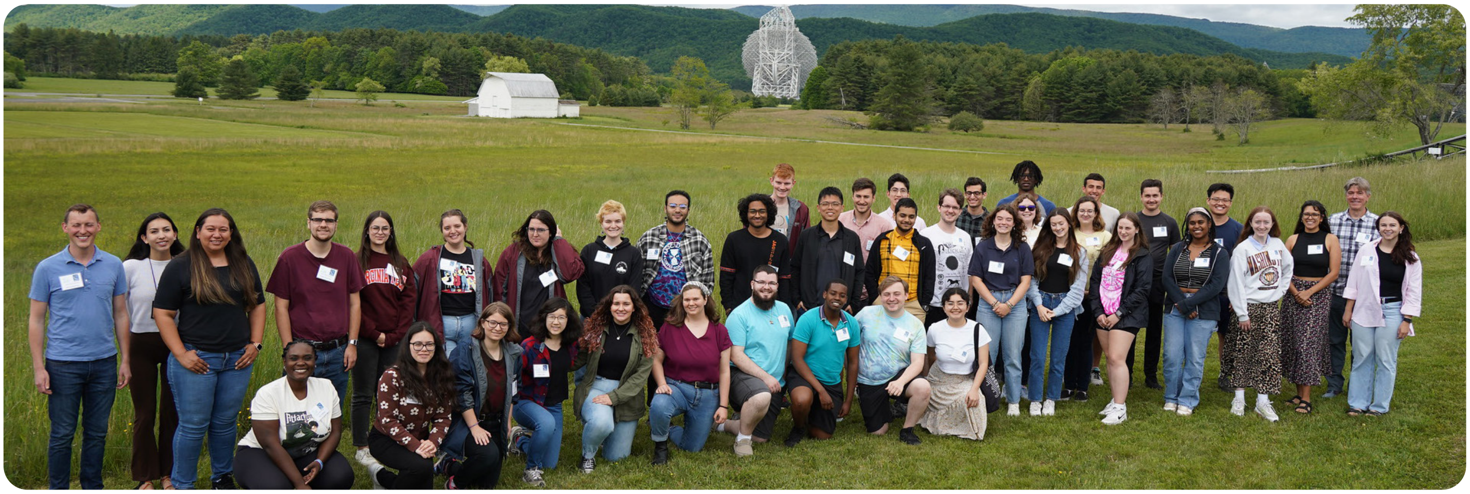
Graduate Student Internships



The Graduate Student Internship program is for early-stage students who are interested in pursuing radio astronomy or related research at one of the NRAO sites. Appointments may be made for periods from a few weeks to six months. Each student is supervised by an NRAO staff member. To apply, students must be U.S. citizens or permanent residents enrolled in an accredited U.S. graduate program, or be otherwise eligible to work in the U.S. Students are awarded a stipend, and some travel and housing assistance may also be available.

Grote Reber Doctoral Fellowship Program

The Grote Reber Doctoral Fellowship Program enables Ph.D. students in the final years of their thesis to conduct research at an NRAO or GBO site, either in Socorro, Charlottesville, or Green Bank under the supervision of an NRAO/GBO advisor. The program is jointly sponsored by the NRAO/GBO and by the student's home university. The program supports thesis projects in radio astronomy, radio instrumentation, and computational techniques. Students are typically nominated for the program by an NRAO/GBO scientist or the student's academic advisor. Students are supported for periods between six months and two years while they work to finish their dissertation. Applications are accepted twice per year: in April for a September start, and July for a January start. The application deadline is announced via an email to NRAO/GBO staff and affiliates. Prospective students are encouraged to seek the support of an NRAO/GBO staff scientist before applying.



Student Observing Support Program

To help train new generations of scientists, the NRAO Student Observing Support (SOS) program funds research by graduate and undergraduate students at U.S. universities and colleges. Scientists who have received observing time on ALMA, the VLA, or the VLBA are currently eligible to apply for funding on behalf of their students. An SOS program to support ALMA archival research will also be available in 2024.

Visitor Program

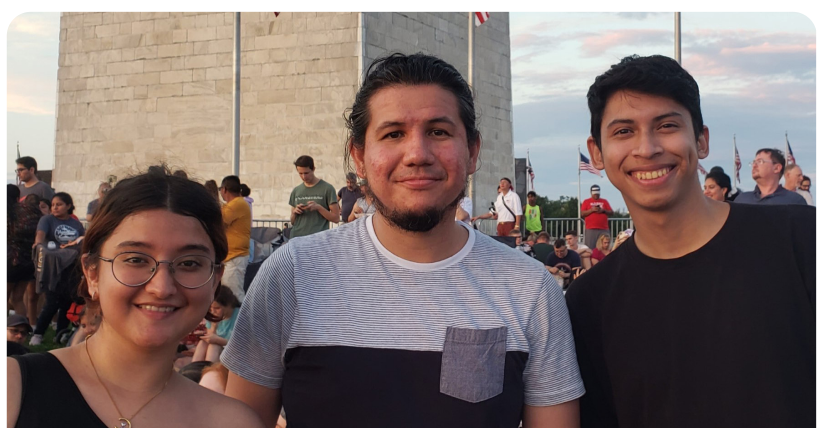
The Visitor Program is open to Ph.D. scientists and engineers in radio astronomy and related fields who wish to visit an NRAO site to collaborate with Observatory staff. The NRAO is particularly interested in supporting visits by junior faculty at colleges and universities, and to encourage collaborations that can lead to first light science with new instruments.

National Astronomy Consortium Program

The National Astronomy Consortium (NAC) program supports students from underrepresented and underserved groups on their way to careers in Science, Technology, Engineering, and Mathematics (STEM) fields. The program is led by NRAO and Associated Universities Inc., in partnership with the National Society of Black Physicists and several universities. NRAO hosts NAC summer student groups at the Socorro and Charlottesville sites, while coordinating with NAC programs at multiple partner institutions. NAC students actively participate in the NRAO summer student program as well as NAC-specific activities before, during, and after their NRAO summer experience. More information is available at **https://science.nrao.edu/opportunities/student-programs/nac**. **Applications are due February 1, 2024.**

National and International Exchange Program

The National and International Non-traditional Exchange (NINE) program is designed to build a pipeline of talent within the radio astronomy field and within under-represented communities. The program focuses on developing worldwide partnerships with fast growing radio astronomy communities capable of facilitating the exchange of NINE trainers and the co-mentoring of underrepresented groups of learners. The NINE provides project management training and hands-on experience with radio astronomy software so that the participant, upon returning to their home location, is prepared to train others to access radio astronomy data. Visit **go.nrao.edu/NINE** for more information about the program.



Students from Honduras and Guatemala participate in the summer NRAO-NINE program, engaging in astronomical research and professional project management. Photo by Anja Fourie (NRAO)

science.nrao.edu/opportunities


NATIONAL RADIO ASTRONOMY OBSERVATORY
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