



NATIONAL RADIO ASTRONOMY OBSERVATORY



RESEARCH FACILITIES  
*for the*  
SCIENTIFIC COMMUNITY

2020

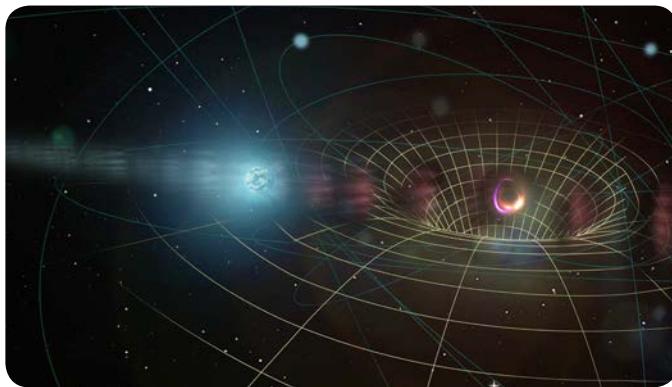


Atacama Large Millimeter/submillimeter Array  
Karl G. Jansky Very Large Array  
Central Development Laboratory  
Very Long Baseline Array

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(above image)

One of the five **ngVLA Key Science Goals** is *Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity*. Pulsars in the Galactic Center represent clocks moving in the space-time potential of a super-massive black hole and would enable qualitatively new tests of theories of gravity. More generally, they offer the opportunity to constrain the history of star formation, stellar dynamics, stellar evolution, and the magneto-ionic medium in the Galactic Center. The ngVLA combination of sensitivity and frequency range will enable it to probe much deeper into the likely Galactic Center pulsar population to address fundamental questions in relativity and stellar evolution. Credit: NRAO/AUI/NSF, S. Dagnello

(cover)

ALMA antennas. Credit: NRAO/AUI/NSF; ALMA, P. Carrillo

(back cover)

ALMA map of Jupiter showing the distribution of ammonia gas below Jupiter's cloud deck.  
Credit: ALMA (ESO/NAOJ/NRAO), I. de Pater et al.; NRAO/AUI NSF, S. Dagnello

## NRAO Overview

The National Radio Astronomy Observatory (NRAO) is delivering transformational scientific capabilities and operating three world-class telescopes that are enabling the astronomy community to address its highest priority science objectives.



ALMA photo courtesy of D. Kordan

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 is opening 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. Cycle 7 Early Science began in October 2019. The ALMA Cycle 8 Call for Proposals is expected in March 2020.

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

## Atacama Large Millimeter/ submillimeter Array (ALMA)

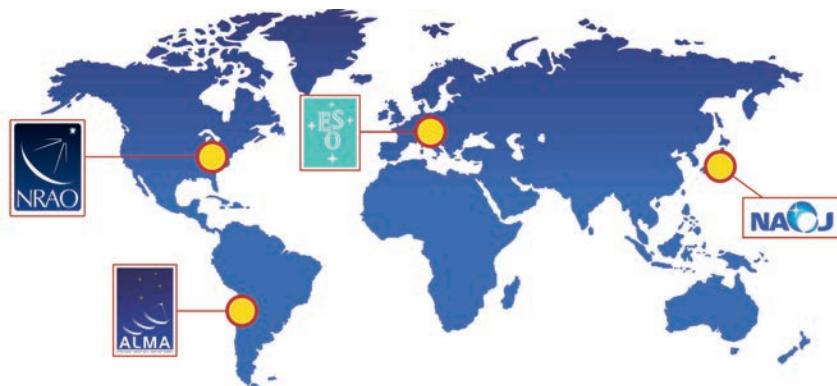
Altiplano de Chajnantor, Chile

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 currently executing Principal Investigator science observations for Cycle 7, which runs from 1 October 2019 through 30 September 2020. Cycle 7 observations employ at least 43 of the antennas in the 12 m Array, and may also use 10 antennas in the 7 m Array and three additional 12 m antennas for total power imaging. Baselines in Cycle 7 extend up to 16 km, depending on the frequency band being used. The Call for Proposals for Cycle 8 will be issued in March 2020 and the proposal deadline is expected in April 2020 for observations that will begin in October 2020. The Call for Proposals and other documentation are available on the ALMA Science Portal ([almascience.nrao.edu](http://almascience.nrao.edu)). ALMA is the most sensitive and capable millimeter interferometer in the world.



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. The NAASC provides a number of additional key services to users, including calibrating, imaging, and distributing ALMA data, organizing and hosting conferences, training sessions, and workshops, and supporting 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 partnership with the National Research Council of Canada, Herzberg Institute of Astrophysics.

## 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 ( $\sim 10\text{-}100$  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 ( $\sim 1$  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.

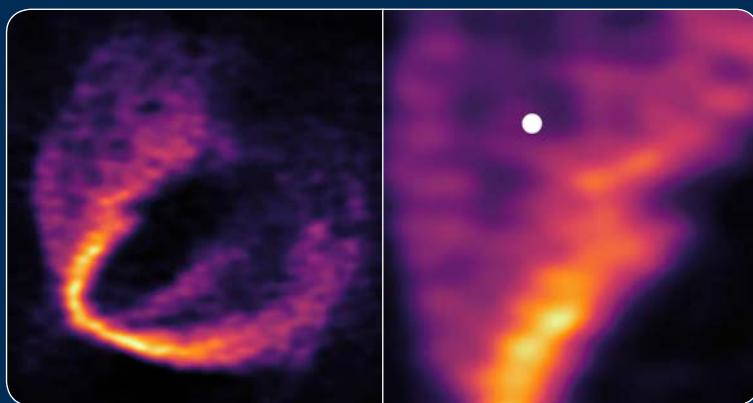
### RECEIVER BANDS

Band #	3	4	5	6	7	8	9	10
Frequency Range (GHz)	84 - 116	125 - 163	163 - 211	211 - 275	275 - 373	385 - 500	602 - 720	787 - 950
Wavelength Range (mm)	3.57 - 2.59	2.40 - 1.84	1.84 - 1.42	1.42 - 1.09	1.09 - 0.80	0.78 - 0.60	0.50 - 0.42	0.38 - 0.32

### Cycle 7

Antennas	>43 x 12 m; 10 x 7 m; 3 x 12 m TP
Bands	Bands* 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
Maximum Angular Resolution	0.02'' ( $\lambda / 1$ mm)(10 km/max baseline)
Maximum Baseline	16.2 km (depends on Band)
Continuum Sensitivity (60 sec, Bands 3 - 10)	~0.08 – 5.4 mJy/beam (43 antennas)
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 - 10)	~ 12 – 98 mJy/beam

\* Bands 1 and 2 will become operational in future Cycles.



*Far left:* Two independent teams of astronomers have uncovered convincing evidence that three young planets are in orbit around an infant star known as HD 163296. Using a new planet-finding strategy, the astronomers identified three discrete disturbances in a young star's gas-filled disk: the strongest evidence yet that newly formed planets are in orbit there. Very sensitive spectral line observations of the 1.3mm wavelength (Band 6) transitions of  $^{12}\text{CO}$ ,  $^{13}\text{CO}$ , and  $\text{C}^{18}\text{O}$  revealed the disturbances, visible in this image as a kink in the emission from the gas flow near the location of the planet (left) whose gravity distorts the gas velocities slightly. Plans are under way to further improve ALMA's sensitivity by upgrading ALMA Band 6 and the correlator. Credit: ESO, ALMA (ESO/NAOJ/NRAO); Pinte et al. Left: White dot shows predicted location of planet.

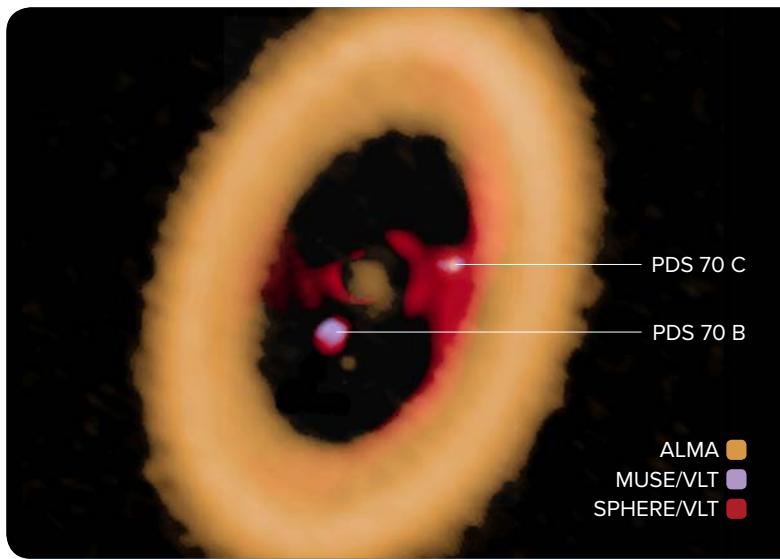
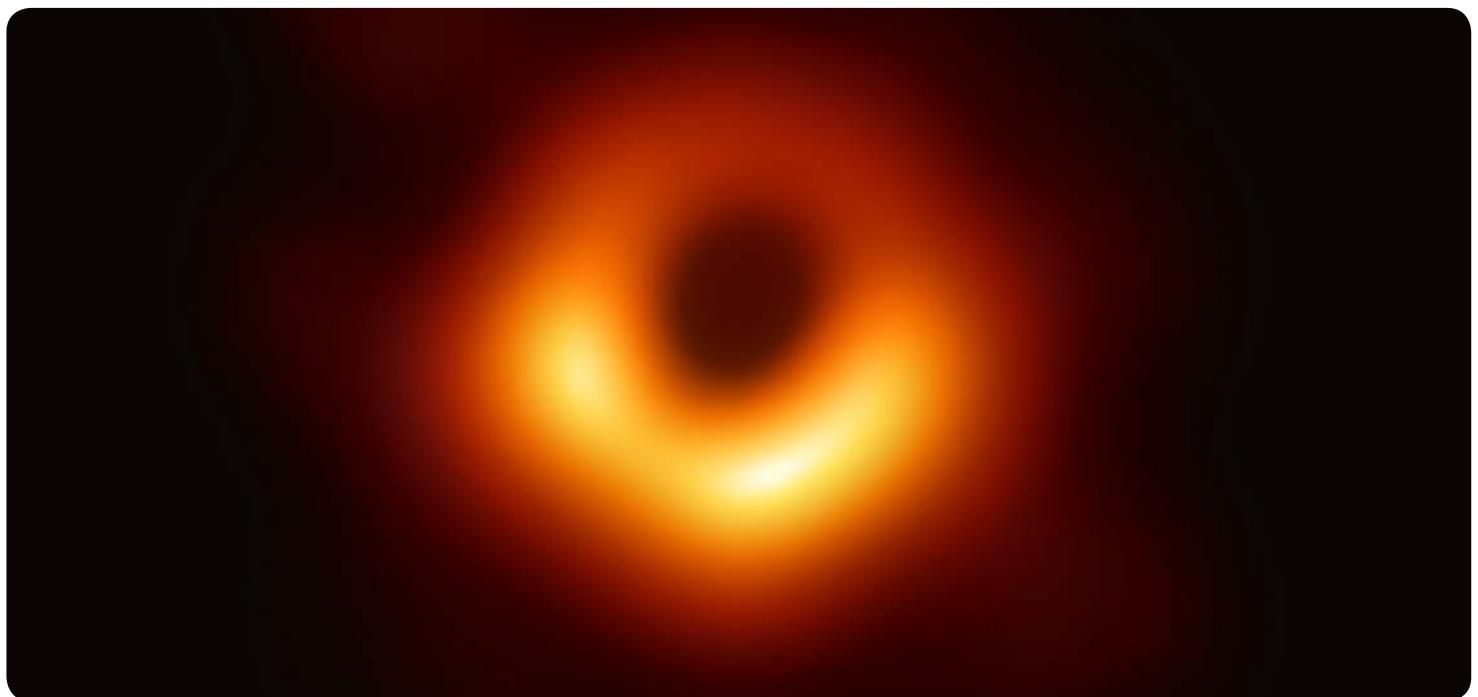
### ALMA on the Web

[science.nrao.edu/facilities/alma](http://science.nrao.edu/facilities/alma)  
[www.almaobservatory.org](http://www.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. The ALMA Development Roadmap\* outlines a roadmap for future developments that will significantly expand ALMA's capabilities and enable it to produce even more exciting science in the coming decades. The Roadmap offers a vision of new and expanded science drivers surpassing the original fundamental science goals of ALMA, which have been essentially achieved in the first five years of ALMA operations. The roadmap has evolved from input on new scientific directions and technical feasibility of future developments from the ALMA Science Advisory Committee (ASAC), the community, and technical documents.

\* Issued as ALMA Memo 612. [http://go.nrao.edu/ALMA\\_Roadmap](http://go.nrao.edu/ALMA_Roadmap)



*Above:* ALMA played a critical role in the science mission of the Event Horizon Telescope (EHT), an international collaboration that created a planet-scale array of eight ground-based telescopes. This stunning image represents the first direct visual evidence for the M87 supermassive black hole and its shadow. Credit: EHT Collaboration.

*Left:* Composite image of the protoplanetary disk PDS70 and its components as seen by ALMA and the VLT. PDS70c is a belt of dust encircling the planet which may give rise to a system of moons, like those found around the Solar System's giant planets.

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

### ALMA on the Web

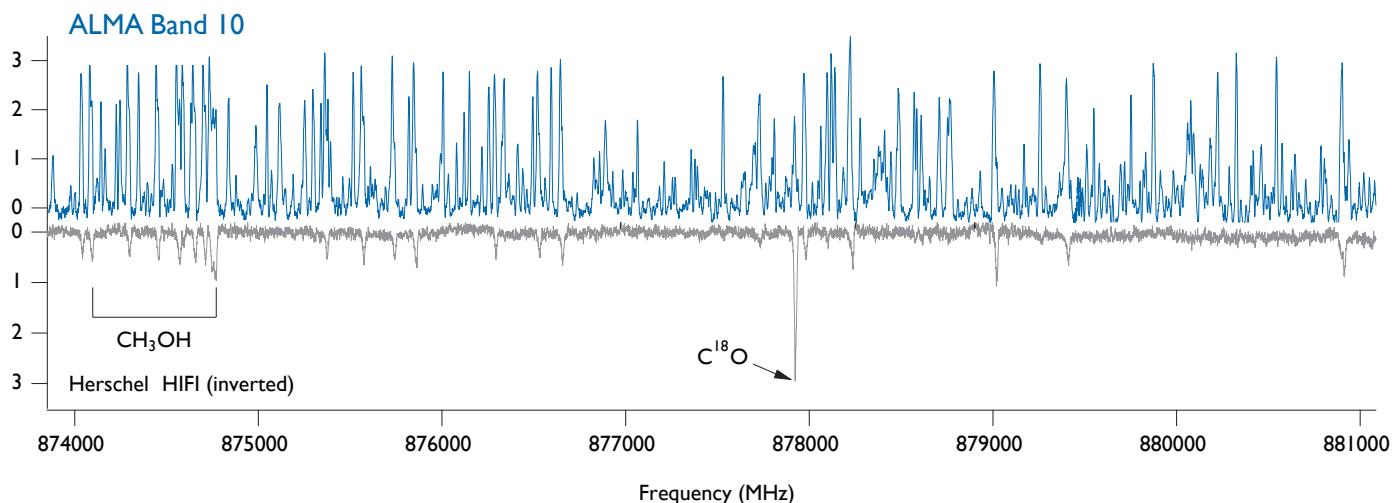
[science.nrao.edu/facilities/alma](http://science.nrao.edu/facilities/alma)

### ALMA Science Portal

[almascience.nrao.edu](http://almascience.nrao.edu)

### NAASC on the Web

[science.nrao.edu/facilities/alma/intro-naasc](http://science.nrao.edu/facilities/alma/intro-naasc)



The upper blue portion of this graph shows the spectral lines ALMA detected in a star-forming region of the Cat's Paw Nebula. The lower black portion shows the lines detected by the European Space Agency's Herschel Space Observatory. The ALMA observations detected more than ten times as many spectral lines. Note that the Herschel data have been inverted for comparison. Two molecular lines are labeled for reference. Credit: NRAO/AUI/NSF; B. McGuire et al.

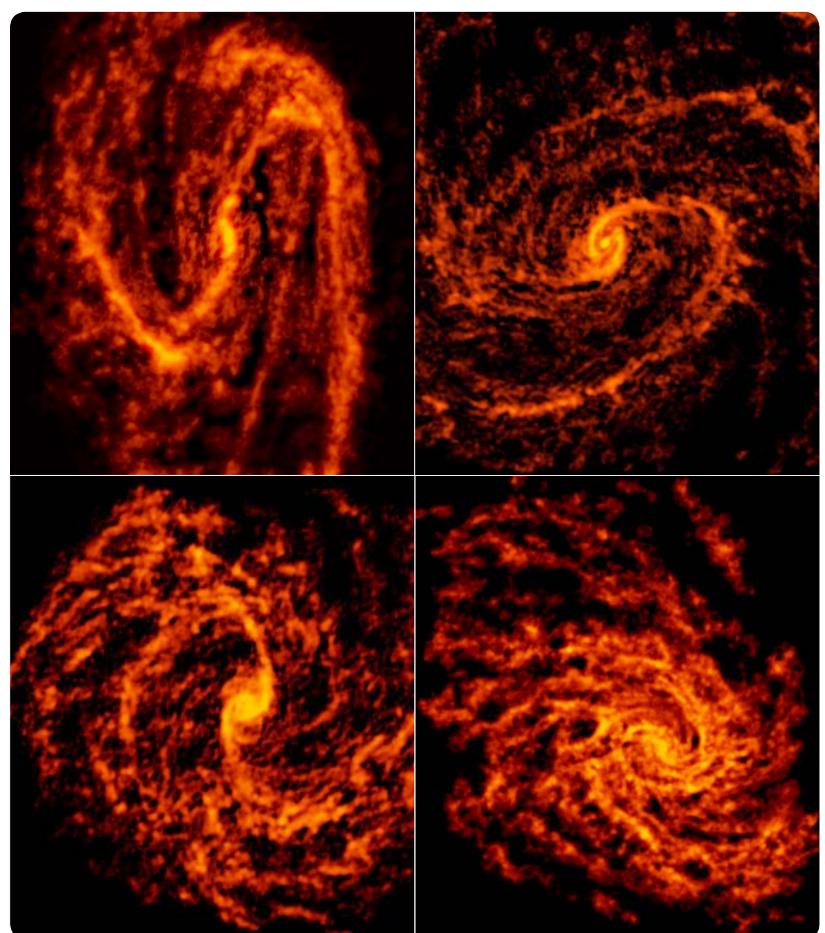
Several programs are under development for upgrades which may be implemented soon.

- Very Long Baseline interferometry has been offered for several Cycles (at 3mm and at 1.3mm). A new Development Program will expand phased ALMA capabilities to Band 7, to spectral lines, and to weaker sources.
- An upgrade to ALMA's 'bread-and-butter' Band 6 (1.3mm) has been proposed to realize all three ALMA2030 science goals; it has passed its conceptual design review and remains under study. It will provide greater tuning flexibility and improved noise performance across a wider IF range.
- The current allowed Band 6 IF 4.5-10 GHz will be upgraded to at least 4-12 GHz (under study)

A new Call for Development Studies was released 1 December 2019. A detailed description of the process and requirements can be reviewed on the Call for Proposals for Development Projects website.

In Cycle 7, eight highly ranked development proposals funded 33 investigators at ten institutions. The set was comprised of five hardware studies and three software studies.

Other enhancements are documented in reports at the ALMA Development website: <https://science.nrao.edu/facilities/alma/alma-develop>

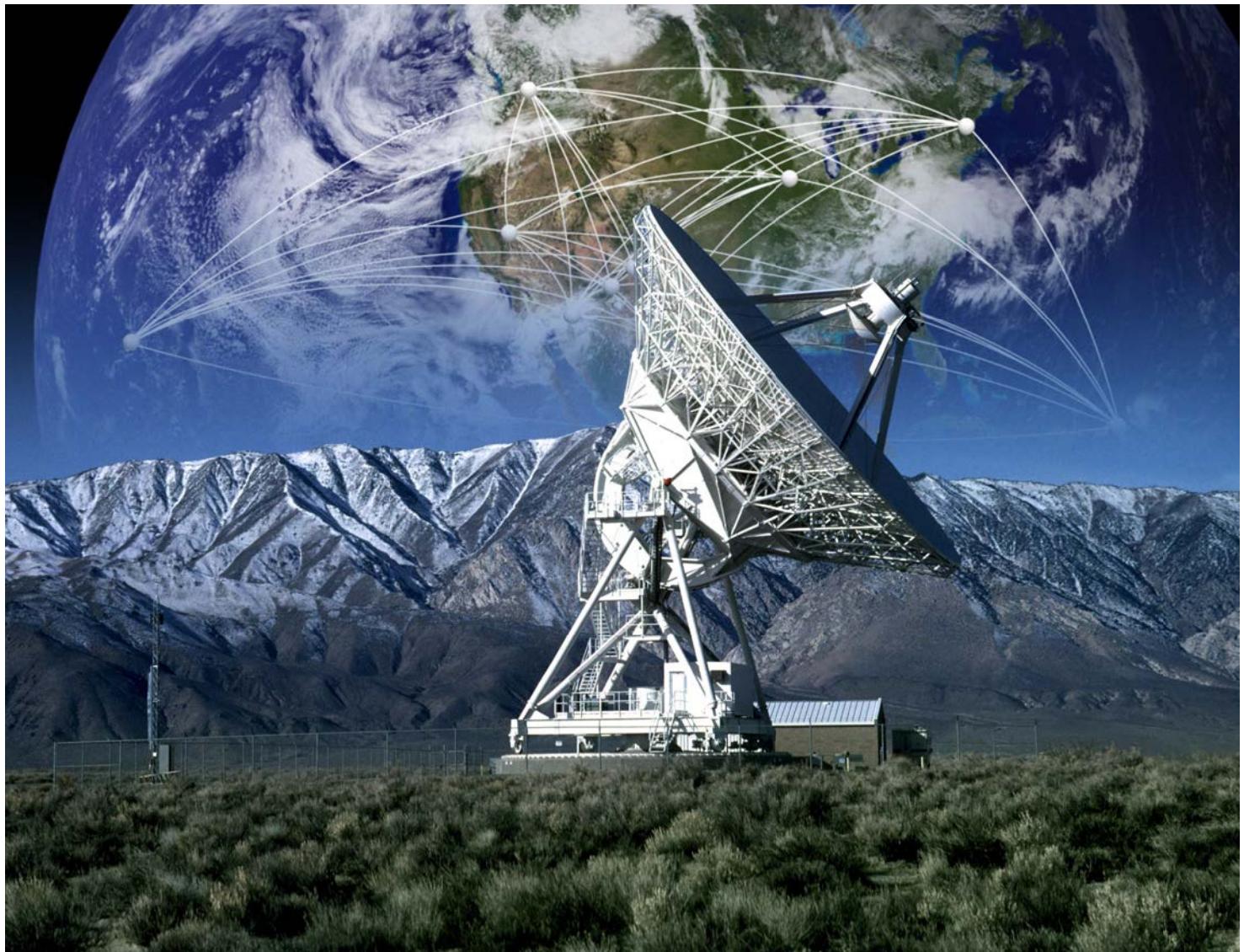


Four of the 74 galaxies imaged in the CO molecule as part of the PHANGS large program to measure properties of star-forming clouds in disk galaxies. Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton

## 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 (Mauna Kea, Hawaii to St. Croix, Virgin Islands), controlled remotely from the Domenici Science Operations Center in Socorro, New Mexico. The array can be scheduled dynamically, taking into account predicted weather conditions across the array.



Ten discrete observing bands are available, 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, the William E. Gordon Telescope in Arecibo, Puerto Rico, and the Max-Planck-Institute for Radio Astronomy telescope in Effelsberg, Germany. In addition, based on recent, successful tests, 3 mm VLBI including the Large Millimeter Telescope at Alfonso Serrano in Mexico is also possible. Together, these facilities form the High Sensitivity Array (HSA), available to astronomers by submission of a single proposal.

## 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.

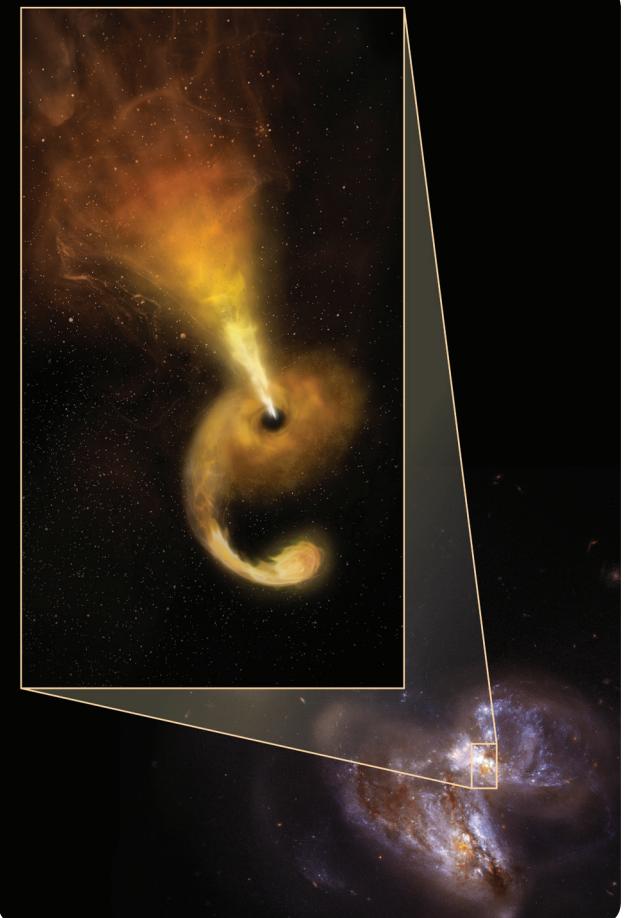
Distance measurements to  $\sim$ 400 high-mass star-forming regions will substantially improve our understanding of the three-dimensional structure of the Milky Way. This program is also measuring the fundamental parameters of Galactic rotation, helping to quantify the distribution of luminous and dark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

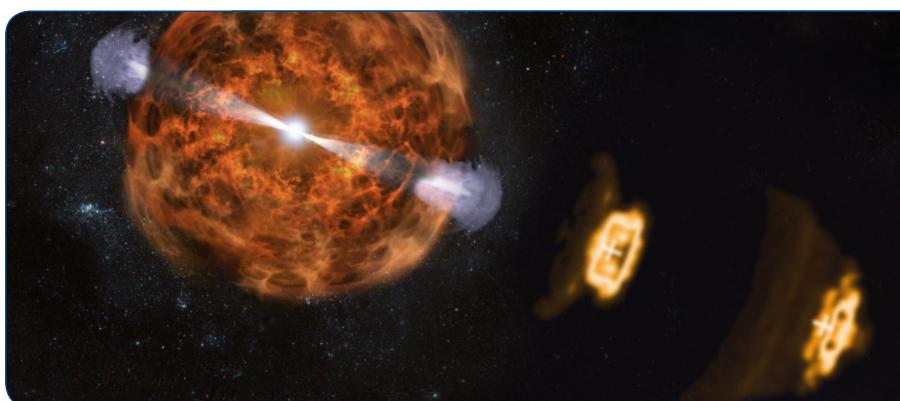
Distance measurements on a much larger, extragalactic scale are also encompassed in the VLBA's scientific program. A geometric technique applicable to galaxies with active nuclei, and H<sub>2</sub>O megamasers in their peripheral regions, has been used to determine distances of tens of megaparsecs with 3% accuracy, leading to an improved (and independently determined) value of the Hubble Constant.

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.

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.



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



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

## VLBA on the World Wide Web

<http://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) 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

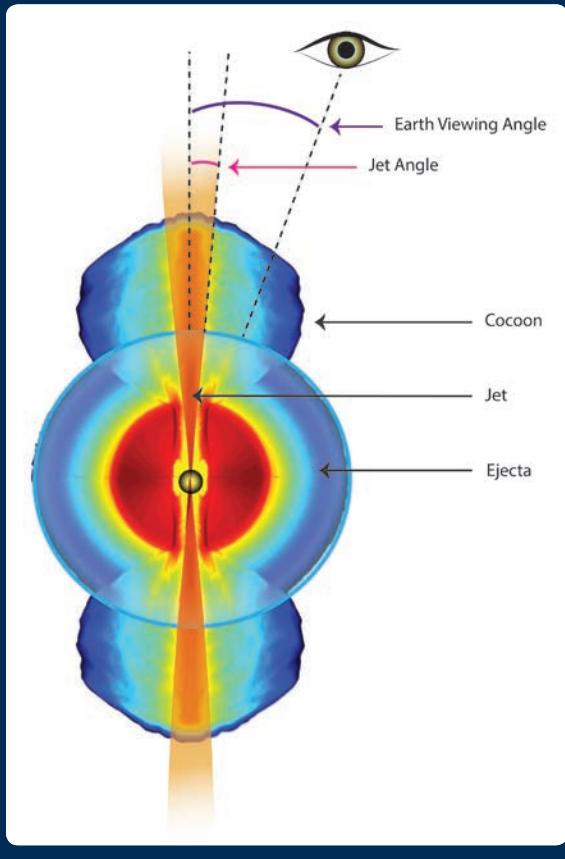
Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The VLA observes through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young stellar objects, 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 LSST), as well as providing an electromagnetic perspective on events discovered using other messengers (such as gravity waves from Advanced LIGO).

## Karl G. Jansky VLA on the World Wide Web

<http://science.nrao.edu/facilities/vla>



The merger of two neutron stars created the gravitational wave event GW 170817. Ejecta from an initial explosion formed a shell around the black hole formed from the merger. A jet of material propelled from a disk surrounding the black hole first interacted with the ejecta material to form a broad “cocoon.” Later, the jet broke through to emerge into interstellar space, where it emitted radio (and X-ray) synchrotron radiation. Credit: Sophia Dagnello, NRAO/AUI/NSF.

The VLA plays a significant role in the emerging field of multi-messenger astronomy. Electromagnetic radiation from gamma-rays to radio waves were detected from the gravitational wave event GW 170817, formed by the coalescence of two neutron stars into a black hole. The VLA was the first to discover radio emission which originated from shocks within the high-velocity ejecta. For more than 13 months, the VLA tracked the evolution of the non-thermal “afterglow” from GW 170817. Important constraints have come from this work, including the geometry of the ejecta, the orientation of the binary orbital plane, the kinetic energy of the ejecta, and the ambient density (e.g. Mooley et al. 2017, Nature 554, 207; Mooley et al. 2018, Nature, 561, 355). Together this evidence has strengthened the long-suspected link between neutron star mergers and short, hard gamma-ray bursts.

Thanks to its excellent sensitivity and resolution, we expect that the VLA will continue playing a lead role in detecting, localizing, and studying the electromagnetic counterparts of gravitational wave events. The VLA is rather unique among radio telescopes in that it can search for counterparts with three different techniques; on-the-fly mosaicing (OTF) for large error regions, rapid snap-shot images of all galaxies in the LIGO/Virgo redshift volume, and deep integrations toward well-localized counterparts found at other wavelengths. This flexible observing strategy provides a comprehensive approach to probe the diverse merger remnants and their afterglows, including the as yet unstudied black hole-neutron star coalescence events.

## 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.

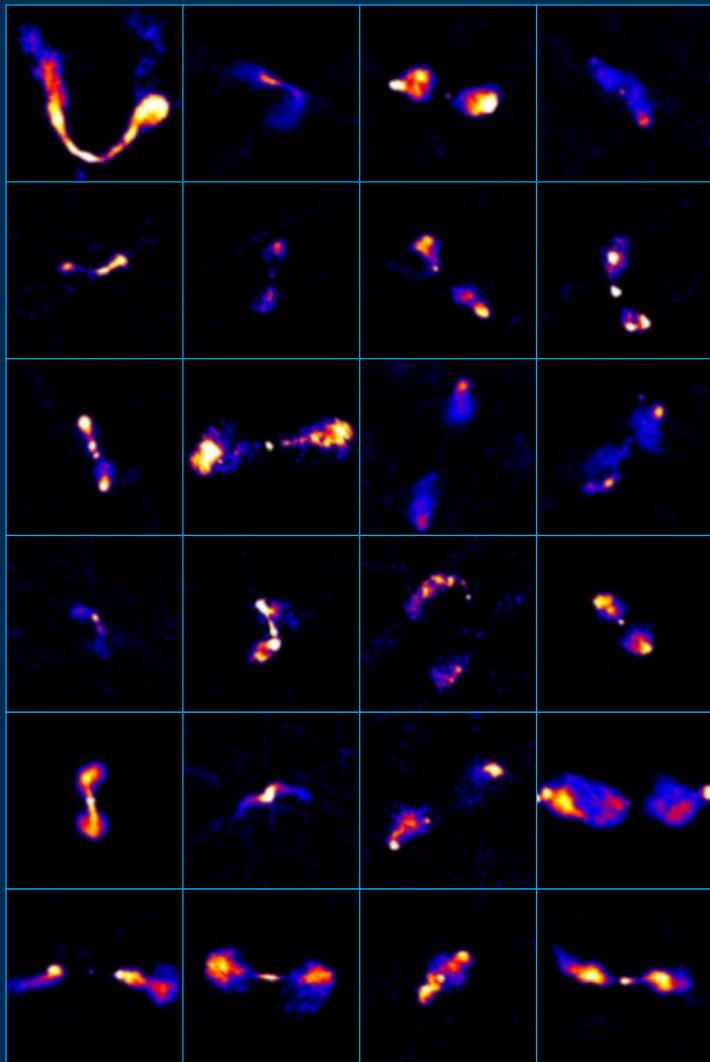
### RECEIVER BANDS

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)

In collaboration and consultation with the astronomy community, NRAO has begun a new survey of the radio sky that is the highest resolution all-sky radio survey ever undertaken. The survey will use about 5500 hours over seven years to cover the sky three times, with a cadence of 32 months. 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 will also be 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 I.I Quick Look images, where all the images shown are 2 arcminutes on a side. Credit: Brian Kent, NRAO/AUI/NSF

**Hidden Explosions:** The VLASS will open up new parameter space for finding supernovae, 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.

Observing for the first half of the first epoch, VLASS I.I, is complete, and Quick Look images are available for the approximately 16,900 square degrees covered. Above is a sample of radio galaxies from VLASS I.I Quick Look images, where all the images are 2 arcminutes on a side. Further information can be found at the website below.

### VLASS on the Web

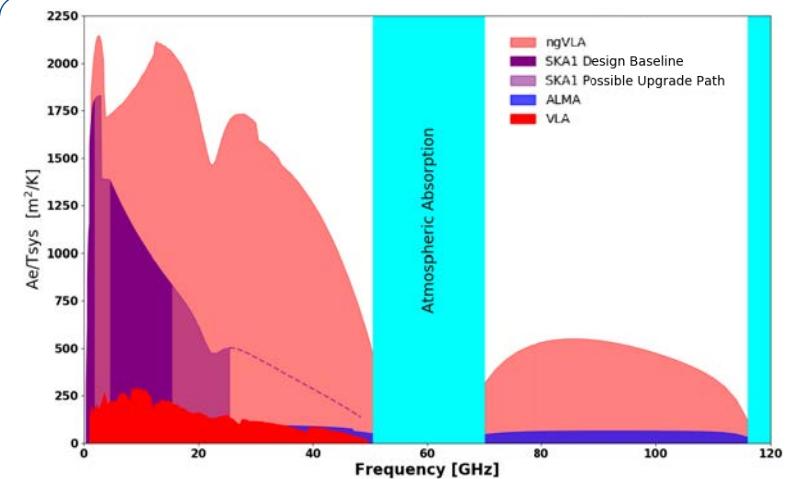
<https://science.nrao.edu/science/surveys/vlass>

## NEXT GENERATION VERY LARGE ARRAY (ngVLA)

Inspired by the dramatic discoveries from the Jansky Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Atacama Large Millimeter/ submillimeter Array (ALMA), the community has initiated discussion of a future large area radio telescope optimized for imaging of thermal emission to milli-arcsecond scales that will open new discovery space from proto-planetary disks to distant galaxies. This next generation Very Large Array (ngVLA) is currently envisioned to include: (a)  $\sim 10$ x the sensitivity of the VLA and ALMA at comparable bands; (b) frequency coverage spanning 1.2 – 116 GHz; (c) interferometric baselines reaching across North America and beyond; and (d) a dense antenna core on km-scales along with a short baseline array of even smaller antennas providing high surface brightness imaging.

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 next generation VLA (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 SAC and TAC are the cornerstones of a program to fully engage the astronomical, computing, and radio engineering communities to develop the ngVLA project for submission to the Astro2020 Decadal Survey.

NRAO 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 of the VLA well into the next decade and beyond. Please visit the ngVLA website for additional information.



Frequency coverage and sensitivity of the centimeter-to-submillimeter wavelength ground-based facilities envisaged to be operational in the 2030's. The ngVLA will be optimized for observations at wavelengths between the exquisite submillimeter wavelength performance of ALMA, and the future centimeter wavelength performance of the Square Kilometre Array-Phase I. The ngVLA will be highly complementary with these facilities. As such, the ngVLA will open a new window on the Universe via ultra-sensitive imaging of thermal line and continuum emission down to milli-arcsecond resolution, and will deliver unprecedented broadband continuum polarimetric imaging of non-thermal processes.



An artist's interpretation of the inner few tens of astronomical units (AUs) around a proto-planetary disk similar to HL Tauri, where ALMA has revealed the rings in 1.3 mm dust continuum emission likely created by Saturn-mass planets orbiting the central star. Detecting planets in the terrestrial planet forming region (1-10 AU) requires longer wavelength observations and higher angular resolution than available with ALMA. The Jansky VLA observations map the 7mm emission from the innermost and densest disk region probing the distribution of pebbles at a spatial resolution of 10 au. Owing to its unprecedented angular resolution at millimeter and centimeter wavelengths, the ngVLA will peer into the innermost and highly obscured dusty regions not accessible by ALMA and the VLA. The ngVLA will reveal the presence of planets with masses as small as a few Earth masses on spatial scales as small as 1 AU.

**ngVLA on the Web**

<http://ngvla.nrao.edu/>



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



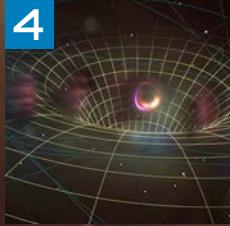
Astrochemistry & Life

3



Galaxies Across Cosmic Time

4



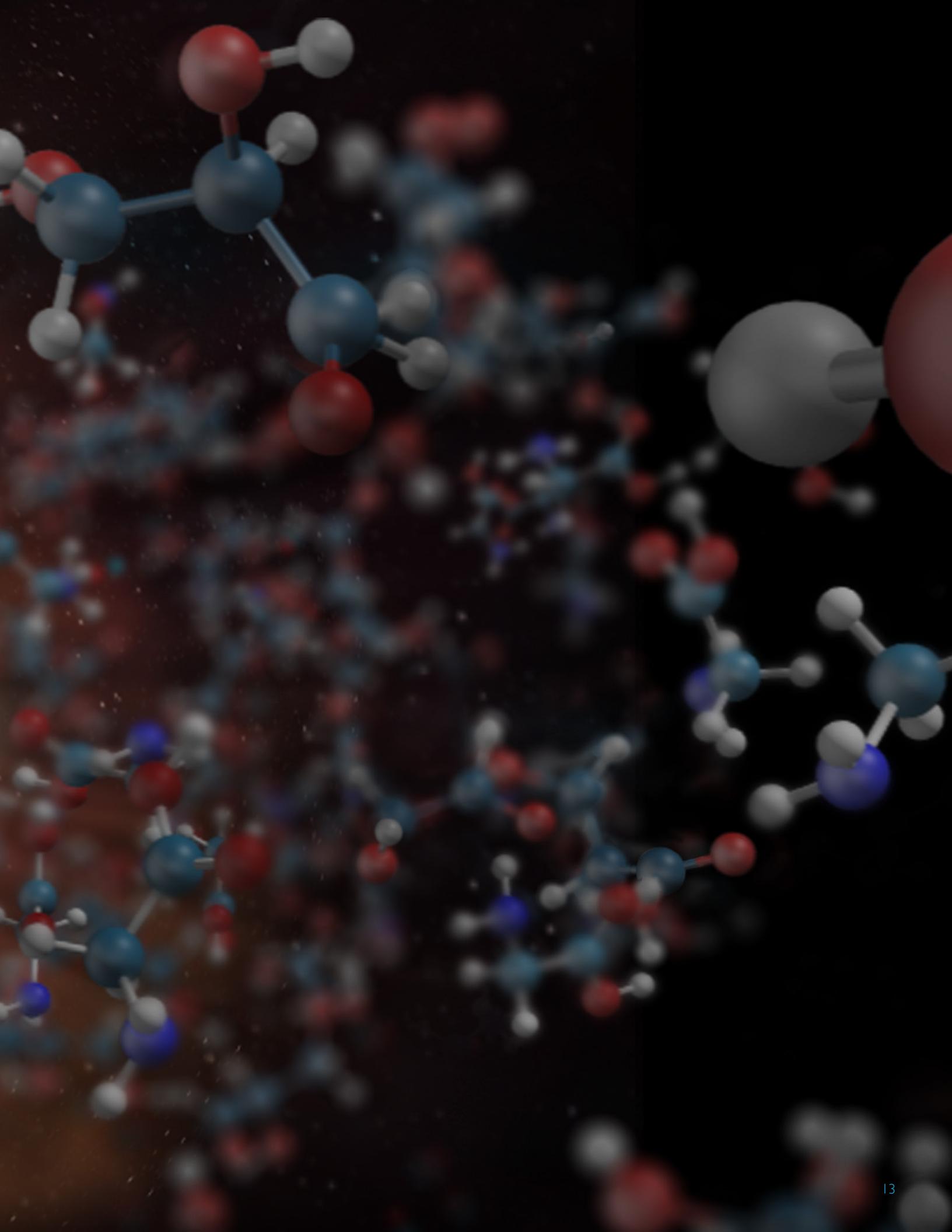
Fundamental Physics

5



Multi-messenger Astrophysics

[ngvla.nrao.edu](http://ngvla.nrao.edu)



## 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, and upgrades to these instruments. CDL maintains a staff of

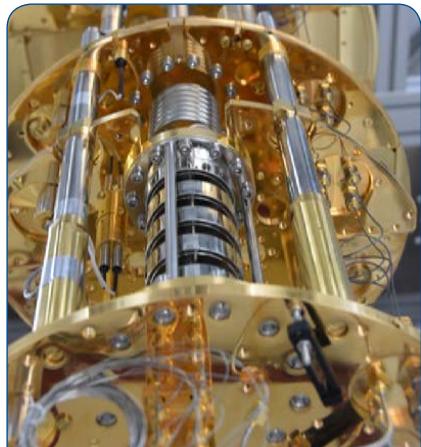
so another important mission of the laboratory is providing maintenance and upgrades to these instruments. CDL maintains a staff of approximately fifty personnel organized into teams of engineers and technicians working across crucial radio telescope technologies, including: digital design and signal 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. Two ALMA Strategic Studies and a technology development project for NRAO's proposed next generation Very Large Array (ngVLA) exemplify our current leading-edge work: (a) research into superconducting quantum-limited very-wideband 4 Kelvin RF and IF amplifiers for ALMA; (b) development of wideband low-noise balanced IF amplifiers for ALMA; and (c) the development of an application-specific integrated circuit (ASIC) for a novel, patented serial analog-to-digital convertor (SADC).

### Local Oscillators (LO)

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.

### Low Noise Amplifiers

CDL produces the world's lowest 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.



The BlueFors dilution refrigerator for testing TKIP amplifiers. These superconducting devices have the potential to revolutionize millimeter wave astronomy.

### 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 Microfabrication Laboratory (UVML). 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 UVML 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.

CDL is working with 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

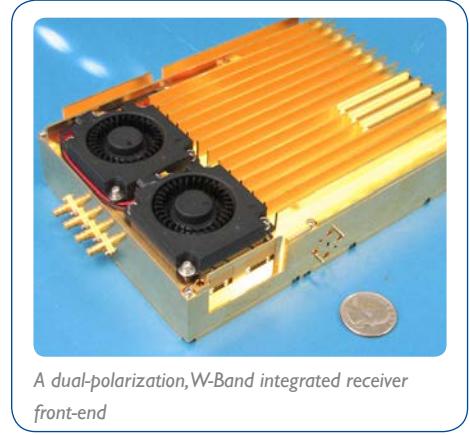
Receiver optics and electromagnetic components – including feeds, orthomode transducers, polarizers, and phase shifters – are crucial to the sensitivity, beam quality, and polarization purity of radio telescopes. The CDL designs and builds these critical passive components, including broadband feeds, to maximize the sensitivity of mm- and cm-wavelength radio astronomy instruments.

## 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 and 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.

## 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. 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.



A dual-polarization, W-Band integrated receiver front-end

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.

## Characterizing Cosmic Dawn

The CDL Low Frequency Radiometer Group (LFRG) 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. The LFRG is introducing the next generation of researchers to instrument development methods via a unique, hands-on learning experience. High school students to post-docs are learning to create new instruments using modern design tools, fabricating the equipment, verifying its laboratory performance, deploying the instrument to a field, and analyzing the experiment data.

The LFRG is actively engaged in the development of antenna feeds and beam characterization methods for the Hydrogen Epoch of Reionization Array deployed in South Africa that will detect hydrogen in the early Universe. The Cosmic Twilight Polarimeter, an NRAO – University of Colorado collaboration, introduces new calibration concepts and measurement strategies to detect neutral hydrogen during the Cosmic Dawn epoch, and is laying groundwork for a lunar-orbiter to more accurately make this key measurement. With the University of Washington, radio frequency components that operate at cryogenic temperatures are being developed to assist the Axion Dark Matter eXperiment in its search for this postulated particle.

## Developing The Next Generation Radio Astronomy Engineer

CDL supports two NRAO Jansky Post-doctoral Fellowships. These post-docs spend ~75% of their time on self-directed research in broad support of CDL's mission of developing the next generation of radio astronomy instrumentation. These researchers are exploring new techniques in electromagnetics engineering and digital signal processing. CDL also has a co-op program for advanced undergraduate and graduate engineering students, and the laboratory also supports short- and long-term internship positions.

## CDL on the World Wide Web

<http://science.nrao.edu/facilities/cdl>

## Student & Visitor Programs

### Summer Student Programs



Summer students conduct research under the supervision of scientific staff members at the NRAO in Socorro, NM and Charlottesville, VA, and at the Green Bank Observatory 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. Summer students also have the opportunity to participate in a summer school with hands-on observing, a lecture series, and other educational opportunities.

NRAO hosts several summer student programs, including the Research Experiences for Undergraduates (REU) program, the NRAO Undergraduate Summer Student Research Assistantship program, the National Astronomy Consortium program, and Physicists Inspiring the Next Generation. In addition, graduate students are eligible to apply for the NRAO Graduate Summer Student Research Assistantship program. 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 1 February 2020.**

### Co-op Program

Each semester the NRAO sponsors one or more paid undergraduate students in a Co-op program, usually hosted at the Socorro site. These co-op students, normally juniors and seniors, spend one or more semesters working with an NRAO mentor. Typical co-op 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 NRAO Grote Reber Doctoral Fellowship Program enables Ph.D. students in the final years of their thesis to conduct research at an NRAO site, either in Socorro or Charlottesville, under the supervision of an NRAO advisor. The program is jointly sponsored by the NRAO 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 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 during the year: in April for a September start, and July for a January start. The application deadline is announced via an email to NRAO staff and affiliates. Prospective students are encouraged to seek the support of an NRAO 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.

### **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) student 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 3 February 2020.**

### **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 under-represented 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.

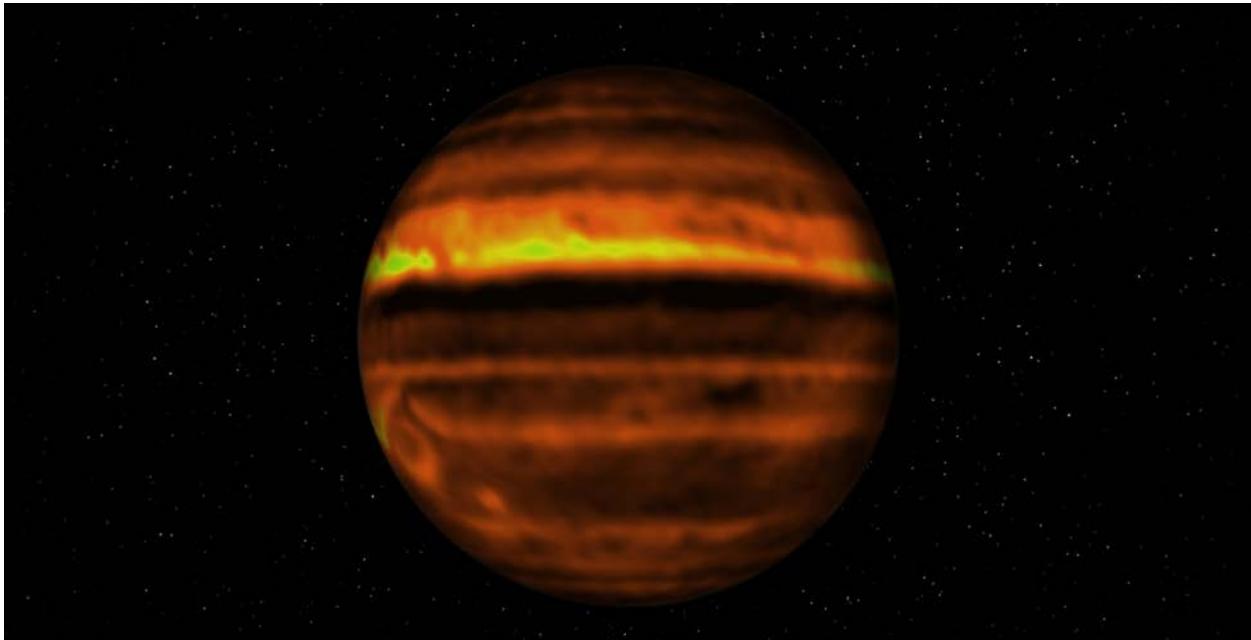
Visit [go.nrao.edu/NINE](http://go.nrao.edu/NINE) for more information about the program.



*Students from the University of the West Indies, Trinidad and Tobago, participate in an NRAO-NINE workshop on radio astronomy and data science.*

## **NRAO Student & Visitor Programs on the World Wide Web**

[http://science.nrao.edu/opportunities](https://science.nrao.edu/opportunities)



The National Radio Astronomy Observatory  
is a facility of the National Science Foundation  
operated by Associated Universities, Inc.

[science.nrao.edu](http://science.nrao.edu)

[public.nrao.edu](http://public.nrao.edu)

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.

<https://go.nrao.edu/ODI>

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