NATIONAL RADIO ASTRONOMY OBSERVATORY

GREEN BANK OBSERVATORY

A Universe of Discovery Awaits…

2025

CONTENTS

RESEARCH FACILITIES 2025

(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 NSF VLA, ALMA and the NSF 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. The prototype antenna structure is shown here from overhead at night in Leipzig, Germany. **ngvla.nrao.edu**

Photo by mtex antenna technology, GmbH, US NSF/AUI/NSF NRAO

(front cover) Robert C. Byrd Green Bank Telescope, Green Bank, West Virginia

Photo by Jee Seymour, US NSF/AUI/NSF NRAO/NSF GBO

(back cover) The NSF Very Long Baseline Array, Owens Valley, California

Photo by Jeff Hellerman, US NSF/AUI/NSF NRAO

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NSF NRAO Overview

Photos ALMA: Pablo Carrillo; VLA: Brian R. Kent; VLBA: Jeff Hellerman; GBT: Jay Young (NSF/AUI/ALMA/NSF NRAO/NSF GBO)

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

The NSF NRAO telescope suite includes the **Atacama Large Millimeter/submillimeter Array (ALMA)**, the **NSF Karl G. Jansky Very Large Array (NSF VLA)**, the **NSF Very Long Baseline Array (NSF VLBA)**, and the **NSF Robert C. Byrd Green Bank Telescope (NSF GBT)**. Collectively, these telescopes lead in their observing domains, enabling scientists to observe from submillimeter to meter wavelengths with excellent resolution, sensitivity, and frequency coverage. The NSF 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, tracking near earth asteroids, 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 is 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.

As the world's most capable and versatile centimeter-wave imaging array, the **NSF VLA** has scientific capabilities at lower frequencies that complement those of ALMA. The on-going Very Large Array Sky Survey (VLASS) is the highest resolution all-sky radio wavelength survey ever undertaken, exploring the magnetic sky, galaxies through cosmic time, and the transient Universe.

The **NSF VLBA** is the premier dedicated Very Long Baseline Interferometry (VLBI) array in the world. Astrometry with the NSF 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.

The 100-meter **NSF GBT** enables scientific studies with the astronomical community in both single dish radio astronomy and the global VLBI network with the High Sensitivity Array. Astrochemistry, radar studies of near earth objects, and time-domain events including pulsar studies and gravitational waves make up critical pieces of the Green Bank observing portfolio.

To maximize the usage and science impact of the NSF NRAO facilities, NSF 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 (SSR) and Data Management and Software (DMS) Departments and are provided by the North American ALMA Science Center in Charlottesville, Virginia, the Pete V. Domenici Science Operations Center for the VLA and VLBA in Socorro, New Mexico, and the NSF Green Bank Observatory in Green Bank, West Virginia.

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 the NSF NRAO, the **Central Development Lab (CDL)** oversees a science-driven research and development engineering program that will help realize key science goals. The community and the NSF NRAO have initiated the testing of a future large area radio telescope, the **Next Generation Very Large Array (ngVLA)**, with a new prototype antenna. The 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 NSF NRAO continues to lead in radio astronomy, an invaluable resource for the astronomy community in the United States and around the world.

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 array 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 12 is expected to be available in Spring 2025 for observations beginning in October 2025. See the documentation available on the ALMA Science Portal at **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 on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the National Science and Technology Council (NSTC) in Taiwan and by NINS in cooperation with the Academia Sinica (AS) in Taiwan and the Korea Astronomy and Space Science Institute (KASI).

ALMA construction and operations are led by ESO on behalf of its Member States; by the NSF National Radio Astronomy Observatory (NSF 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 ALMA Project reached a milestone with 10 years of groundbreaking scientific innovation and discovery.

The North American ALMA Science Center (NAASC)

The North American ALMA Science Center, based at the NSF 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, financial support to early-career researchers through conferences, training sessions, and workshops, and the SOS program for students, 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 the NSF NRAO in Charlottesville Virginia, in collaboration with Canada's NRC Herzberg, and the National Science and Technology Council in Taiwan. Users may request assistance from the NAASC through the ALMA Helpdesk at **help.almascience.org**.

science.nrao.edu/facilities/alma

KEY SCIENCE

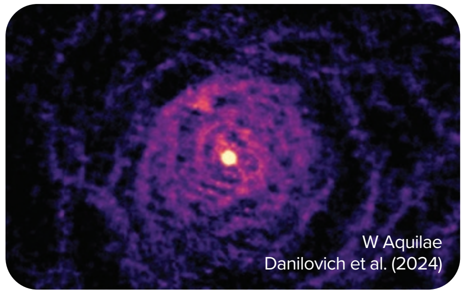
Origins and Evolution of Galaxies

ALMA traces the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z = 2–4) to mapping nearby galaxies by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum.

NGC 1566
PHANGS
Leroy et al. (2021)

Origins of Chemical Complexity

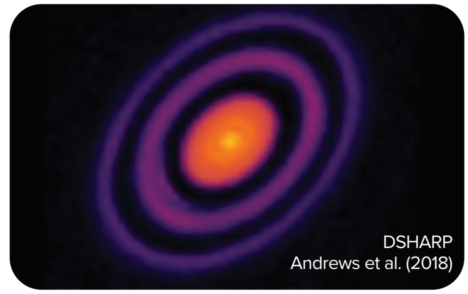
ALMA traces the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 AU) by performing full-band frequency scans at a rate of 2-4 protostars per day.



W Aquilae
Danilovich et al. (2024)

Origins of Planets

ALMA images 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 in formation.



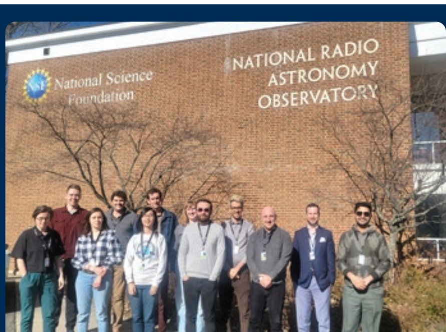
DSHARP
Andrews et al. (2018)

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 12
Antennas	>43 x 12 m; 10 x 7 m; 3 x 12 m TP
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 12 : 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)

** Band 2 will become available 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 2024. 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 (Photo by Pablo Carrillo, US NSF/AUI/ALMA/ NSF NRAO). 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 is leading astronomical research into the 2020 decade and beyond. With over 10,000 users and oversubscription greater than 7.4 to 1, future development must increase science throughput to accommodate scientific demand. The ALMA Development Roadmap (ALMA Memo 612; **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 ALMA's entire wavelength range through a series of major hardware upgrades of nearly all the telescope's components.

Extragalactic Molecular Gas with ALCHEMI

The ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI) program at ALMA has traced the dense gas chemistry across the disk of the prototype starburst galaxy, NGC 253. The molecular gas is more than ten times as dense as the gas found in the center of the Milky Way, likely causing the enhanced star formation rate. Over 44 molecular species have been identified, including numerous shock-heated complex organics, and enhanced H_3O and HOC in massive star forming regions.

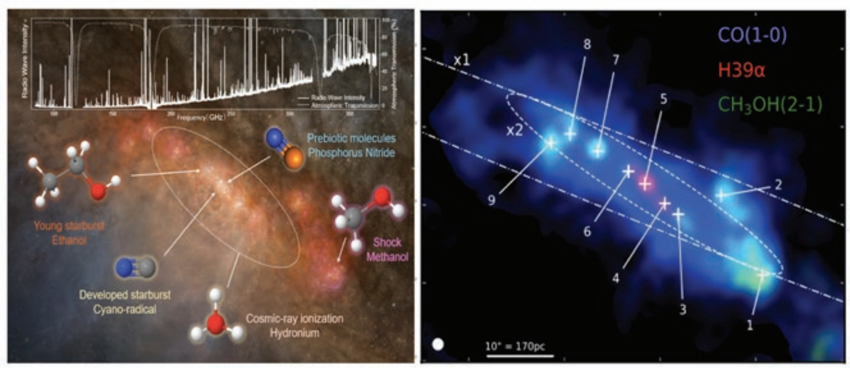
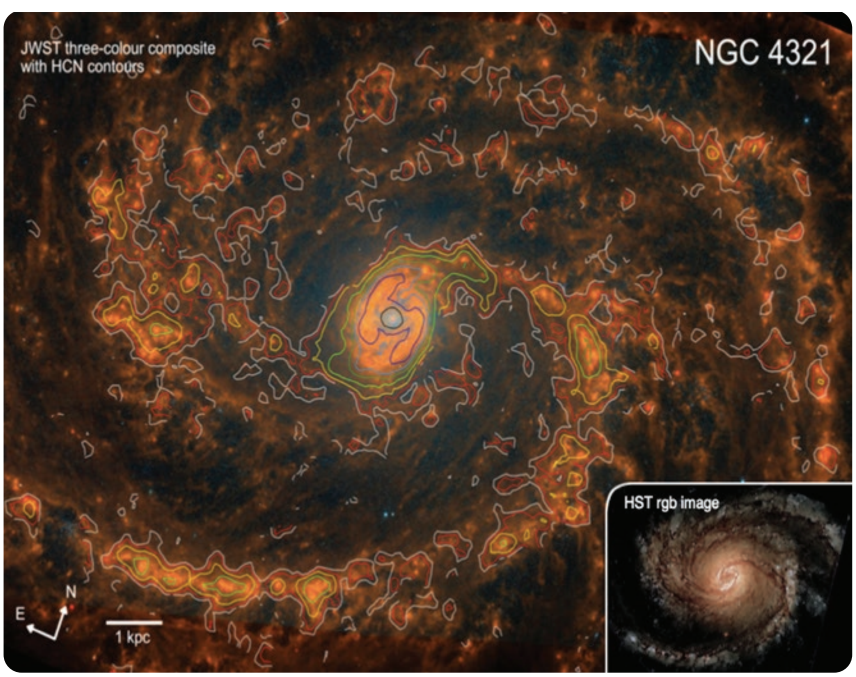


Figure Above Left: optical image of NGC 253 with an ALCHEMI spectrum from 90 GHz to 360 GHz, with some complex molecules identified. Right: Image of H39α recombination line and molecular line emission across the starburst region (Harada et al. 2024).



Dense Gas Tracers with NGC 4321

ALMA has performed a study of the dense gas tracer, HCN, in the spiral galaxy NGC 4321, comparing the dense gas morphology to that of the more global molecular gas tracer, CO, and with the stellar distribution determined with observations by the JWST and Very Large Telescope (VLT). This study has revealed the details of star formation across the disk down to a resolution of 260 pc, approaching the scale of giant molecular clouds. Toward the center of the galaxy, the HCN/CO ratio systematically increases while the star formation rate to HCN decreases. Spiral arms, interarm regions, and bar ends show similar HCN/CO and SFR/HCN.

Figure Left: JWST three-color image of NGC 4321 showing the stellar distribution, overlaid with ALMA HCN contours, tracing the dense molecular gas. The sites of star formation (reddish hues) appear spatially well-correlated with the dense gas traced by HCN (Neumann et al. 2024).

almascience.nrao.edu

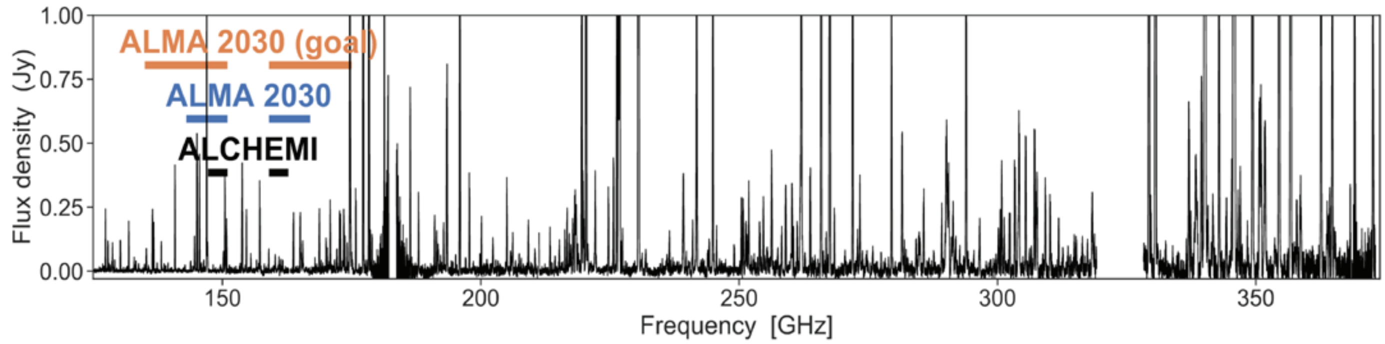
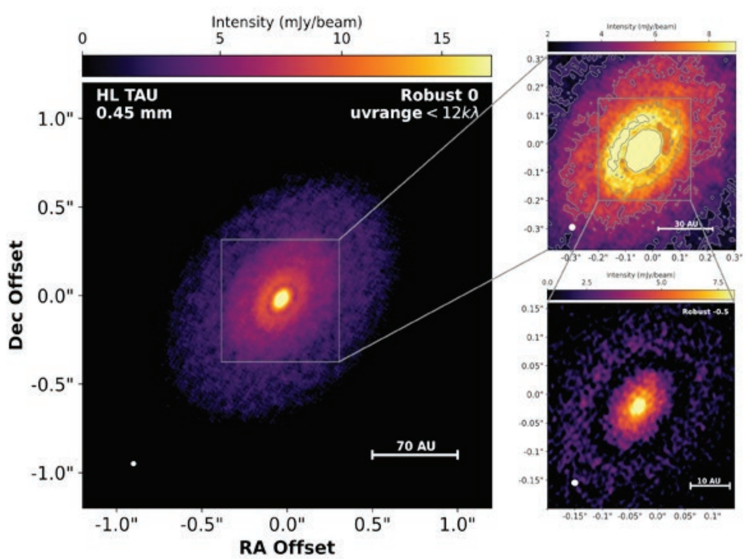


Illustration of the improvement that the Wideband Sensitivity Upgrade (WSU) will provide for spectral scan observations. The plot shows the spectral scans across multiple bands obtained for NGC 253 (Martín et al. 2021). The instantaneous spectral coverage of the actual observation is shown in black, 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: **arxiv.org/pdf/2211.00195.pdf**



Highest Resolution Imaging of Protoplanetary Disk HL Tau

ALMA has imaged HL Tau at 0.45 mm at the highest resolution for any proto-planetary disk to date of 11 mas. The optically thick emission provides the best constraints on the dust temperature and particle size radial profile. The maximum particle size is about 1 cm in the inner disk to 60 AU radius. At larger radii, the grain sizes are between 300 μm and 1 mm. The total dust mass of the disk is 2.1 M_J for compact grains, or 6.3 M_J for porous particles. The dust scale height H/R is greater than 0.08 for the inner disk. The unprecedented resolution of a few AU scales reveals an increase in dust brightness temperature inside the water snowline, possibly indicating dust pile-up in the inner disk (Guerra-Alvarado et al. 2024).

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 the 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/community/alma-development-content

NSF Very Long Baseline Array (NSF 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 NSF Very Long Baseline Array (NSF 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. *Owens Valley photo below by Jeff Hellerman, US NSF/AUI/NSF NRAO.*

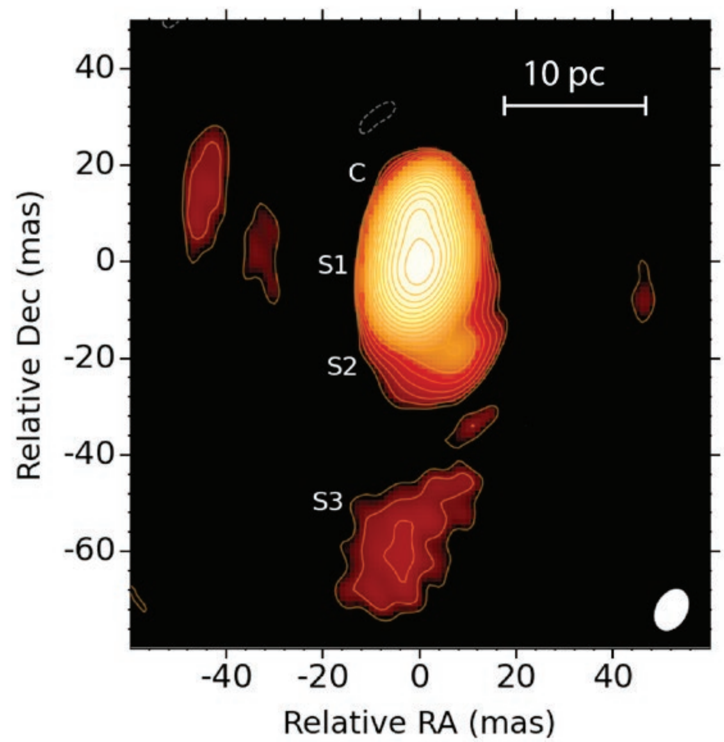
Ten discrete observing bands are available, with wavelengths ranging from 90 cm to 3 mm (300 MHz to 96 GHz). Signals received at each antenna are sampled, processed digitally, and recorded on fast, high capacity recorders. The recorded data are sent from the individual VLBA stations to the Science Operations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

The VLBA's sensitivity can be extended significantly in combination with the phased NSF Karl G. Jansky Very Large Array, the NSF 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 NSF 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 NSF VLBA scientific centerpiece. With the NSF 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.



Naturally weighted NSF VLBA continuum map of 3C84 (Perseus A). The core (C), southern bright jet (S1), its diffuse extension (S2), and the diffuse lobe farther south of the core (S3) are all detected. The peak flux density is 3.5 Jy / beam at S1 with an integrated flux of 9.14 Jy across all components (Morganti et al. 2023).

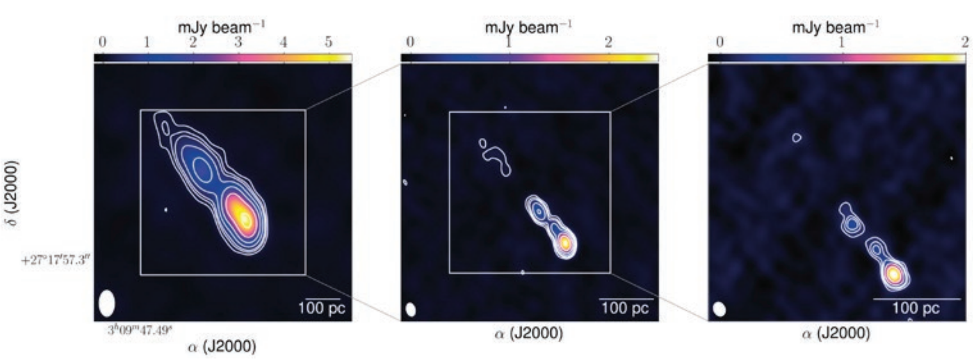
Distance measurements to ~400 high-mass star-forming regions will substantially improve our understanding of the three-dimensional structure of the Milky Way. This program is also measuring the fundamental parameters of Galactic rotation, helping to quantify the distribution of luminous and dark matter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

The NSF VLBA played a significant role in understanding the physics behind the neutron star merger event detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO). 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.



Self-calibrated images from the NSF VLBA of PSO J0309+27 at 1.5 GHz (left), 5 GHz (centre), and 8.4 GHz (right). The contours are drawn at (−3, 3, 6, 9, 18, 36, 72, and 144) times the off-source noise of each map, which are given in Table B.1. The white bar indicates 100 pc in projection at z = 6.1. The restoring Gaussian beam is shown in white in the bottom left corner of each image; north is up, and east is left (Spingola et al. 2020).

science.nrao.edu/facilities/vlba

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

The NSF Karl G. Jansky Very Large Array (*right; Photo by Bettymaya Foott, US NSF/AUI/NSF NRAO*) 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. The NSF 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.
- Continuum sensitivity with up to 8 GHz of instantaneous bandwidth per polarization, 64 independently tunable sub-band pairs, each with full polarization.
- 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.
- NSF 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 NSF 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.

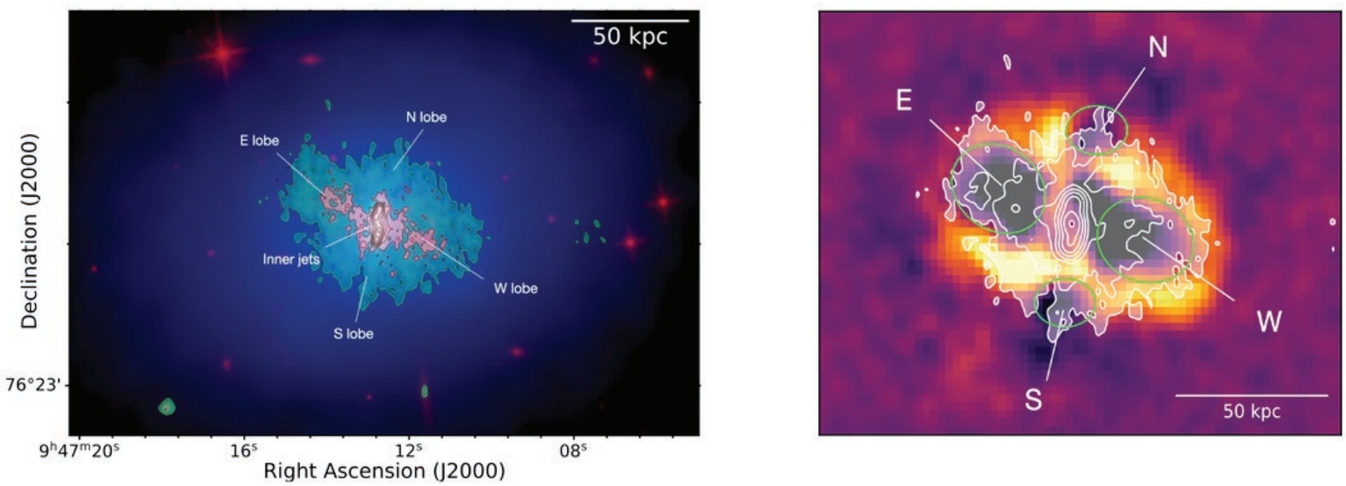
The Obscured Universe

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 NSF 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 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 NSF 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 NSF 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 NSF 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



Left: Composite optical (HST, red), Chandra (X-ray, blue), 3 GHz (NSF VLA, green), 144 MHz (LOFAR-International, pink) image of RBS 797 with labeled structures. Black contours outline the 144 MHz emission of the radio galaxy (Ubertosi et al. 2024).

Right: Residual Chandra image of RBS 797, with overlaid white contours from the NSF VLA 3 GHz data. The X-ray cavities described in Ubertosi et al. (2021) are shown with green ellipses and labeled (Ubertosi et al. 2024).

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 NSF 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 NSF VLA. Thus, the NSF VLA is the counterpart to ALMA in the distant Universe.

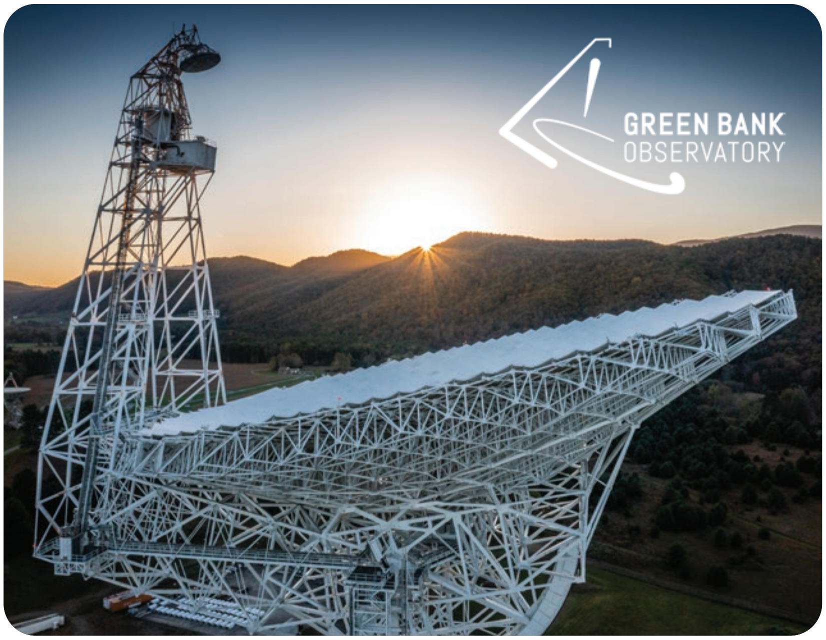
RECEIVER BANDS

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 number of 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

NSF Green Bank Telescope (NSF GBT)

Green Bank, WV



The NSF Green Bank Observatory (NSF GBO) in West Virginia is home to the 100-meter Robert C. Byrd Green Bank Telescope (NSF GBT), the world's largest fully steerable single-dish radio telescope. The GBT's 100-meter diameter collecting area, unblocked aperture, and excellent surface offer the scientific community unrivaled research capabilities at 0.29-116 GHz (1m-2.6mm). *Photo by Jay Young, US NSF/ AUI/NSF NRAO/NSF GBO.*

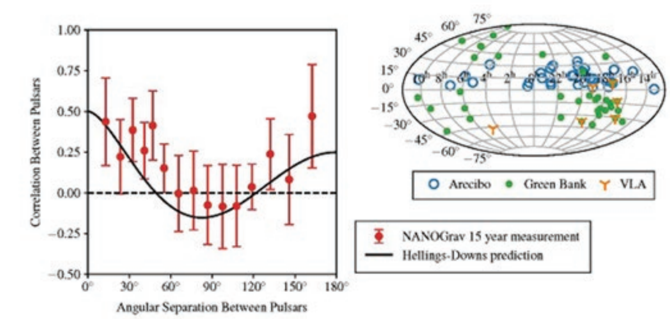
The NSF GBT receivers cover a frequency range from 290 MHz to 116 GHz (non-contiguous). In addition to several single-pixel and dual-pixel receivers, the NSF GBT also offers three array receivers: a 7-pixel heterodyne focal plane array at 18–26 GHz, a 16-pixel single-polarization array from 74–116 GHz and a 215 pixel bolometer array at 75–105 GHz.

The NSF GBT features signal processing systems enabling large dynamic range, wide bandwidth (up to 10 GHz), and high time and frequency resolution for spectral line and pulsar observations. The NSF GBT makes use of two backends, the Digital Continuum Receiver (DCR) and the Versatile GBT Astronomical Spectrometer (VEGAS) with a variety of observing modes. NSF GBO is located in the 13,000 square mile National Radio Quiet Zone (NRQZ) and the 10 mile radius West Virginia Radio Astronomy Zone (WVRAZ), providing unique protection from many forms of human-made radio frequency interference.

KEY SCIENCE

Pulsars, Fast Radio Bursts, and Time Domain Science

Pulsar timing and searching represents a core science mission for the GBT, and the flagship pulsar timing project is NANOGrav. In 2023, the NANOGrav team reported the initial detection of the ultra-low frequency gravitational wave background (Agazie et al. 2023; Figure right). This fundamental result will usher in a new era of pulsar timing research.



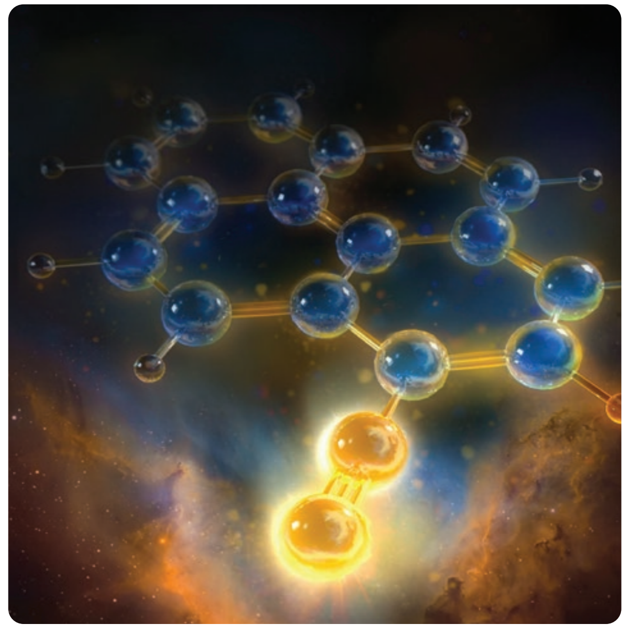
(Left) Correlations between pulsar timing measurements binned as a function of angular separation of pairs showing the detection of the predicted signature (black line) from gravitational waves. (Right) The location on the sky of the pulsars where the green dots are the pulsars observed with the NSF GBT (Agazie et al. The NANOGrav Collaboration 2023, ApJ, 951, L8).

Recent GBT observations, along with observations from other radio telescopes, have measured frequency dependent polarization of repeating FRBs which provides insights into their origin. In 2022 the Canadian Hydrogen Intensity Mapping Experiment (CHIME) project built a cylindrical outrigger antenna at Green Bank to complement the four antennas already operating at the Dominion Radio Astronomy Observatory in Penticton, Canada. The expansion of the CHIME array enables the discovery and localization of FRBs, which can then be characterized by follow up observations with the NSF GBT and other telescopes.

Star Formation and Nearby Galaxies

Several large GBT programs focus on the star-forming molecular gas within star-forming regions in our galaxy and nearby galaxies. Dynamics in Star-forming Cores: a GBT-Argus Survey (DiSCo GAS) is measuring the kinematics of over 100 proto-stellar cores in the Perseus molecular cloud using the dense gas tracer N_2H+. The Dense Extragalactic GBT+Argus Survey (DEGAS) is measuring the

HCN(1-0) and HCO+(1-0) transitions in nearby star-forming galaxies, and the GBT Extragalactic Database for Galaxy Evolution (EDGE) is measuring CO(1-0) in 150 low-*z* galaxies with existing optical Integral Field Unit (IFU) spectroscopy to compare the molecular gas distribution with that of the star-forming regions.



An artist's impression of cyanopyrene which was recently discovered using the NSF GBT by the GOTHAM team. US NSF/AUI/NSF NRAO/NSF GBO/S. Dagnello.

Astrochemistry

Astrochemistry, the study of the formation of complex molecules in gas clouds, is a NSF GBO core science mission. Large surveys to detect ever more complex molecules are underway, including NSF GBT Observations of TMC-1: Hunting Aromatic Molecules (GOTHAM), Molecular Exploration of the Diffuse Interstellar Medium (MEDIUM), and the GBT L1544 Unbiased Complex Organics Survey (GLUCOSE). GOTHAM's latest discovery is the discovery of 1-cyanopyrene which is a building block for complex organic matter (Wenzel et al. 2024, Science; Figure right). The molecule 1-cyanopyrene is a complex organic molecule made up of multiple fused benzene rings and belongs to a class of compounds known as Polycyclic Aromatic Hydrocarbons (PAHs). PAHs were previously believed to form only at high temperatures and were not expected within the cold Taurus Molecular Cold (TMC-1) where the molecule was discovered by the GOTHAM team.

Radar

The NSF GBT has long played an important role as a radar receiving station. With the collapse of Arecibo and the associated loss in the US radar science capabilities, the NSF GBT role in radar science may expand in the future. Plans are underway to develop a possible new Ku-band radar transmitter for the NSF GBT which could be transformational for solar system science and the study of Near-Earth Objects (NEOs).

Astrobiology, SETI, and Technosignatures

The search for life beyond the solar system can be divided into two primary research areas: astrobiology (the search for complex molecules generated by life) and technosignatures (the search for signatures of a technological civilization). NSF GBO has long played a significant role in the search for technosignatures, beginning with Project Ozma's use of the Green Bank Tatel telescope to monitor Tau Ceti and Epsilon Eridani for technosignatures in 1960, and the formulation of the Drake Equation in 1961. At present, the majority of the NSF GBO's work in technosignatures is through the Breakthrough Listen project which searches for extraterrestrial radio communication.

RECEIVER BANDS AND OBSERVING

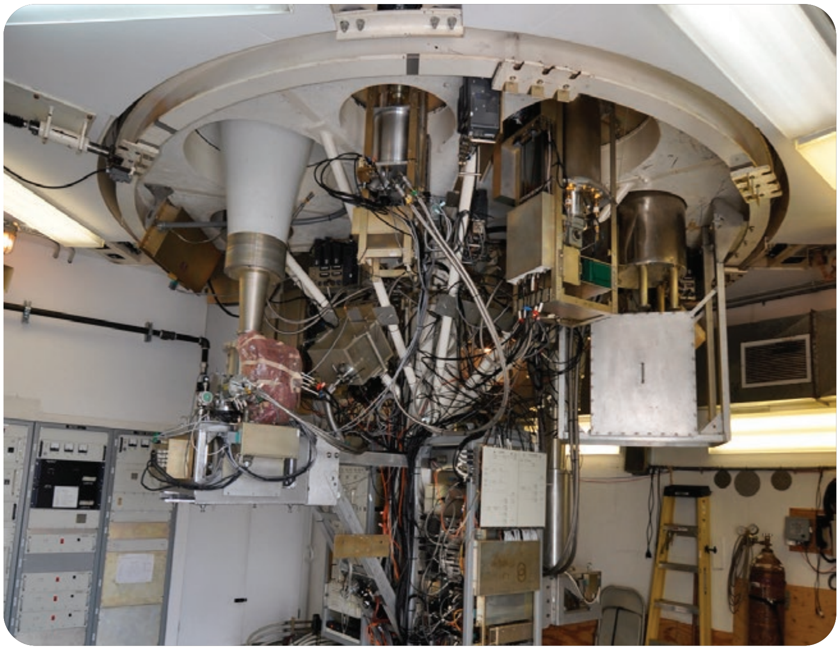
Band Name	Prime Focus 1	UWBR	L	S	C	X	Ku	K FPA	Ka	Q	W	Argus	Mustang-2
Frequency Range (GHz)	0.29-0.395 0.68-0.92	0.7-42	1.15-1.73	1.73-2.6	3.95-7.8	7.8-12	12-15.4	18-27.5 7 pixels	26-39.5	39.2-50.5	67-92	74-116 16 pixels	75-105 215 pixels

Partnering for GBT Observations

Partners should be aware that no more than 30% of available observing time in a given fiscal year will be made available for contracts. High Frequency availability is particularly limited, and the majority of this time is reserved for the Open Skies community. Currently, no more than 10% of purchased time may be for High Frequency observations on the NSF GBT. The NSF GBO charges additional fees for high frequency time, LST ranges near the Galactic Center, time sensitive observations on short notice (< 8 weeks), or observations that use a substantial amount of observing time at the same position in the sky.

Partnership requests and queries should be directed to: **gbo-partner@nrao.edu**

greenbankobservatory.org



GBO TECHNOLOGY DEVELOPMENT

Ultrawideband Receiver The 0.7-4.2 GHz receiver, UWBR, is a precise tool for pulsar studies of low frequency gravitational waves and fast radio bursts and can be used for molecular spectroscopy and measurement of radio recombination lines. UWBR is funded in part by the Gordon and Betty Moore Foundation.

ALPACA The Advanced Cryogenic L-Band Phased Array Camera is under development by Brigham Young University and Cornell University. This 40-beam L-band phased array would operate from 1.3-1.7 GHz and boast a field-of-view of 0.35 square degrees, enabling wide-area searches of HI gas, FRBs, pulsars, and technosignatures. The team plans to submit a funding proposal to enable the future commissioning and deployment of the instrument on the NSF GBT.

ngRADAR NSF GBO, AUI, NSF NRAO, and Raytheon Technologies Inc. are collaborating to develop a Ku-band radar transmitter on the GBT. A radar demonstration project using a low-power (700 W) radar transmitter produced the highest resolution image of the Moon ever obtained from the ground (~1.5 m or ~1 milliarcsec). Plans to build a high-power (500 kW) radar transmitter could provide unprecedented performance for solar system radar studies. There are ongoing efforts to obtain funding with an anticipated deployment in the late 2020s.

Cyclic Spectroscopy CS is a powerful data processing technique for pulsar astronomy that provides higher time and frequency resolution than traditional methods. GBO is building an easy-to-use, pseudo-real time CS system in operation. This system will advance multi-messenger astrophysics through its ability to measure and mitigate Interstellar Medium (ISM) induced noise, while also enabling the detailed study of the ISM along the line of sight to pulsars.

Wideband Digital Signal Processing Astrochemistry programs are limited by the available instantaneous spectroscopic bandwidth with the NSF GBT. Currently, to achieve sufficient velocity resolution (< 0.1 km/s) at high frequency, NSF GBT spectroscopic observations have a maximum instantaneous bandwidth of about 680 MHz. The GBO electronics team has developed a plan to improve the bandwidth for high spectral resolution on the Ka-, Q-, and W-band receivers by modifying the IF system and enhancing the VEGAS system. These modifications could increase the bandwidth for high spectral resolution by an order of magnitude to increase the speed for carrying out spectroscopic surveys.

ELECTRONICS AND TELESCOPE OPERATIONS

The Electronics Division incorporates a multidisciplinary staff of engineering and technical specialists to maintain all electronic and cryogenic systems. The division works to improve the reliability of electronic systems, ensure data quality, and modify existing equipment for new applications, while also collaborating with the astronomical community at large to develop new products. Within the division, the Microwave Group maintains the suite of receiver systems, and the Digital Group maintains the NSF GBT's active surface, telescope control systems, and digital signal processing equipment. The Microwave Group maintains a laboratory equipped with state-of-the-art test and measurement equipment, including a bonding machine and probe station for building and testing Monolithic Microwave Integrated Circuit (MMIC) devices, an Anritsu Vector Star network analyzer capable of measuring microwave components up to 115 GHz, and an assortment of RF and fiber optic devices. The RF laboratory routinely produces working RF board and optic designs up to 115 GHz using CST Microwave and Microwave Office development software. The staff also routinely experiments with commercially available MMIC devices to improve gain stability and baseline performance of the current NSF GBT systems. The Digital Group has experience with Field Programmable Gate Array (FPGA) design concepts and produces many specialized digital processing systems.

The Telescope Operations Division performs preventive and corrective maintenance tasks on all the site telescopes and their systems, all within the master preventative maintenance schedule. Engineers and technicians from the Electronics division guide repair tasks for the servo motors of the telescope, with assistance from Telescope Operations. Preventive maintenance tasks include routine lubrication, scheduled equipment change outs, painting, and inspections. In addition to routine telescope maintenance, the team facilitates projects to revitalize overall GBO infrastructure.

TRAINING AND PROPOSAL CALLS

Training workshops are offered for each observing semester. See our website for current workshop dates and to register:
greenbankobservatory.org/science/gatherings/training-workshop/

Proposal calls are held twice a year for Open Skies Time. The principle of Open Skies science is to maximize the scientific output of an instrument or facility by allowing any scientist in the world to apply for time on that instrument through a peer-reviewed process. The time available for Open Skies is equal to the fraction of the operational funds contributed by the NSF. NSF GBO's proposal process is coordinated with the NSF NRAO. All proposals are evaluated on the basis of scientific merit by science review panels. Proposals for GBT Director's Discretionary Time can be submitted at any time to support targets of opportunity, exploratory observations, and time critical observations. GBO staff provide training workshops several times a year on how to create proposals, how to use the NSF GBT, and how single dish radio telescopes work. Calls for proposals to observe using the NSF GBT are issued twice a year: **greenbankobservatory.org/portal/gbt/proposing/**

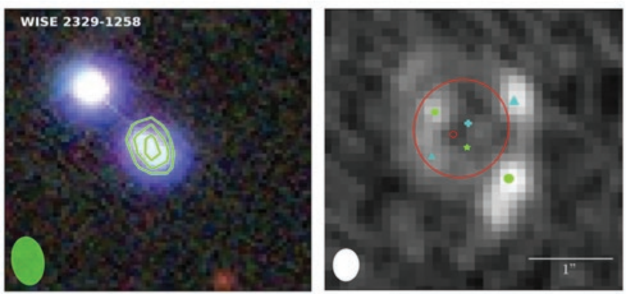
GREEN BANK SCIENCE CENTER

The Science Center offers hands-on science in the Catching the Wave Exhibit Hall, shopping in the Galaxy Gift Shop, and dining at the Starlight Café. Presentations and site tours are offered at regular intervals throughout the day. Additional programs are scheduled seasonally or monthly, including High Tech tours of the Jansky Lab, SETI tours, monthly Star Parties, field trips and special events. See our online events calendar for dates. Visitors are also welcome to take a self-guided walking tour of the NSF GBO. The Science Center is free, but fees are charged for all tours and some special events. Days of operation and hours change seasonally.

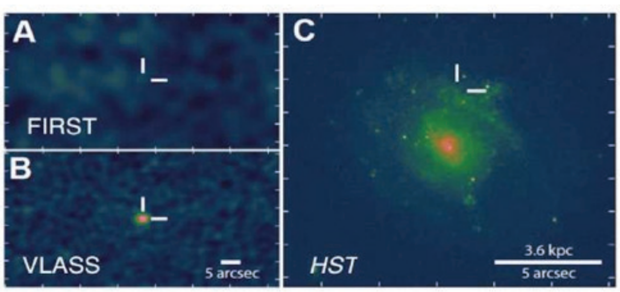
greenbankobservatory.org

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, is observing the entire sky visible to the NSF VLA in multiple epochs. The first epoch was observed from 2017-2019, the second from 2020-2022, and the third epoch completed observations in 2024 . Half of the sky will be also be observed for a 4th Epoch in 2025-2026. The unique ability of the NSF 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.



Left: VLASS contours and optical image of a lensed quasar at z = 1.3. Right: VLA 0.2" 2-12 GHz image of the system showing a complete Einstein ring matching the lensing potential of the foreground galaxy (red circle; Martinez et al. 2024).



A transient radio source (VT 1210+4956) consistent with a merger-triggered core collapse supernova. Panel A shows the non-detection in FIRST, panel B shows the discovery in VLASS Epoch 1, and panel C shows an optical image of the host galaxy taken with the Hubble Space Telescope (Dong et al. 2021).

Hidden Explosions: The VLASS has opened 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 has revealed 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 can 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.

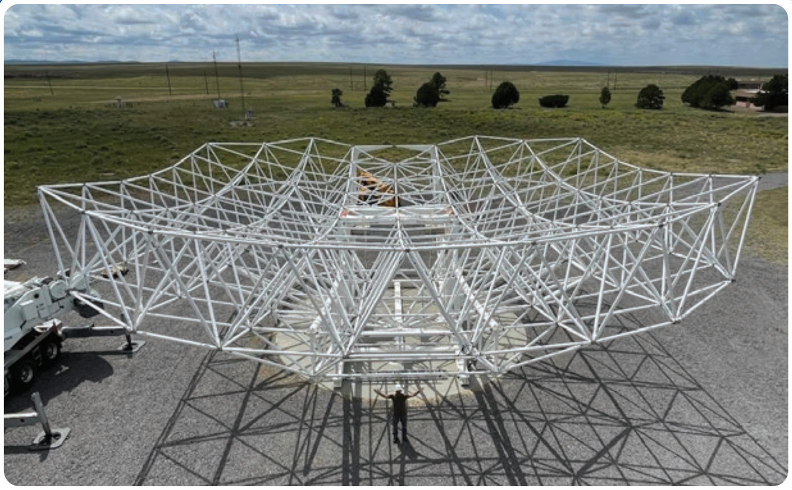
Galaxies through Cosmic Time: Jets of radio-emitting plasma can heat the gas within and around galaxies, slowing the formation of stars. The VLASS will help obtain a full census of these radio jets and AGN, needed to determine whether this heating is sufficient to restrict the growth of galaxies via 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 has already led to significant discoveries such as late-time radio flares from tidal disruption events.

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. Science results are shown above with lensed quasars and transient events. Further information can be found at the website below.

science.nrao.edu/vlass

NEXT GENERATION VERY LARGE ARRAY (ngVLA)



Above: The ngVLA antenna structure prototype begins assembly at the VLA site in New Mexico. This 18-meter antenna design with an octangonal reflector shape will be used for testing and characterizing this critical ngVLA system component. Photo by Philip Bolton, US NSF/AUI/NSF NRAO.

Inspired by the dramatic discoveries from the NSF VLA, NSF VLBA, GBT, and ALMA, NSF NRAO and the international science community are currently implementing 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 NSF VLA and ALMA, operating at 1.2 - 116 GHz.

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. The ngVLA successfully passed a Conceptual Design Review in 2024. The prototype antenna has been delivered by *mtex antenna technologies, GmbH* to New Mexico for testing and evaluation. The ngVLA project will now be considered by the US National Science Foundation for entry to the next phase - Preliminary Design - to further advance the project's definition and execution plan.

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

The Next Generation Very Large Array prototype antenna, seen here on the plains of San Agustin, New Mexico with the reflector backup structure and pedestal, will be used for testing system components. The design was a result of years of NSF/AUI/NSF NRAO investment with several contractors to advance multiple concepts to reduce risks and increase confidence in the feasibility of the design by mtex antenna technologies, GmbH. This prototype will lead to the final design of a high-performance antenna capable of achieving ngVLA science, and thereby the platform from which ngVLA can grow.

ngvla.nrao.edu

Central Development Laboratory (CDL)

Charlottesville, Virginia

CDL-developed technology is integral to all NSF 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 world-leading radio telescope technologies, including: digital design and signal processing; low noise amplifiers; millimeter and submillimeter detectors; optics and electromagnetic components; and new receiver architectures.

Local Oscillators (LO) and Low Noise Amplifiers

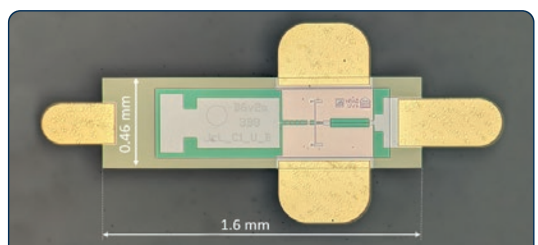
This CDL group specializes in precision LO phase and timing reference distribution and generation of local oscillator signals up to 950 GHz for down-converters used in millimeter and submillimeter receivers. The designs incorporate advanced photonics as well as millimeter and submillimeter techniques 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 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 NSF VLA, GBT, NSF 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. 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.

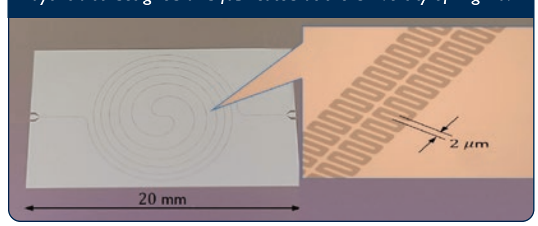
Millimeter and Submillimeter Receivers

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 for development of an ALMA Band 6 upgrade in support of the ALMA 2030 roadmap.

CDL is working with the University of Virginia, the Technical University of Delft, 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.



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.

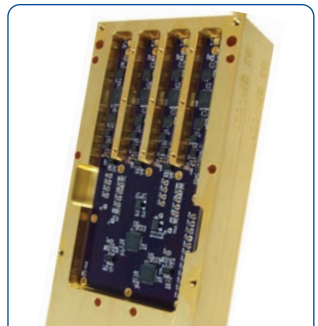


Electromagnetic Components and Optics

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.

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 training engineers, a fellowship program at CDL supports outstanding postdoctoral 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 program also provides opportunities for 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

Data Management and Software

CASA

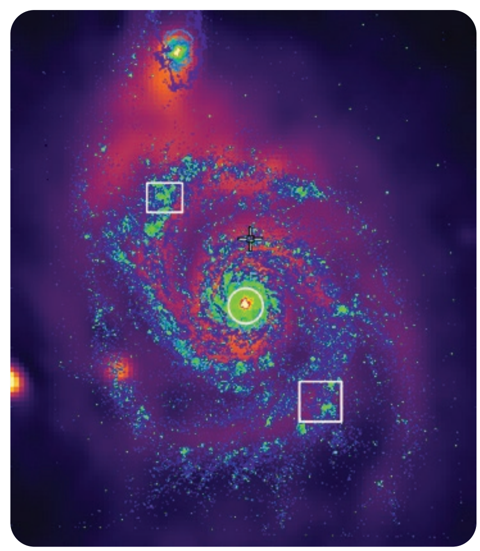
CASA, the Common Astronomy Software Applications package, is the primary data processing software for ALMA and the VLA, and is frequently used also for other radio telescopes. The CASA software can process data from both single-dish and aperture-synthesis telescopes, and one of its core functionalities is to support the data reduction and imaging pipelines for ALMA, VLA, and the VLA Sky Survey (VLASS). CASA is developed by an international team of scientists based at the NSF NRAO, ESO, and NAOJ, under the guidance of NRAO. **casa.nrao.edu**

CARTA

CARTA, the Cube Analysis and Rendering Tool for Astronomy, is a next-generation image visualization and analysis tool designed for ALMA, VLA, and SKA pathfinders.

CARTA adopts a client-server architecture which is suitable for visualizing images with large file sizes (GB to TB) easily obtained from ALMA, NSF VLA, or SKA pathfinder observations. It is impractical to process such a huge file with a personal computer or laptop. In a client-server architecture, computation and data storage are handled by remote enterprise-class servers or clusters with high performance storage, while processed products are sent to clients only for visualization with modern web features, such as GPU-accelerated rendering. This architecture also enables users to interact with the ALMA and VLA science archives by using CARTA as an interface.

CARTA has two flavors: Desktop and Server. The former is suitable for single-user usage with a laptop, a desktop, or a remote server in the “remote” execution mode. The latter is suitable for institution-wide deployment to support multiple users with user authentication and additional server-side features. **cartavis.org**



Data Archives

The NSF NRAO Data Archive System provides access to all publicly available NSF VLA, NSF VLBA, and GBT data. The tool also includes ALMA data in its search returns. NRAO data that remains within its proprietary period can be accessed. Advanced search capability is available. A collection of NSF VLA and NSF VLBA images are also available for browsing and downloads. All scientific data acquired with NRAO telescopes are stored in the Data Archive. Scientific data are reserved for the exclusive use of the observing team usually for 12 months after a project’s final observing session has been completed. In certain circumstances, the default proprietary period may be lengthened; some Rapid Response Science proposals have shorter proprietary periods. The science teams of large GBT programs providing Science Ready Data Products are distributed via a GBO web interface as part of the GBT Legacy Science Product Archive system. **data.nrao.edu** **almascience.nrao.edu/aq/** **greenbankobservatory.org/portal/gbt/data-access/**

DYSH

GBT users have frequently requested a Python-based toolkit for data analysis. GBO is collaborating with the University of Maryland to develop a Python-based data reduction software system called Dysh. By the end of 2024, modules to reduce data from a few core observing modes for spectral line data (such as position switching) and a preliminary Graphical User Interface (GUI) will be ready for user demonstration and feedback. **dysh.readthedocs.io**

Doctoral and Postdoctoral Opportunities

Karl G. Jansky Postdoctoral Fellowship

Jansky Postdoctoral Fellows spend most, if not all, of their time on self-directed independent research. The Jansky Fellowship appointment will be awarded initially for a two-year period, renewable for a third year. Fellows are encouraged to develop research collaborations with NSF NRAO/GBO scientific staff, scientists at U.S. universities, and colleagues in the international astronomical or instrumentation community. The Jansky Fellowship Program provides numerous opportunities for early career scientists to acquire deep knowledge and understanding of the state-of-the-art radio astronomy science and instrumentation, to engage in activities related to the development and delivery of radio astronomy techniques and capabilities, and to contribute to the NSF NRAO/GBO research environment. The Fellows are expected to establish themselves as innovative, independent research scientists and engineers, and become the top leaders in the field. *Photo right: Jansky Fellow Dr. Samantha Scibelli at the Green Bank Telescope.*

Appointments may be made at the three NSF NRAO/GBO sites (Socorro, NM, Charlottesville, VA, and Green Bank, WV). Applicants should describe how their research or technical interests couple with NRAO's mission, telescopes, and science. In compelling cases, a 'split appointment' Jansky Fellowships between a U.S. based university and a NSF NRAO site, or a 'non-resident' Jansky Fellowship hosted at a university within the United States, may be offered. Non-resident Jansky Fellows are expected to develop a research program that fosters close ties with the NRAO, and describe how residence at their proposed host university will accomplish this. Frequent and/or long-term visits to NRAO sites during the non-resident Fellowship are strongly encouraged. NSF NRAO supports partial teleworking arrangements for scientific postdoctoral fellows.
science.nrao.edu/opportunities/postdoctoral-programs/jansky

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 in Socorro, Charlottesville, or Green Bank under the supervision of a NSF 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 a NSF 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 NSF NRAO/GBO staff and affiliates. Prospective students are encouraged to seek the support of a NSF NRAO/GBO staff scientist before applying.
science.nrao.edu/opportunities/student-programs/ReberFellowships

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 NSF NRAO/GBO sites. Appointments may be made for periods from a few weeks to six months. Each student is supervised by an NRAO/GBO 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.

Student Observing Support Program

To help train new generations of scientists, the NSF 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 NSF VLA, or the NSF 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 2025.

science.nrao.edu/opportunities

Student, Education, Teacher, and Visitor Programs

Summer Student Programs

Summer students conduct research under the supervision of scientific and engineering staff members on site at the NSF NRAO in Socorro, NM, Charlottesville, VA, or 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 NSF 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. In addition, graduate students may apply for Graduate Summer Student Research Assistantships. All summer programs use the same application form, and applications are due on February 1, 2025.
science.nrao.edu/opportunities/student-programs

Co-op Program

Each semester the NSF 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 a NSF 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.

Visitor Program

The Visitor Program is open to Ph.D. scientists and engineers in radio astronomy and related fields who wish to visit a NSF NRAO site to collaborate with Observatory staff. The NSF 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.

Pulsar Search Collaboratory

The PSC engages high school students and their teachers in the quest to discover new pulsars and transient sources by analyzing data from the GBT. Twice each academic year, GBO holds a 6-week online training course. Participants may apply to summer camp at the Observatory, and attend annual capstone events.

West Virginia Science Public Outreach

WV SPOT began in 2013 as a partnership with NASA's WV Space Grant Consortium. The program trains undergraduates to deliver interactive science, technology, and engineering presentations to K–ð12 classrooms and youth programs. To date, over 900 presentations have been given, impacting the lives of over 26,000 students.

Skynet Junior Scholars

SJS allows educators and students to gain access to telescopes around the world, including GBO's 20-meter radio telescope. Students remotely access telescopes to collect real project data and collaborate with each other in online communities. Educators and youth leaders can form their own clubs.

Mission2Mars

GBO partnered with The Franklin Institute to provide professional development to amateur astronomers and informal educators and build community networks. These networks host events to excite families about NASA's Artemis Missions and stargazing. **mission2mars.fi.edu**

Research Experiences for Teachers (RET)

In conjunction with West Virginia University, this six week summer research program trains teachers in digital signal processing in radio astronomy. Participants learn how to use an inexpensive, versatile and rapidly developing technology (software defined radios) which can be implemented for astronomy applications as well as for receiving signals from satellites, like the NOAA weather satellites. Each summer, up to eight teachers spend four weeks at WVU, and two weeks at GBO.

Students from NRAO programs tour the Green Bank Telescope with scientist Dr. Emily Moravec during the Summer Student boot camp.

science.nrao.edu/opportunities

NATIONAL RADIO ASTRONOMY OBSERVATORY

A Universe of Discovery Awaits...

2025