NATIONAL RADIO ASTRONOMY OBSERVATORY

RESEARCH FACILITIES *for the* SCIENTIFIC COMMUNITY

2017

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array

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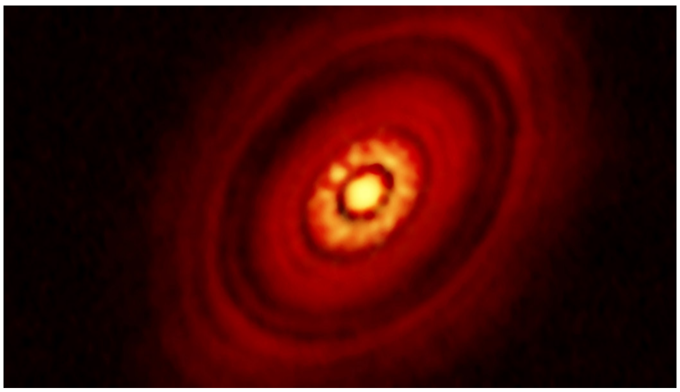
RESEARCH FACILITIES 2017



(above image)

VLA images of HL Tau (yellow) combined with ALMA image (red) reveal a distinct clump of dust in the inner region of the disk. Researchers believe this clump represents the earliest stage in the formation of protoplanets. Credit: Carrasco-Gonzalez, et al.; Bill Saxton, NRAO/AUI/NSF

(cover)

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. 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. Credit: A. Angelich, B. Saxton, C. Brogan; NRAO/AUI/NSF; ALMA (ESO/NRAO/NAOJ)

(back cover)

Spectacular jets powered by the gravitational energy of a supermassive black hole in the core of the elliptical galaxy Hercules A illustrate the combined imaging power of two of astronomy's cutting-edge tools, the Hubble Space Telescope's Wide Field Camera 3, and the recently upgraded Karl G. Jansky Very Large Array (VLA) radio telescope in west-central New Mexico. Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA).

NRAO Overview

The National Radio Astronomy Observatory (NRAO) is delivering transformational scientific capabilities and operating two world-class telescopes that are enabling the astronomy community to address the science objectives described in the Astro2010 Decadal Survey report, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH).

The NRAO telescope suite includes the Atacama Large Millimeter/submillimeter Array (ALMA) and the Karl G. Jansky Very Large Array (VLA). 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 address many of the NWNH science themes, 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 4 Early Science began in October 2016. The ALMA Cycle 5 Call for Proposals is expected in March 2017.

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.

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 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 NWNH science goals, such as the detection of gravitational waves via pulsar timing and the study of the epoch of reionization.

After more than five 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.

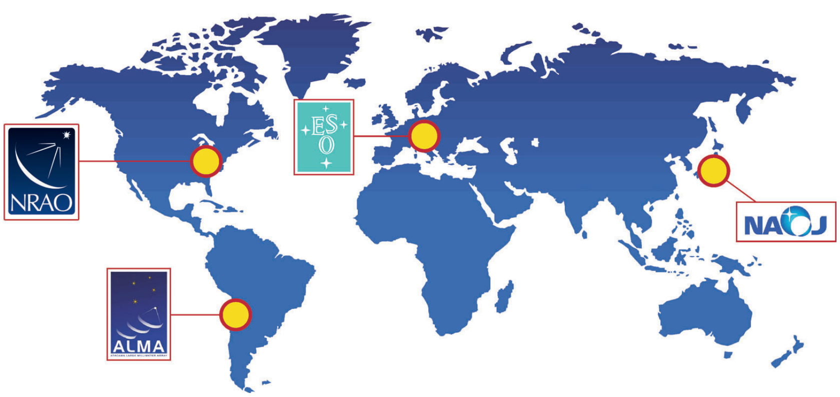
Atacama Large Millimeter/ submillimeter Array (ALMA)

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 PI science observations for Cycle 4, which runs from October 1, 2016 through September 30, 2017. Cycle 4 observations employ at least 40 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 4 extend up to 12.6 km, depending on the frequency band being used. The Call for Proposals for Cycle 5 will be issued in March 2017 and the proposal deadline is expected in April 2017 for observations that will begin in October 2017. The Call for Proposals and other documentation are available on the ALMA Science Portal: http://almascience.nrao.edu. As ALMA approaches Full Operations, it is already the most sensitive and capable millimeter interferometer in the world.



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 Council of Taiwan (NSC) 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 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

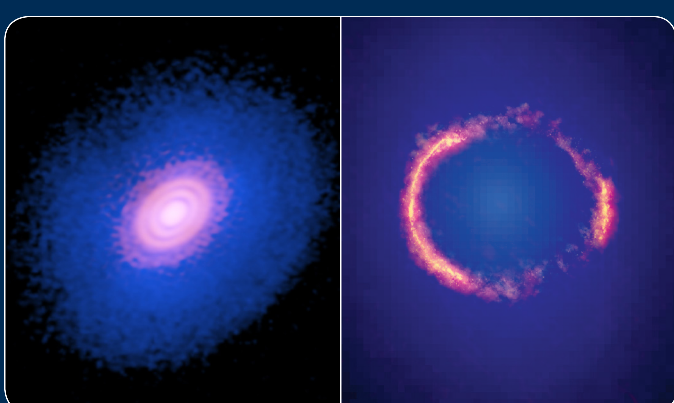
ALMA is designed to accomplish, at a minimum, three "Level 1" science goals: (1) detect CO/C+ in less than 24 hours from a normal galaxy like the Milky Way at redshift z = 3; (2) resolve protoplanetary disks around stars at a distance of 150 pc; and (3) provide precise imaging at submillimeter wavelengths with 0.1" resolution, where the sky brightness is accurately represented for all points above 0.1% of the peak flux in the map. ALMA will be capable of high fidelity imaging both in continuum and in spectral lines. It has wideband frequency coverage (8 GHz in dual polarization) and is capable of imaging fields larger than the primary beam using mosaics.

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

RECEIVER BANDS

Band #	1	3	4	5	6	7	8	9	10
Frequency Range (GHz)	35-51	84 - 116	125 - 163	163 - 211	211 - 275	275 - 373	385 - 500	602 - 720	787 - 950
Wavelength Range (mm)	8.6-5.9	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 4	Full Operations
Antennas	>40 x 12 m; 10 x 7 m; 3 x 12 m TP	50 x 12 m; 12 x 7 m; 4 x 12 m TP
Bands	Bands 3, 4, 6, 7, 8, 9, 10	Bands 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Continuum Bandwidth	7.5 GHz x 2 pol	7.5 GHz x 2 pol
Finest spectral resolution at 100 GHz	0.01 km/s	0.01 km/s
Maximum Angular Resolution	0.02" (λ /1 mm)(10 km/max baseline)	0.02" (λ /1 mm)(10 km/max baseline)
Maximum Baseline	12.6 km (depends on Band)	15 km
Continuum Sensitivity (60 sec, Bands 3 – 9)	~ 0.08 – 1.7 mJy/beam	~ 0.06 – 1.4 mJy/beam
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 – 9)	~ 12 – 98 mJy/beam	~ 10 – 78 mJy/beam



***Far left:** Composite image of the star HD 163296. The inner red area shows the dust of the protoplanetary disk. The broader blue disk is the carbon monoxide gas in the system. ALMA observed that in the outer two gaps in the dust, there was a significant dip in the in the concentration of carbon monoxide, suggesting two planets are forming there. ALMA (ESO/NAOJ/NRAO); A. Isella; B. Saxton (NRAO/AUI/NSF) **Left:** An ALMA/HST composite image of the gravitationally lensed galaxy SDP.81. The brightest orange features in the center of the ring reveal glowing dust emission, and represent the highest resolution observation yet made with ALMA. Emission from carbon monoxide is represented as the more diffuse orange component in the ring. Shown in blue is the foreground lensing galaxy, imaged with the Hubble Space Telescope. Credit: ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF; NASA/ESA Hubble, T. Hunter (NRAO).*

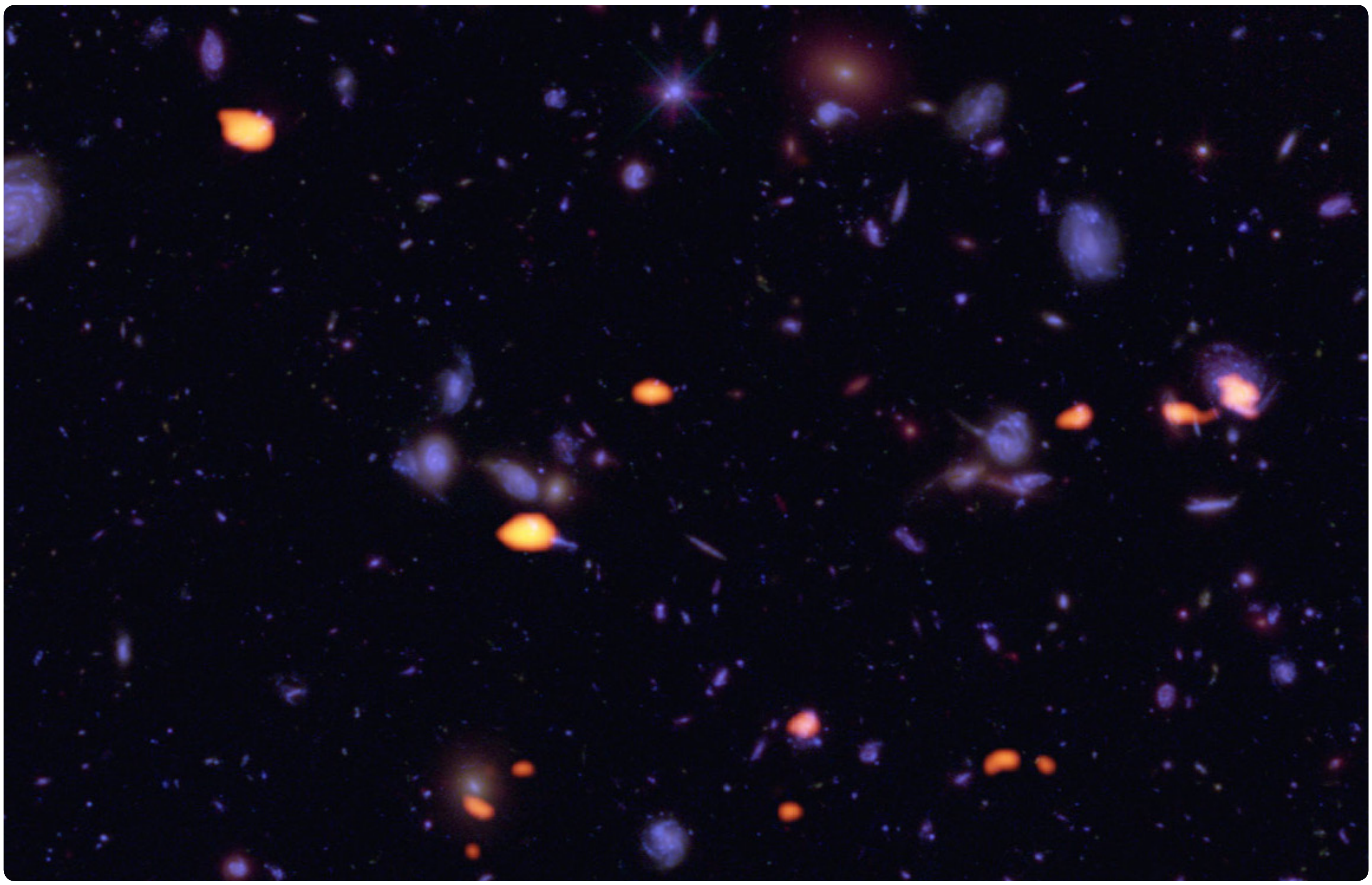
ALMA on the World Wide Web
http://science.nrao.edu/facilities/alma
http://www.almaobservatory.org

ALMA Science Portal
http://almascience.nrao.edu

NAASC on the World Wide Web
http://science.nrao.edu/facilities/alma/intro-naasc

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. Several potential ALMA Development programs have been identified by the science community in the document *ALMA2030: A Roadmap for Developing ALMA*, which is available on the ALMA Development website: http://science.nrao.edu/facilities/alma/alma-develop.



A trove of galaxies, rich in dust and cold gas (indicating star-forming potential) was imaged by ALMA (orange) in the Hubble Ultra Deep Field. The average galaxy seen by the Hubble Space Telescope is seen at an age similar to the age of the Milky Way, while the average galaxy seen by ALMA is at a much earlier age, i.e., as these galaxies were 10 billion years ago. Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); NASA/ESA Hubble

- Very Long Baseline Interferometry (VLBI) was offered in Cycle 4. Twenty-two VLBI proposals were submitted in Cycle 4 and nine – three at 3mm and six at 1.3mm – are scheduled for execution.

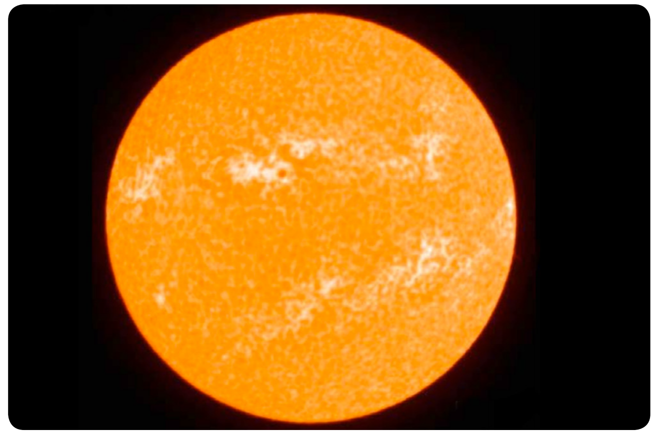
- Receivers for ALMA Band 5 (163-211 GHz) were constructed jointly by ESO and NRAO, led by ESO. Science Verification data is available at the ALMA science portal, and observing in the band will be offered in Cycle 5. Receivers for Band 1 (35-51 GHz) are under construction in East Asia with North American and Chilean participation.

• Solar observation capability was offered on ALMA in Cycle 4, enabled by studies involving community members from all partners. Fifty-three proposals for solar observing were received.

• A low bandwidth radio link was upgraded to fiber through a project led by the Joint ALMA Observatory (JAO) with funding from North America and Europe.

• The ALMA Data Mining Toolkit (ADMIT) is an archive enhancement created by the University of Maryland, University of Illinois, and NRAO that has now been deployed. ADMIT is a value-added Python software package that integrates with the ALMA archive and CASA to provide scientists with quick access to traditional science data products such as moment maps, as well as with new innovative tools for exploring data cubes and their many derived products.

• The ALMA complement of subarrays was increased from four to five.



ALMA total power image of the Sun obtained at 450 microns. ALMA's precision antenna surfaces are engineered to a thickness of a fraction of a human hair and maintain that precision even when heated by the tropical sun.

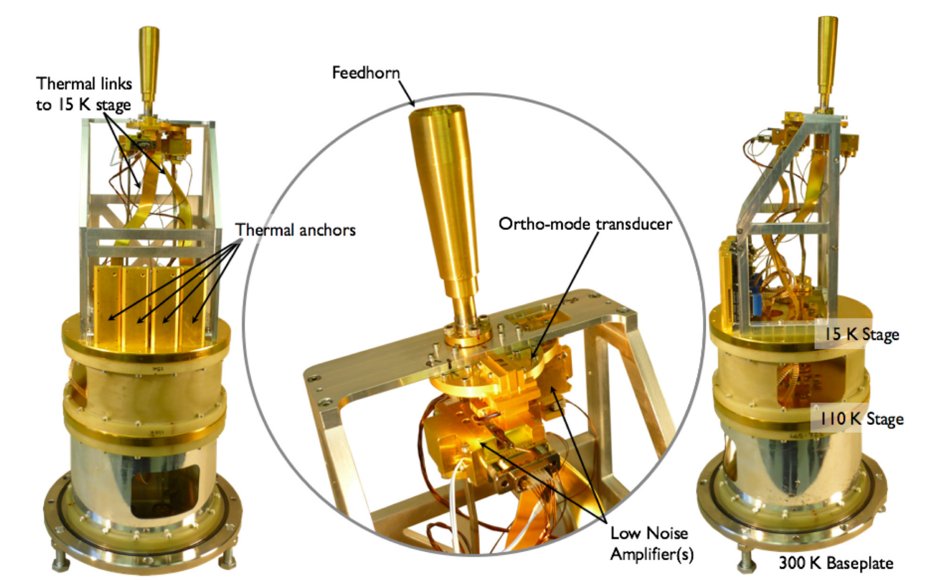
Several ALMA Development programs are underway that will define upgrades that may be implemented soon. An upgrade to the ALMA Correlator is under study which would: (a) increase the number of channels by 8X, enabling broader windows at high resolution; (b) double the sampling, increasing sensitivity; and (c) with digitization upgrades, double the current bandwidth to two sidebands with 8 GHz coverage and full polarization capability.

A receiver to cover 67-95 GHz using microwave integrated circuit (MMIC) elements has been developed at the CDL; this receiver can deliver the full upgraded bandwidth to the upgraded correlator.

Other enhancements are documented in reports at the ALMA Development website.

Call for Proposals

A Call for Proposals for ALMA Development Projects was released 10 October 2016. A detailed description of the process and requirements can be reviewed on the Call for Proposals for Development Projects website. The deadline for proposals will be 30 January 2017. The Cycle 5 ALMA Development Program is expected to include an integrated, multi-year award pool for North American development studies and projects that may total up to $14M USD.



ALMA Band 2+ prototype receiver developed, built and tested at the NRAO Central Development Laboratory (CDL) to cover 67-95 GHz and provide two sidebands and two polarizations, each covering 8 GHz, using microwave integrated circuit (MMIC) technology.

A new Call for Development Studies will be issued in March 2017 for Cycle 5 of the studies. In Cycle 4, six studies were funded from 32 investigators at ten institutions.

ALMA Development on the World Wide Web

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

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 1.0 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

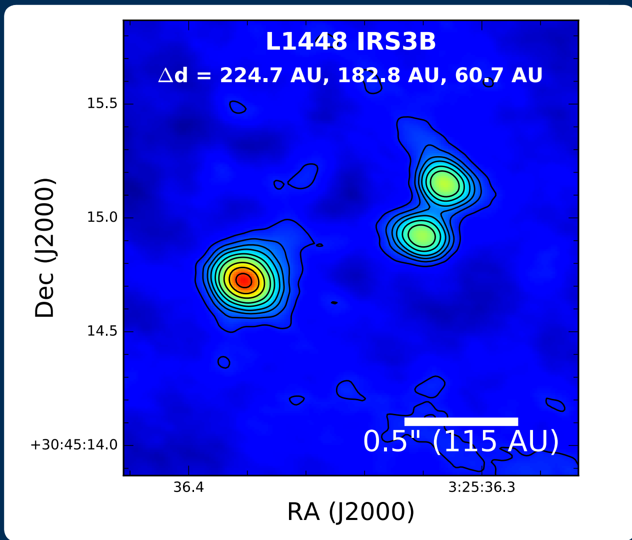
Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The VLA observes through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young stellar objects, 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 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).

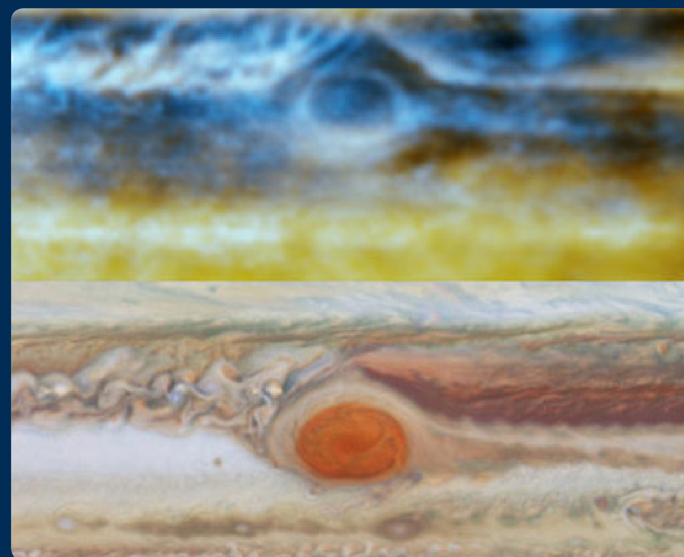
Karl G. Jansky VLA on the World Wide Web

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



Above: The high sensitivity and angular resolution of the VLA have enabled an unbiased survey of all known protostars in the Perseus molecular cloud (Tobin et al. 2016, ApJ, 818, 73). The results reveal substructures on different scales, indicating two separate stellar formation mechanisms. Turbulent fragmentation of the cloud leads to multiple star systems separated by thousands of AU. The protostellar disk around a newly forming star can further fragment by gravitational instability, leading to tightly spaced companion stars separated by just tens of AU as illustrated here.

Below: A VLA radio image (top) of Jupiter's famous Great Red Spot, a giant storm in the planet's atmosphere, and for reference a visible-light image (bottom) made with the Hubble Space Telescope. The VLA observations provided an unprecedented look into the atmosphere of Jupiter, revealing that features seen in visible light at the planet's cloud surfaces have effects tens of kilometers downward. The radio image shows the complex upwellings and downwellings of ammonia gas in a vertical range of over 100 kilometers below the visible clouds (de Pater et al. 2016, Science, 352, 1198).



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

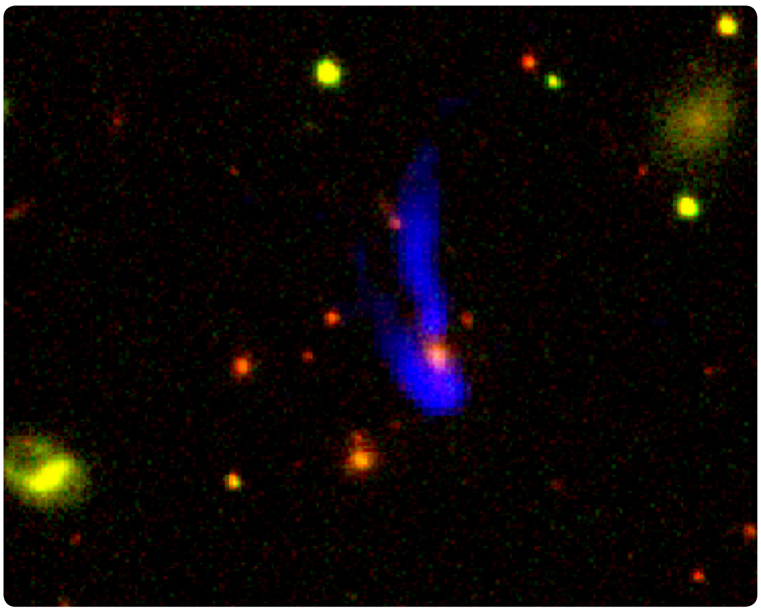
Band Name	4m	P	L	S	C	X	Ku	K	Ka	Q
Frequency Range (GHz)	0.058 - 0.084	0.22 - 0.50	1.0 - 2.0	2.0 - 4.0	4.0 - 8.0	8.0 - 12.0	12.0 - 18.0	18.0 - 26.5	26.5 - 40.0	40.0 - 50.0

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	7.4 microJy/beam
Continuum Sensitivity in 60 min, 8 GHz bandwidth at Q-band	9.6 microJy/beam
Spectral Line Sensitivity in 60 min, 1km/s (5 KHz) at 1.5 GHz	2.9 microJy/beam
Spectral Line Sensitivity in 60 min, 1km/s (150 KHz) at 45 GHz	1.9 microJy/beam

NEW INITIATIVES

VLA Sky Survey (VLASS)

With the new VLA capabilities NRAO, in collaboration and consultation with the astronomy community, is planning a new survey of the radio sky that will be the highest resolution all-sky radio survey ever undertaken. The survey will use about 5500 hr 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 (2-4GHz) in a single observation will allow 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, we will be able to find transient radio sources that appear or disappear during the survey period. In total, the VLASS will detect nearly 10 million radio sources, about four times more than currently cataloged. The key science areas for this survey are described below.



Sloan Digital Sky Survey (red/green) image overlay on VLASS pilot data (blue), obtained summer 2016. The improved resolution of VLASS over previous radio surveys allows classification of the radio source as a galaxy at z=0.25, possibly in a cluster.

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.

The survey is currently in its design phase in preparation for observing to begin in September 2017, subject to its successfully passing its design reviews. Further information can be found at the website below.

Next Generation Very Large Array (ngVLA)

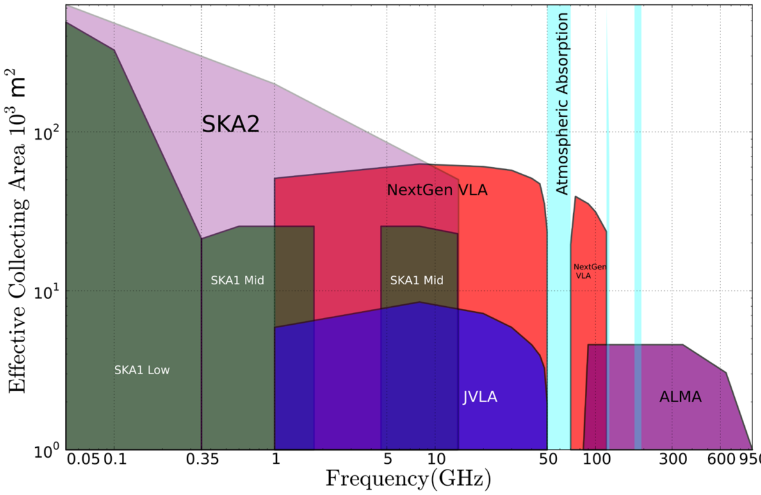
Inspired by dramatic discoveries from the Jansky Very Large Array (VLA) and the Atacama Large Millimeter/submillimeter Array (ALMA), the community has initiated discussion of a future large area radio array optimized for imaging of thermal emission to milli-arcsecond scales that will open new discovery space from proto-planetary disks to distant galaxies. This next generation Very Large Array (ngVLA) is currently envisioned to include: (a) ~10x the effective collecting area of the VLA and ALMA at comparable bands; (b) frequency coverage spanning

VLASS on the World Wide Web

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

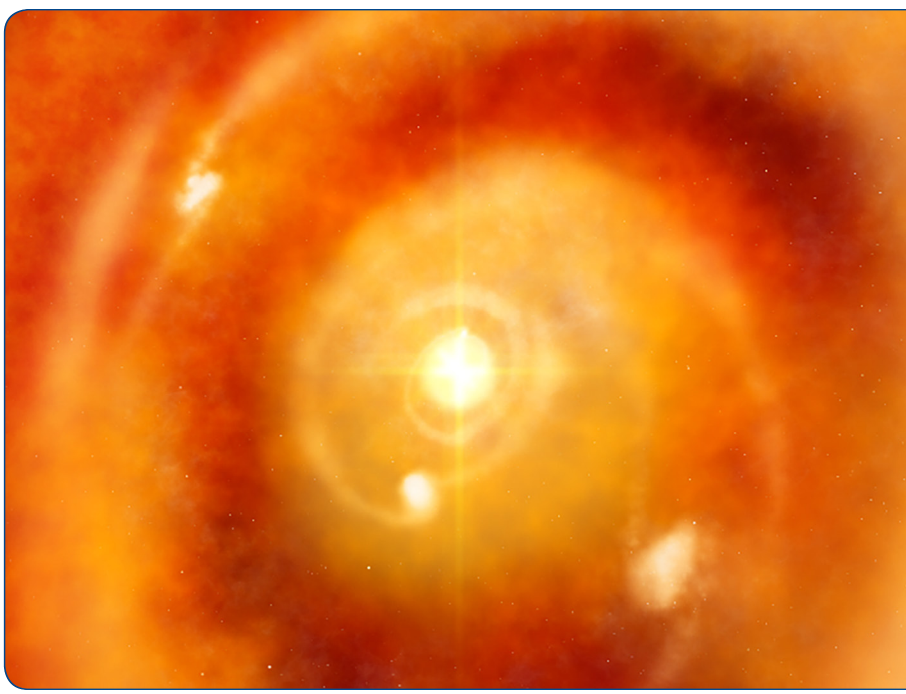
1.2 – 116 GHz; (c) interferometric baselines up to 300 km to achieve milli-arcsecond resolution, with consideration for longer baselines and Very Long Baseline Interferometry; and (d) a dense antenna core on km-scales providing high surface brightness imaging.

In an effort to ensure strong community engagement as the ngVLA moves towards a final design concept, NRAO has launched a Community Studies program and established an external Science Advisory Council (SAC). The ngVLA Community Studies, 25 of which have been approved, provide a mechanism for members of the community to become major contributors in the construction of a final design concept to be brought to Astro2020. 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. In addition to the SAC, the ngVLA Technical Advisory Council (TAC) will work in parallel advising NRAO on technical design issues. 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.



Frequency coverage and effective collecting area 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-1. 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.

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 (url below) for additional information.



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 World Wide Web

https://science.nrao.edu/futures/ngvla

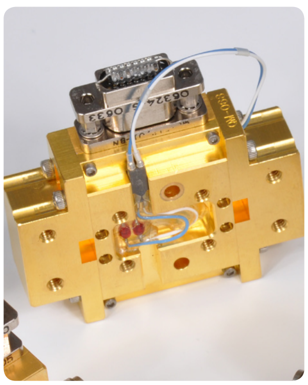
Central Development Laboratory (CDL)

Charlottesville, Virginia

The CDL mission supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to build the next generations of radio astronomy instruments. This is accomplished through development of the enabling technologies: low noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components including feeds and phased arrays, digital signal processing, and new receiver architectures. The CDL has a long history as a world leader in each of these areas. CDL staff have developed and produced these critical components and subsystem not only for NRAO telescopes, but also for the worldwide astronomical community.

Image courtesy of NRAO/AUI

LOW NOISE AMPLIFIERS

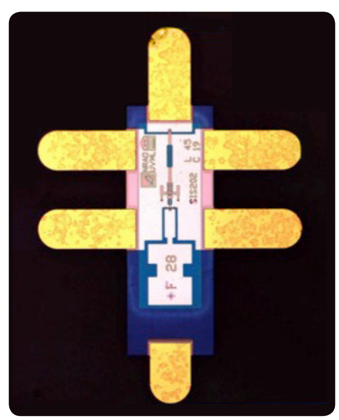


Cryogenic low-noise amplifiers from 0.1-115 GHz designed and produced at the CDL are used in astronomical instruments around the world.

The CDL has for the past three decades provided the international astronomical community with the world's lowest noise amplifiers from 0.1-115 GHz. These amplifiers have been responsible for the high sensitivity and success of the NRAO VLA, GBT, VLBA, and ALMA, and have also 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, including the Wilkinson Microwave Anisotropy Probe, Combined Array for Research in Millimeter-wave Astronomy, Degree Angular Scale Interferometer, Cosmic Background Imager, Effelsberg 100 m Radio Telescope, RadioAstron satellite, Very Small Array, Arc-minute Microkelvin Imager and many others. 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.

MILLIMETER AND SUBMILLIMETER RECEIVERS

The current generation of NRAO millimeter and submillimeter Superconductor-Insulator-Superconductor (SIS) receivers, as used on ALMA, was the result of lengthy development at the CDL in collaboration with the University of Virginia Microfabrication Laboratory (UVML). This includes the introduction of niobium-based superconducting circuits for radio astronomy, development of wideband SIS mixer MMICs, and the use of sideband-separating SIS mixers that were pioneered at the CDL. The CDL and UVML continue to pursue improvements in devices, materials, and fabrication technology to develop quantum-limited receivers up to and beyond 1 THz.



385-500 GHz Nb/AlN/Nb SIS mixer for 385-500 GHz on a Si membrane with gold beam leads. Actual size is 0.77 mm by 1.10 mm.

ELECTROMAGNETIC COMPONENTS AND OPTICS

The receiver optics and electromagnetic components – such as feeds, orthomode transducers, polarizers, and phase shifters – are crucial to the sensitivity, beam quality, and polarization purity of radio telescope. The CDL designs and builds these critical passive components and develops broadband feeds that provide equal or better sensitivity compared to the existing systems for cm-wavelength radio astronomy.

A turnstile junction orthomode transducer (OMT) for ALMA Band 2 (67-90 GHz), designed and fabricated at the CDL.

DIGITAL SIGNAL PROCESSING

Essentially all new instrumentation development requires advanced digital signal processing (DSP), and in many cases DSP development is a dominant part of the project. NRAO has a long tradition of providing complex DSP instrumentation for its telescopes. A recent example is an upgrade to the 64-antenna ALMA correlator. This upgrade will permit ALMA to perform phased-array science including Very Long Baseline Interferometry (observing in conjunction with other telescopes scattered across the world to obtain the highest resolution astronomical observations in all of astronomy) and pulsar searches. The CDL has also designed an Analog to Digital Converter system that may have applications in HERA and other low-frequency telescopes. Although the ALMA telescope is still in its infancy, the CDL is researching ways of significantly upgrading the bandwidth and resolution of the existing correlator.

ADVANCED INTEGRATED RECEIVERS

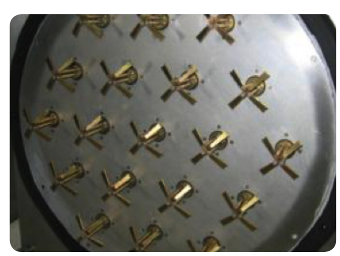
The extreme demands of future instrumentation and facilities, such as large-format focal plane arrays and next generation interferometers, will require innovative receiver architectures. These new designs must realize substantial improvements in cost, compactness, power dissipation, and maintainability, while expanding the parameter space in either bandwidth or field-of-view, with little or no compromise in system noise temperature. Following a path outlined in an Astro2010 Decadal Survey whitepaper, the CDL has embarked on the development of a highly integrated receiver beginning at the antenna feed terminals or waveguide, and ending in a digital data stream that may be delivered to any number of 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 much more accurate digital signal processing, and multiple frequency conversions will be replaced by a single mixer with 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.

CHARACTERIZING COSMIC DAWN

Senior CDL Research Engineer Rich Bradley instructs South African students on instrument operation and assembly during the 64-element Precision Array to Probe the Epoch of Reionization (PAPER) deployment in the Karoo region of the Northern Cape.

The emergence of the first stars and their host galaxies from the fabric of the largely featureless infant Universe is a key scientific goal endorsed by the Astro2010 Decadal Survey. The Hydrogen Epoch of Reionization Arrays (HERA) road map is a strategy for achieving this goal that proposes building a staged sequence of increasingly powerful radio arrays to reveal and model, in increasing detail, the physical processes that led to the contemporary Universe. The CDL is a major institutional partner in HERA and is devoting scientific, technical, and managerial expertise to ensure its success. The Precision Array for Probing the Epoch of Reionization (PAPER) – a partnership between NRAO and UC-Berkeley, the University of Virginia, the University of Pennsylvania, and SKA South Africa – is one of two HERA instruments under development. The CDL will continue its expansion of the PAPER experiment in South Africa and commence observations attempting to detect the Epoch of Reionization signature.

PHASED ARRAY TECHNOLOGY



A Phased Array L-Band cryogenic receiver showing 19 crossed dipoles.

Phased Array refers to an array of small antennas which have their beams combined in such a way to replace the function of a single larger antenna. NRAO is developing the use of phased arrays placed at the focal point of a large reflector antenna which, when coupled with a multi-channel backend and digital signal processing, allows real-time formation of multiple simultaneous sky-beams. This technique can theoretically provide a substantial increase in the telescope field-of-view and increase observing efficiency. Important to the demonstration and improvement of phased arrays receivers for radio astronomy are: accurate design and modeling of small antenna radiators, the design of low-noise amplifiers suitable for array use, optimization of cryogenics for efficiency, and the reduction of the size and power consumption of the receiving systems to make large phased arrays feasible.

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 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 results at 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 enrichment 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, first and second year 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 February 1, 2017.**

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 one of the NRAO sites, 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 typicaly nominated for the program by an NRAO scientist or the student's academic advisor. Students may be supported for six months to 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 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. Regular observing proposals submitted for ALMA and the VLA are currently eligible for funding.

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 February 1, 2017.**

National and International Exchange Program

The National and International Exchange (NINE) program fosters partnerships with fast growing radio astronomy communities around the world, including South Africa, Australia, Chile, China, and India. NINE supports the next generation of scientists and engineers with high quality programs designed to benefit the participant, each partner institute, and the broader radio astronomy community. Graduate students, faculty, and other professional-level applicants may request application materials at any time via an email to odi@nrao.edu. NINE program applications are accepted throughout the year. NRAO anticipates supporting two to four NINE program participants at each NRAO site for three months each year. Visit the NINE website for additional information.

NRAO Student & Visitor Programs on the World Wide Web

http://science.nrao.edu/opportunities

The National Radio Astronomy Observatory

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www.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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