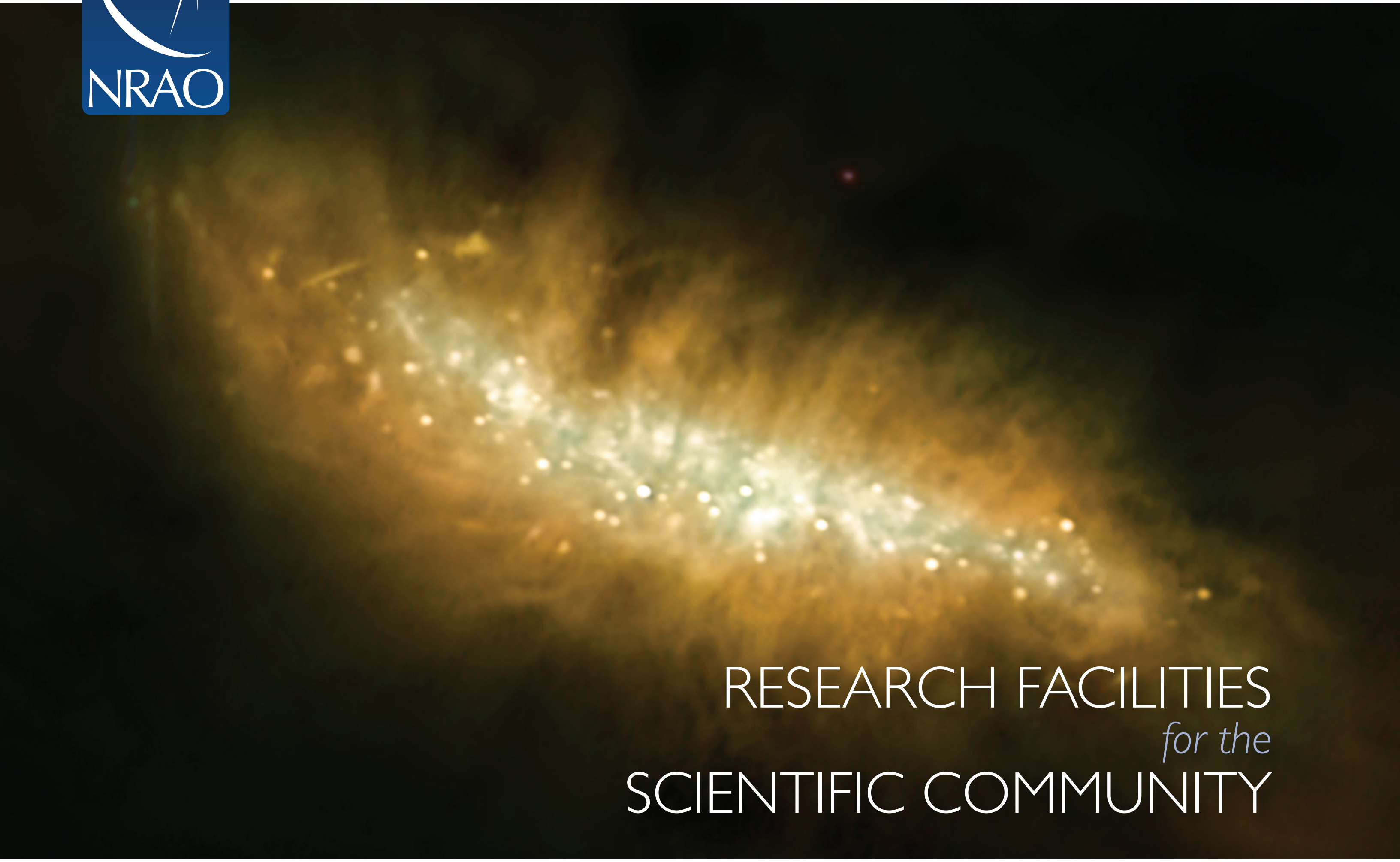
NATIONAL RADIO ASTRONOMY OBSERVATORY



RESEARCH FACILITIES *for the* SCIENTIFIC COMMUNITY

2014




Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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RESEARCH FACILITIES 2014

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(above image)
The radio emission (orange) detected by the NRAO Very Large Array (VLA) is synchrotron radiation emitted by electrons moving at nearly the speed of light in a cosmic magnetic field. These electrons originate in enormous energy outflows from jets fueled by a supermassive black hole at the center of the galaxy NGC 1316 (center, blue-white). Credit: NRAO/AUI/NSF, J. M. Uson

(cover)
This is the closest galaxy that is undergoing a rapid burst of star formation, known as a starburst. About 12 million light-years away, it is seen nearly edge-on. This radio image, made with the Jansky VLA, reveals new information about the central part of this galaxy. The bright dots are either areas where new stars are forming or are supernova remnants, the debris from stellar explosions. The newly-upgraded VLA tells scientists which of these are which, and also reveals previously unseen, faint, wispy features that indicate fast-moving electrons interacting with interstellar magnetic fields. Credits: NRAO/AUI/NSF, J. Marvil, B. Saxton.

(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).

The NRAO in the Coming Decade

The National Radio Astronomy Observatory (NRAO) is delivering transformational scientific capabilities and operating a suite of four 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), the Karl G. Jansky Very Large Array (VLA), the Robert C. Byrd Green Bank Telescope (GBT), 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 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 will provide, for the first time, detailed images of stars and planets in formation, young galaxies being assembled throughout cosmic history, and much more. Early Science was initiated with ALMA in September 2011, and Cycle 2 Early Science observing is expected to begin in June 2014.

At the adjacent centimeter-wavelength range, the recently expanded and updated 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. A special issue of the Astrophysical Journal Letters devoted to Early Science results of the updated VLA was published in September 2011 and described cutting-edge research results from the Solar System to the distant Universe. In late 2012, the Jansky VLA transitioned to full science operation as the world's most capable and versatile centimeter-wave imaging array.

With comparable collecting area and sensitivity to ALMA and VLA, the 100m GBT is the preeminent filled-aperture radio telescope operating at meter to millimeter wavelengths. Its 2+ acre collecting area, unblocked aperture, and excellent surface accuracy enable a wide range of forefront science, including precision pulsar timing to detect gravitational wave radiation, testing the strong field limit of General Relativity, and observing distant HI emission via the innovative Intensity Mapping technique.

The VLBA is the premier dedicated Very Long Baseline Interferometer (VLBI) array in the world. Astrometry with the VLBA has reached the 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 moving with the Hubble flow. An NRAO initiative completed in 2012 quadrupled the VLBA bandwidth. This bandwidth increase, combined with receiver upgrades, has increased VLBA sensitivity up to a factor of 4. When used in conjunction with the phased VLA and the GBT, the resultant High Sensitivity Array greatly enhances VLBI sensitivity and broadens the range of novel scientific research.

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, the Pete V. Domenici Science Operations Center for the VLA and VLBA in Socorro, and the Green Bank Science Operations Center for the GBT.

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 (NANOGrav) and the study of the epoch of reionization (PAPER/HERA).

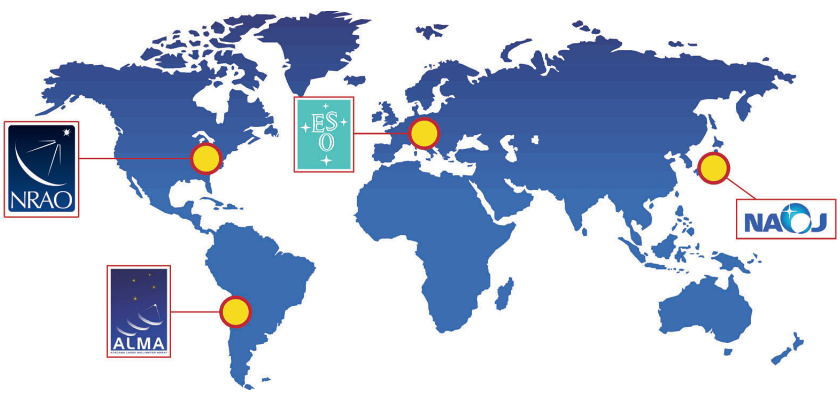
After more than five decades of continual improvement, the NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for the astronomy community in the US and around the world.

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 first stars and galaxies, and can image interstellar gas in the process of forming new planets, thus providing a new 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. At full operational capability, ALMA will have 66 high-precision antennas and will be capable of imaging the sky at resolutions as fine as 0.005 arcsec, a factor of ten better than the Hubble Space Telescope.

Prior to Full Operations, significant observing time is being made available to the community as Early Science. ALMA began Early Science observations on 30 September 2011. Proposals for the next round of observations (Cycle 2) were due on December 5, 2013, and Cycle 2 observations are expected to begin in June 2014. For Cycle 2, ALMA will employ 34 antennas in the 12-m Array as well as 9 antennas in the 7 m Array, and two 12 m antennas will be used for total power imaging. The Call for Proposals and other documentation are available on the ALMA Science Portal: http://almascience.nrao.edu. Even during Early Science, ALMA is the most sensitive and capable millimeter interferometer in the world.



ALMA is an international astronomy facility, a partnership of Europe, Japan, and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere (ESO) and in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan, and in North America by the US National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

The North American ALMA Science Center (NAASC)

The North American ALMA Science Center, based at the NRAO headquarters in Charlottesville, Virginia, supports the scientific use of ALMA by the North American astronomical community, and the research and development for future ALMA upgrades. Users can visit the NAASC site in Charlottesville to reduce 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 organizing and hosting conferences and training 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 operates the ALMA helpdesk. The NAASC is operated by NRAO in partnership with the National Research Council of Canada – Herzberg Institute of Astrophysics.

KEY SCIENCE

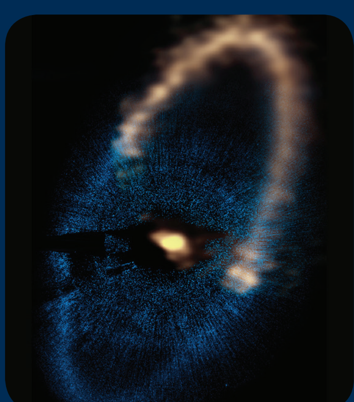
ALMA is designed to accomplish, at a minimum, three "Level 1" science goals: (1) detect CO/C+ in less than 24 hours from a normal galaxy like the Milky Way at redshift z = 3; (2) resolve protoplanetary disks around stars at a distance of 150 pc; and (3) provide precise imaging at submillimeter wavelengths with 0.1 arcsec resolution, in which the sky brightness is accurately represented for all points above 0.1% of the peak flux in the map. ALMA will thus be capable of high fidelity imaging both in the 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 in Full Operations will be able to image dust continuum emission from galaxies at z = 10, showing how galaxies assemble during their earliest stage of formation. ALMA will enable blind surveys of molecular gas in the early Universe, thus revealing the star-formation history of the Universe. ALMA will image molecular gas in the nuclei of nearby active galaxies with spatial resolutions of 10-100 pc, revealing the structure of the putative obscuring torus in active galactic nuclei. ALMA will also enable detailed studies of the full life cycle of stars and will be able to detect heavy, prebiotic molecules in newly forming solar systems. ALMA will probe the gas dynamics in young stellar systems as the disk, jet, and central star itself form. And in the spectacular supernova explosions that mark the end of the stellar life cycle, ALMA will show 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

	Early Science (Cycle 2)	Full Operations
Antennas	34 x 12 m; 9 x 7 m; 2 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	Bands 3, 4, 6, 7, 8, 9, 10
Maximum Bandwidth	16 GHz (2 pol x 8 GHz)	16 GHz (2 pol x 8 GHz)
Correlator Configurations	Subset of Array Completion	71 configs (0.01-40 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	1.5 km; 1 km (Bands 8 & 9)	15 km
Continuum Sensitivity (60 sec, Bands 3 – 9)	~ 0.1 – 1.7 mJy/beam	~ 0.07 – 1.1 mJy/beam
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 – 9)	~ 15 – 95 mJy/beam	~ 10 – 64 mJy/beam



Far left: An ALMA (yellow) and Hubble Space Telescope (blue) image of the dust ring orbiting the nearby star Fomalhaut. The star is at the center of the ring, coincident with the bright emission. The sharply-defined edges of the dust ring as seen by ALMA led scientists to conclude that the dust is confined by the gravity of two planets similar in size to the Earth, one orbiting within the ring and the other outside it. Credit: A.C. Boley, M.J. Payne, E.B. Ford, M. Shabran (Univ Florida); S. Corder (NRAO NAASC); W. Dent (ALMA); NRAO/AUI/NSF; NASA; ESA; P. Kalas, J. Graham, E. Chiang, E. Kite (UC, Berkeley); M. Clampin (NASA Goddard); M. Fitzgerald (LLNL); K. Stapelfeldt, J. Krist (NASA JPL). Left: An ALMA antenna rides atop a transporter to the 5000 m elevation Array Operations Site in northern Chile.

ALMA on the World Wide Web

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

http://www.almaobservatory.org

NAASC on the World Wide Web

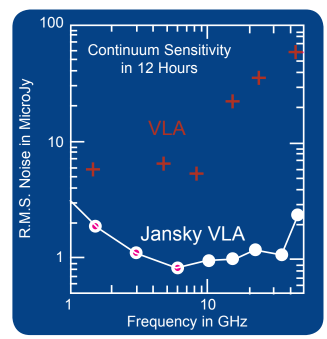
http://science.nrao.edu/facilities/alma/intro-naasc

Karl G. Jansky Very Large Array (VLA)

Socorro, New Mexico

The Karl G. Jansky Very Large Array is a radio telescope of unprecedented sensitivity, frequency coverage, and imaging capability created by modernizing the "classic" Very Large Array. A suite of new receivers on all 28 antennas of the array, along with a new digital data transmission system and a new Wideband Interferometric Digital Architecture (WIDAR) correlator, combine to provide superb spectral resolution and fidelity over very wide instantaneous bandwidth, enabling astronomers to make full-beam images with very high spatial resolution and dramatically improved continuum sensitivity at frequencies from 1 to 50 GHz. The new WIDAR correlator was installed at the beginning of 2010, with first science observations in March 2010, marking the beginning of Early Science with the Jansky VLA. At that time up to 256 MHz bandwidth was offered to the general community, already a factor of 2.5 improvement over the VLA's original receiver suite. In September 2011 this increased to 2 GHz bandwidth, and in January 2013 the VLA began full science operations, offering up to 8 GHz bandwidth. This modernized VLA provides the cm-wavelength radio complement to ALMA and other next-generation instruments coming online over the next few years, with the following capabilities:

- Continuum sensitivity improvement over the classic VLA by factors of 5 to 20.
- Operation at any frequency between 1.0 and 50 GHz, with up to 8 GHz bandwidth per polarization, 64 independently tunable sub-band pairs, each providing full polarization capabilities.
- Up to 16,384 spectral channels, adjustable frequency resolution between 2 MHz and 0.2 Hz, and extensive capabilities to allocate correlator resources with a planned increase to up to 4,194,304 spectral channels.
- Spatial dynamic range > 10^6, frequency dynamic range > 10^5, with noise-limited, full-field imaging in all Stokes parameters.
- Dynamic scheduling based on weather, array configuration, and science requirements. Calibrated visibilities and reference images for quality assurance automatically produced, with all data products archived.



The expanded VLA project was funded by the U.S. National Science Foundation, with additional contributions from the National Research Council in Canada, and the Consejo Nacional de Ciencia y Tecnologia in Mexico.

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

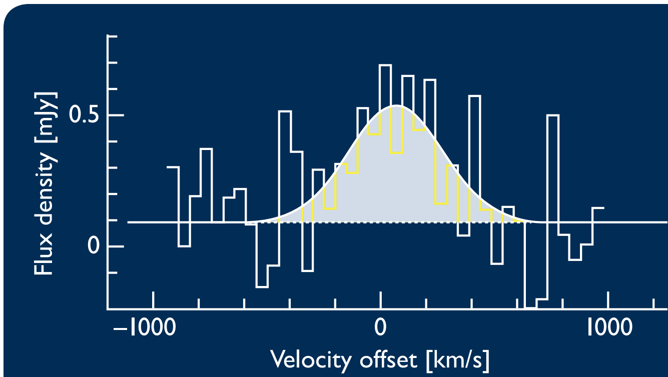
Astronomical transient sources tend to be compact objects that emit synchrotron radiation from high-energy particles, radiation best observed at radio wavelengths. The VLA is ideal for studies of variable sources because of its high sensitivity, ability to observe day and night under most weather conditions, 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).

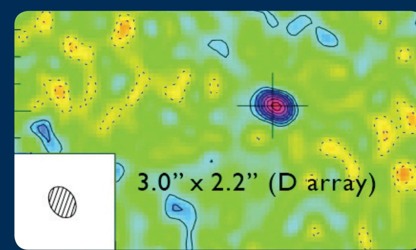
The Evolving Universe

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 submillimeter 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.

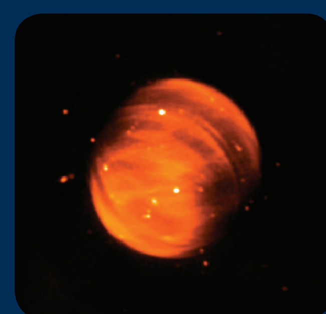
Karl G. Jansky VLA on the World Wide Web

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





The CO(2-1) emission from the most distant hyper-starburst galaxy (AzTEC-3), at z = 5.3, about 1 billion years after the Big Bang. These VLA data show the cold gas fueling the star formation and indicates more than 10^{10} solar masses of dense gas in this still-forming elliptical galaxy (Riechers et al, 2010).



The supernova remnant (SNR) G93.3 at 5 GHz. Predictions indicate there should be many more Galactic SNRs than are known. SN remnants are typically hidden by the Galactic Plane and detectable only at radio wavelengths. A single VLA observation can provide data on the emission mechanisms and magnetic field strengths in these and other radio sources, inside and outside our Galaxy. A special issue of the Astrophysical Journal Letters published on September 20, 2011, showcases other examples of the modernized VLA's new capabilities and science.

SPECIFICATIONS

The Karl G. Jansky VLA Performance	3 GHz	30 GHz
Maximum instantaneous bandwidth	2 GHz	8 GHz
Continuum sensitivity (1σ, 9 hr, max bandwidth)	2 μJy	2 μJy
Spectral line sensitivity (1σ, 9 hr, 1 km/s velocity width)	740 μJy	440 μJy
Maximum angular resolution	0.65 arcsec	0.065 arcsec
Areal survey speed (at 100 μJy continuum depth, 1σ)	16.5 deg^2/hr	0.12 deg^2/hr

New versus Old	Classic VLA	Karl G. Jansky VLA
Maximum instantaneous bandwidth	0.1 GHz	8 GHz
Number of frequency channels at maximum bandwidth	16	16,384
Maximum number of frequency channels	512	4,194,304
Finest frequency resolution	381 Hz	0.12 Hz
Frequency coverage, 1 - 50 GHz	22%	100%

Robert C. Byrd Green Bank Telescope (GBT)

Green Bank, West Virginia

Image courtesy of NRAO/AUI

The Green Bank Telescope (GBT) is the premier single-dish radio telescope operating at centimeter and millimeter wavelengths. Its enormous 100-meter diameter collecting area, its unblocked aperture, and its excellent surface accuracy provide unmatched sensitivity across the telescope's full 0.1 – 116 GHz (3.0m – 2.6mm) operating range. The GBT has a suite of detectors optimized for spectroscopy, pulsar observations, continuum, and very long baseline interferometry (VLBI). Located in the National Radio Quiet Zone, the GBT benefits from a low radio-frequency interference environment. It can make measurement down to declinations -46° and thus can reach 85% of the entire celestial sphere,

The single focal plane is ideally suited for multi-pixel radio cameras; it serves as the wide-field imaging complement to ALMA and the VLA. Its operation is highly efficient, and it is used for astronomy about 6500 hours every year, with about 2000 hours per year available for high frequency science. It is scheduled dynamically to match project needs to the available weather.

Part of the scientific strength of the GBT is its flexibility and ease of use, allowing for rapid response to new scientific ideas. The GBT is regularly reconfigured with new and experimental instrumentation, adopting the best technology for any scientific pursuit. The facilities at the Green Bank site are also used for other scientific research, for many programs in education and public outreach, and for training students and teachers.

GREEN BANK TELESCOPE CAMERA DEVELOPMENT PROGRAM

The NRAO, in partnership with more than 20 University, college and industry research groups, is designing, building, and commissioning new radio camera systems that will provide a major advance in GBT scientific capabilities. These instruments include conventional feed horn arrays, phased array receivers, and bolometer arrays.

Bolometer Arrays

The MUSTANG, 64-pixel bolometer array covering 81-98 GHz (3 mm), with 9 arcsec resolution and a 40 x 40 arcsec fully sampled field-of-view, is in routine use at the GBT. A more robust, significantly more sensitive array, using feed-horn coupled technology, is under development and will be ready for use in 2014.

Phased Array Receivers

The NRAO is working with several organizations, including Brigham Young University and West Virginia University (funded through the NSF ATI program), on the development of phased array receiver technologies with the goal of building sensitive, multi-pixel receivers for the GBT. A cooled, dual-polarization, 19-element 1.4 GHz receiving system is currently being tested. A phased array receiver to operate at 100 GHz is under development at the University of Massachusetts, also with support from the NSF ATI program, and will be tested in 2014.

Heterodyne Arrays

K-band Focal Plane Array: A 7-pixel, dual-polarization array of heterodyne receivers for 18-26.5 GHz is available for regular use. Though optimized for mapping in the NH_3 lines it can be readily used for other spectral lines. Receiver temperatures are ~ 25 K across the band, giving total zenith system temperatures as low as 39 K in good weather at an aperture efficiency of 69%.

W-Band Focal Plane Array: A 16-pixel, single polarization array for use from 75-116 GHz on the GBT is under development by Stanford University, the University of Maryland, California Institute of Technology, and other organizations, funded by the Advanced Technologies and Instrumentation (ATI) program of the NSF. The array will be commissioned in late 2014.

NEW DIGITAL SIGNAL PROCESSORS

The Center for Astronomy Signal Processing and Electronics Research at the University of California, Berkeley, with funding from the NSF ATI program, is building an advanced multi-beam spectrometer for the GBT in cooperation with NRAO staff. The new spectrometer will replace existing instruments and is optimized for use with focal plane array receivers. It is thus well matched to the GBT's multi-pixel camera development program. The spectrometer will be capable of processing 8 dual polarized beams at up to 1.25 GHz bandwidth each, or a single dual polarized beam at a bandwidth up to 10 GHz. It will begin operations in 2014.

RECEIVER UPGRADES

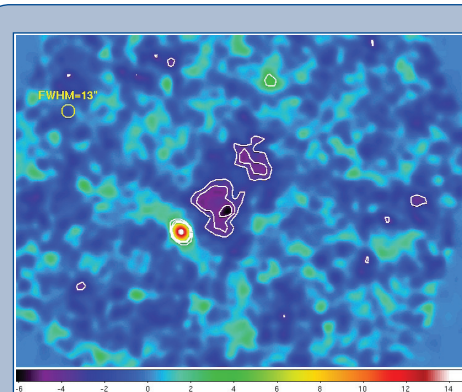
A dual-beam receiver that covers 68-92 GHz is in full science operation on the GBT. A new set of amplifiers has been installed and tested, and the total system temperature is now in the range 60-80 K.

The GBT's C-band receiver is being upgraded to expand its frequency coverage to 8 GHz from its current upper limit of 6 GHz. The receiver will be available for shared risk science in 2014.

KEY SCIENCE

Fundamental Physics

With its sensitivity, broad frequency and sky coverage, and state-of-the-art instrumentation, the GBT is a premier instrument for studying pulsars and other compact objects that probe fundamental physics. The GBT is a key instrument of the NANOGrav collaboration that seeks to use pulsar timing measurements to detect gravitational radiation directly. Through measurement of molecular transitions at high redshift, the GBT is used to limit the variation of fundamental physical constants with time.



A high-angular resolution map of the Sunyaev-Zel'dovich (SZE) effect in a cluster of galaxies measured with the GBT. Two areas of SZE decrement (contours) mark regions of hot shocked gas within a cluster. A bright active galactic nucleus lies at the center (Mroczkowski et al. 2012).

Star Formation

With good angular resolution and high sensitivity to extended sources, the GBT is making wide-field maps of molecular clouds in numerous molecular species to determine the physical conditions at various stages of star formation. These studies cover environments ranging from starless cores to molecular clouds near the Galactic Center and are now being extended to nearby galaxies.

Galaxies Across Cosmic Time

The MUSTANG 3mm bolometer array has discovered hitherto unknown structures in the hot gas of galaxy clusters that reveal the evidence of mergers and cluster formation. The GBT is being used to image the collective signal from HI in galaxies at a redshift z~1, tracing the dark matter structure and HI content of galaxies that cannot be resolved individually. Through measurement of H_2O masers in the accretion disks surrounding nuclear black holes, the GBT has established the mass of many black holes and shown that they are not always related to the mass of the galaxy's stellar bulge. With its ability to detect extremely faint HI emission, the GBT was used to discover a population of HI clouds in the Local Group between the galaxies M31 and M33. The discovery with the GBT of H_2O masers in the HII regions of M31 provides targets for VLBI observations that will measure the proper motion and distance of this dominant galaxy in the Local Group.

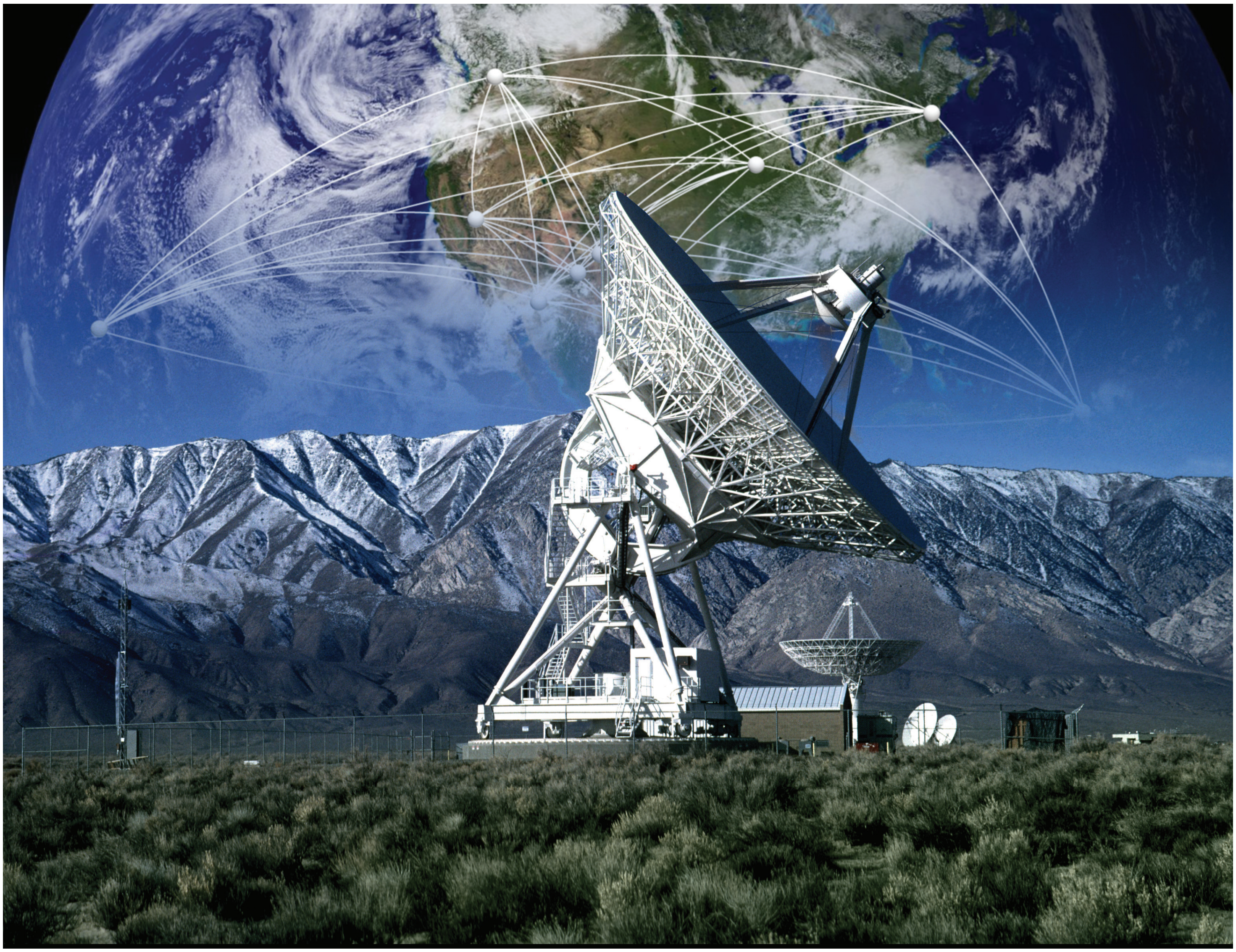
Origin of Life

Determining the origin of life on Earth requires research across biology, chemistry, physics, and astronomy. The GBT is playing a major and unique role in this work by measuring interstellar chemical processes and their variation across the Milky Way, determining the characteristics and extent of pre-biotic chemistry in star-forming regions, and by rapid imaging of the molecular content of comets in our Solar System.

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 10 identical antennas with baseline lengths up to 8600 km (Mauna Kea, Hawaii to St. Croix, Virgin Islands). The VLBA is controlled remotely from the Science Operations Center in Socorro, New Mexico. Each VLBA station consists of a 25 m antenna and an adjacent control building. The received signals are amplified, digitized, and recorded on fast, high capacity recorders. The recorded data are sent from the individual VLBA stations to the correlator in Socorro.



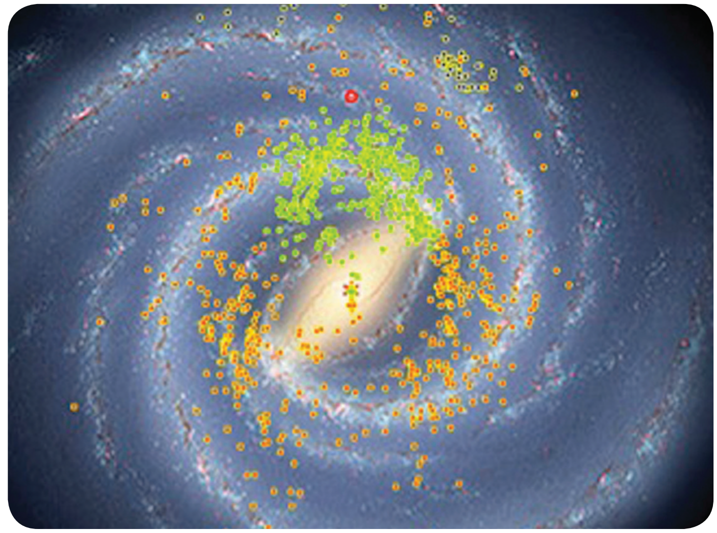
The VLBA observes at wavelengths of 90 cm to 3 mm (300 MHz to 96 GHz) in ten discrete bands. New receivers have been installed on the VLBA that are capable of tuning between 4 and 8 GHz, which not only greatly enhanced the frequency range available but also significantly increased the sensitivity in this band. The array can be scheduled dynamically, and its continuum sensitivity can be improved significantly by adding the Green Bank Telescope, the phased Karl G. Jansky Very Large Array, the Arecibo Telescope in Puerto Rico, and the Radio Telescope Effelsberg in Germany.

KEY SCIENCE

Precision astrometry is a VLBA science centerpiece. The VLBA's relative astrometric accuracy of ~ 10 μas is complementary to the accuracy the Gaia satellite will achieve. The VLBA can probe the Galactic plane well beyond the solar neighborhood because radio emission is affected little by extinction.

In 2010, the VLBA began a long-term program to determine the 3D structure of the Milky Way by measuring parallaxes with 10 μas accuracy or better to ~ 400 high-mass star-formation regions. This program has measured the fundamental galactic rotation parameters with 3% accuracy and is expected to eventually achieve 1% accuracy, helping to quantify the distribution of luminous and dark matter in the Galaxy.

The VLBA is also anchoring ongoing High Sensitivity Array observations of the center of M31 in an effort to detect the galaxy's nucleus with significant signal-to-noise and enable a first-epoch position measurement. The ultimate goal is measurement of the motion of M31 relative to the Milky Way, which should help distinguish between scenarios proposed for the formation of the Local Group and provide a measurement of the mass of M31 and its dark-matter halo.



The Bar and Spiral Structure Legacy Survey program (Mark Reid et al.) is measuring accurate distances and proper motions for about 400 high-mass star-forming regions in the Milky Way between 2010 and 2015. This survey will yield accurate distances to most of the high-mass star-forming regions in our Galaxy that are visible from the northern hemisphere, as well as very accurate measurements of fundamental parameters such as the distance to the Galactic center, and the Milky Way rotation velocity and rotation curve. Credit: IPAC-R. Hurt/CfA-Mark Reid/NRAO/AUI/NSF.

The NASA Fermi Gamma-ray Space Telescope released its first gamma-ray source catalog in 2009. In 2011, the VLBA began to participate in several cooperative observational programs with Fermi. These programs focus on active galactic nuclei, or blazars, several thousand of which should be detected by Fermi over the next few years. Proposers approved for VLBA time through the Fermi proposal process also have access to NASA funding for data reduction and analysis.

A long-term VLBA program to study Active Galactic Nuclei containing central H_2O megamasers will continue. This program has two primary scientific goals: (1) acquire geometric distance measurements that enable an accurate determination of the Hubble Constant and related dark-energy parameters; and (2) directly measure the masses of central black holes with accuracies of at least 10%, much better than any other technique used for sources outside the Milky Way.

SENSITIVITY ENHANCEMENT PROGRAM

In 2007 NRAO commenced a program to increase the sensitivity of the VLBA. This program, which quadrupled the bandwidth available at the VLBA, was completed in 2012. This bandwidth increase combined with the upgrade of the C-band (4-8GHz) receivers has increased the sensitivity up to a factor of 4. For example, an 8 hour observation at 5 GHz can achieve a 1-sigma rms of 6μJy/beam. These sensitivity improvements were undertaken with our international partners to provide new scientific capabilities for the VLBA user community.

VLBA on the World Wide Web

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

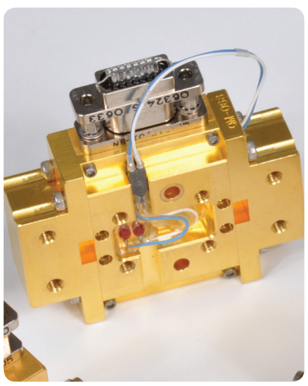
Central Development Laboratory (CDL)

Charlottesville, Virginia

The CDL mission supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to build the next generation 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.

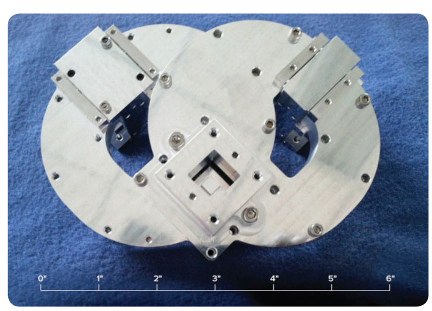
The CDL has for the past three decades provided the international astronomical community with the world's lowest noise amplifiers from 0.1-115 GHz. These amplifiers have been responsible for the high sensitivity and success of the NRAO VLA, GBT, VLBA, and ALMA, and have also been key to the success of 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.

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 Ku-band (11-18 GHz) turnstile junction orthomode transducer (OMT) designed and fabricated by the CDL for the Green Bank Telescope Ku-band pulsar receiver.

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. Recent examples include the 64-antenna ALMA correlator, the VEGAS backend for the GBT, the Green Bank GUPPI pulsar searching/timing backend, and the VLBI Digital Backend. The CDL is currently upgrading the ALMA correlator to permit the phasing of ALMA for Very Long Baseline Interferometry, enabling its participation in the Event Horizon Telescope. The CDL is also designing an Analog to Digital Converter system that may have applications in HERA and other low-bandwidth telescopes.

ADVANCED INTEGRATED RECEIVERS

The extreme demands of future instrumentation and facilities, such as large-format focal plane arrays and the Square Kilometre Array, will require innovative receiver architectures. These new designs must realize substantial improvements in cost, compactness, and power dissipation, 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.

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.

CHARACTERIZING COSMIC DAWN

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.

CDL on the World Wide Web

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

Student & Visitor Programs

Summer Student Programs

Summer students conduct research at the NRAO under the supervision of a scientific staff member in Socorro, Green Bank, or Charlottesville. The project may involve any aspect of astronomy and often results in scientific journal publications. Students receive relocation support, a monthly stipend, and partial support may be available to present summer research results at an American Astronomical Society meeting. Students also participate in an extensive lecture series.

Undergraduate students who are U.S. citizens or permanent residents are eligible for the NRAO Research Experiences for Undergraduates (REU) program. Students who do not meet REU guidelines may be eligible to apply for the NRAO Undergraduate Summer Student Research Assistantship program. First and second year graduate students are eligible to apply for the NRAO Graduate Summer Student Research Assistantship program. **Applications are due at the end of January each year.**

Co-op Program

The NRAO has developed relationships with many U.S. universities with strong engineering and computer science departments. Each semester the NRAO sponsors one or more paid undergraduate students. These co-op students, normally juniors and seniors, spend three alternating 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 students in the early years of a graduate program who are interested in radio astronomy or related research. Students who are U.S. citizens or permanent residents, are enrolled in an accredited U.S. graduate program, or who are otherwise eligible to work in the U.S., will receive a stipend. Some travel and housing assistance may also be available. Appointments may be made for periods from a few weeks to six months. An NRAO staff member supervises each student.

Grote Reber Doctoral Fellowship Program

The Grote Reber Doctoral Fellowship Program supports upper-level graduate students who have completed their academic institution's requirements for becoming doctoral candidates. Astronomy, engineering, and computer science students are encouraged to participate. Under the joint supervision of an

NRAO staff member and his/her academic advisor, the student pursues research full-time toward completion of a doctoral dissertation. An NRAO scientist or a student's academic advisor nominates them for the program. Students may be supported for six months to two years or longer while they work at an NRAO site. Applications are accepted throughout the year, though candidates are strongly encouraged to seek the support of an NRAO scientist before applying.

Student Observing Support Program

To help train new generations of scientists, the NRAO supports research by graduate and undergraduate students at US universities and colleges. Regular observing time proposals submitted for ALMA are currently eligible for funding under this program.

Visitor Program

The Visitor Program is open to PhD 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 university, and to encourage collaborations that can lead to *first light* science with new instruments.

NRAO Student & Visitor Programs on the World Wide Web

http://science.nrao.edu/opportunities

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