The Impact of the National Radio Astronomy Observatory

State of the Profession White Paper

Astro2010

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Abstract

The NRAO Mission

The National Radio Astronomy Observatory enables forefront research into the Universe at radio wavelengths. In partnership with the scientific community, we:

- *provide world-leading telescopes, instrumentation and expertise,*
- *help train the next generation of scientists and engineers, and*
- *promote astronomy to foster a more scientifically literate society.*

In the next decade, to fulfill its mission, the NRAO will be operating a suite of forefront telescopes: ALMA, EVLA, GBT and VLBA, observing from meter to sub-millimeter wavelengths, with an order of magnitude or more improvement in resolution, sensitivity, frequency coverage, spectral line capabilities, and field of view, over this entire wavelength range. These telescopes will complement the key observatories at other wavelengths as essential tools for discovery in all areas of modern astrophysics. To maximize the scientific impact of its facilities, the NRAO will provide easier access and enhanced support to the broader multi-wavelength user community. To help realize the SKA Program in the longer term, the NRAO will increase its efforts in relevant SKA technology research and development, in collaboration with the US and international community. The NRAO will also take concrete steps in the SKA development through continual development of its facilities, such as building focal plane cameras for the GBT to achieve a quantum leap in its observing speed and field of view, exploring real-time wide-bandwidth correlation for the VLBA via the internet, and expanding beyond EVLA to the North America Array as a pathfinder to the SKA-High.

1. Science Impact

1.1 Future Vision

Astronomical facilities at meter through sub-millimeter ("radio") wavelengths play critical roles in all areas of modern astrophysics. As the primary US national observatory for this wavelength regime, NRAO is committed to providing a wide range of world-leading observing resources to the broad astronomical community. Our facilities offer capabilities that are unique as well as complementary to those of optical, IR, and X-ray telescopes, obtaining a complete view of complex cosmic processes. Radio astronomy probes deep into the earliest, most intense, and optically obscured, phases of planet, star, galaxy, and black hole formation, as well as revealing the cool dense gas, the material from which stars form. Radio astronomy provides the highest resolution imaging (sub-mas) and astrometry (10 μas) currently available, as well as providing essential tools for study of magnetic fields and energetic particles throughout the cosmos. Radio instruments carry out precision cosmological measurements, test fundamental physics, and probe astrophysics and chemistry in extreme environments. These facilities are the engines for exploration. Technology developed at NRAO enables our community to carry out research and discovery at the frontiers of physics and astronomy.

In the next decade, NRAO will be operating a transformative suite of telescopes which will continue this golden age of astrophysical discovery. The Atacama Large Millimeter / submillimeter Array (ALMA) provides between one and two orders of magnitude improvement in resolution, sensitivity, and frequency coverage. The Expanded Very Large Array (EVLA) leverages existing infrastructure to improve continuum sensitivity at cm wavelengths by up to an order of magnitude, as well as providing complete frequency coverage from 1 GHz to 50 GHz with state-of-the-art spectral line capabilities. The EVLA will remain the most powerful radio telescope in the world operating in this frequency range through the next decade. The Robert C. Byrd Green Bank Telescope (GBT) will make full-use of its focal plane to perform deep, wide-field studies of the Galaxy and the Universe, and the Very Long Baseline Array (VLBA) will remain the only dedicated telescope with sub-milli-arc-second resolution.

The impact of NRAO telescopes has been highlighted in numerous community science white papers for A2010[1]. We briefly describe a few areas of particular promise here. These are not meant to be exhaustive, simply illustrative of the tremendous science potential in the next decade[2].

Basic physics: Direct detection of gravitational waves via pulsar timing. One of the most exciting projects currently under way is the search for nano-Hertz gravitational waves (GWs) from individual super-massive black hole (SMBH) binaries and/or a stochastic background of such waves from the ensemble of SMBH binaries throughout the Universe. Detection requires 100 ns timing residuals at two observing frequencies, over 5-10 yr, from at least 10 millisecond pulsars spread across the sky. These pulsars act as the far ends of the arms of a Galactic-scale GW detector. The North American effort involving Arecibo and the GBT, known as

[1] http://www.nrao.edu/A2010/whitepapers/
[2] http://www.nrao.edu/A2010/DS2010/

NANOGrav, has steadily increased capabilities through improved hardware, software, techniques, and observing patterns over the past several years. Dramatic improvements are expected in the next decade with new pulsar timing back-ends currently under construction, finding new millisecond pulsars, and continual efforts to reduce systematics. While complementing the higher frequency searches with laser interferometers such as Advanced LIGO and LISA, NANOGrav, combined with coordinated international efforts in Australia, Europe and soon China, has a very promising prospect of detecting nano-Hertz GW perhaps in the next decade.

Cosmology: Measurement of H_0 to 1% accuracy using water megamasers. A 1% determination of H_0 will enable a new, robust and independent constraint on the Equation of State of dark energy and other cosmological parameters, complementing other precision cosmology programs, such as Planck and JDEM. Such a measurement is possible using H_2O maser disks around SMBHs in galactic nuclei at distances where the Hubble flow dominates the peculiar motions. Reaching the 1% goal entails a search for H_2O masers in $>10^4$ galaxies out to $z \sim 0.06$ using large single-dish cm telescopes, such as the GBT. A resulting sample of order 100 sources is expected with properties adequate for follow-up very long baseline interferometry (VLBI) and time-series spectroscopy to measure centripetal accelerations, from which the angular diameter distances to the host galaxy can be derived to obtain an accurate determination of H_0. This study requires intercontinental 22 GHz VLBI arrays with sensitive telescopes (VLBA, GBT, EVLA, Effelsberg, LMT, DSN), and would benefit from a space VLBI antenna (VSOP-2) yielding baselines up to 30,000 km.

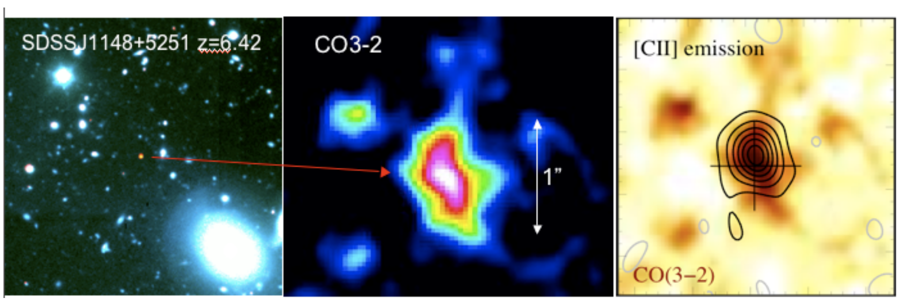
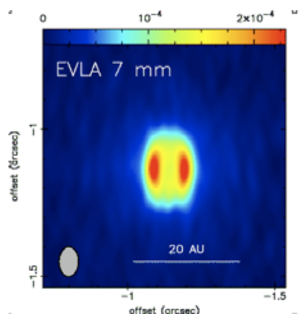


Figure 1.1. Left is the optical SDSS image of the z=6.42 quasar J1148+5251. Center is the VLA CO image showing a huge reservoir of molecular gas in the host galaxy on a scale of 6 kpc. Right is the [CII] 158 micron emission observed by the Plateau de Bure Interferometer, revealing a 'maximal starburst disk' on scales ~ 1.5 kpc (Walter et al. 2008, Nature, 457, 699).

Galaxies across cosmic time: First light at radio wavelengths. How do the first galaxies and SMBHs form, and how do they reionize the Universe? These questions are primary science drivers for large-area telescopes at all wavelengths. A crucial role will be played by observations at cm through submm wavelengths, including studies of submm molecular lines (to probe the fuel for star formation in galaxies), the atomic fine structure lines (dominant ISM gas coolants), the thermal dust continuum emission (a key star formation rate estimator), and radio synchrotron emission (measure of star formation and relativistic jets). High resolution spectroscopic imaging, that can only be done with the EVLA and ALMA for normal galaxies at high redshift will reveal galaxy dynamics and star formation on sub-kpc scales. Thes cm through submm observations are the essential complement to near-IR observations, which probe the stars and ionized gas, and X-ray observations, which reveal the AGN. Together, next generation observatories operating from cm to X-ray wavelengths in the coming decade will provide the requisite panchromatic view of the processes involved in the formation of the first generation of galaxies and SMBHs, and cosmic reionization. Such capabilities to image routinely galaxies reaching back to the Epoch of Reionization were unimaginable perhaps even a decade ago. An example of the current impact of cm through submm observations on the study of the first galaxies is shown in Figure 1.1.

Star and Planet Formation: Probing the Birth of Extrasolar Planets. The field of extrasolar planets and planet formation has entered a new age, with the discovery of hundreds of planets and proto-planetary disks at optical, near-IR, and radio wavelengths. Radio observations play a crucial role in the study of the early phases of planet formation, by imaging the dust and gas in protoplanetary disks down to AU-scales. The EVLA and ALMA will provide a resolution of tens of mas, required to image dust gaps cleared by forming planets in protoplanetary disks. ALMA also may detect the warm dust associated with forming Jupiter-like planets directly; EVLA will be crucial for probing the most optically thick inner regions of protoplanetary disks, and will be sensitive to large dust grains. The GBT bolometer array will perform large-scale surveys for dark, protoplanetary disks, and study the composition of debris disks. A higher sensitivity VLBA will detect planets by their astrometric signatures on nearby radio-emitting stars. The radio observations complement the studies of proplyds, or the dusty shadows of protoplanetary disks, as imaged in the optical, and the IR studies of dust spectra. Examples of the ALMA and EVLA potential are shown in Figure 1.2.



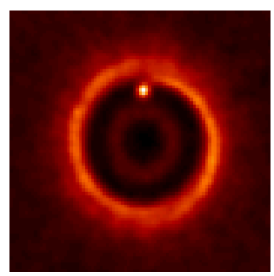


Figure 1.2. The left shows the EVLA image at 7mm of the TW Hya proto-stellar disk. The right shows a simulation of the TW Hya disk plus gap as seen by ALMA at 850 GHz with 20 mas resolution. The disk gap is clear, as is potential emission from a hot phase of the protoplanet (Wolfe & D'Angelo 2005, ApJ, 619, 1114; Wilner in prep).

1.2 Historical Perspective

A national facility such as NRAO enables investigations by more than 1,000 astronomers each year, a number that will increase significantly after ALMA and EVLA become operational early in the next decade, combining their diverse scientific interests with the most powerful radio telescopes on Earth. NRAO telescopes discovered the first interstellar molecules, including CO near and far, uncovering the "molecular universe," the study of which is the primary reason ALMA is being built. Sgr A* was discovered and had its motion measured. The gaseous structure of the Galaxy was mapped, and accurate distances to spiral arms were measured. The most sensitive high-resolution surveys of the radio sky were made. Microquasars were discovered, the SMBH-accretion disk paradigm was confirmed via mapping of a megamaser, SMBH masses were measured, and tens of millisecond pulsars were found in globular clusters. A statistical study by Trimble & Zaich (2006, PASP, 118, 933) indicating that "The VLA is, therefore, proportionately even more influential in world radio astronomy than HST is in world optical astronomy" is another indicator of the impact of the NRAO.

2. Community Impact

In addition to providing telescope time to the community on a peer-review basis, NRAO programs reach out to broader communities: professional, educational, and lay public. Some provide hands-on training for the next generation of scientists and engineers from the secondary to post-doctoral levels. Others provide research experiences for K-12 teachers and students, and training for K-12 and undergraduate science teachers. Below we describe the impact of these programs on astronomy (research and education), engineering, and the general public.

2.1 Science Metrics/Demographics

NRAO presently operates the VLA, the VLBA, and the GBT as a system of complementary telescopes accessible to all astronomers, and looks forward to the completion of EVLA and ALMA early in the next decade. In Table 2.1, we provide some condensed user demographics, telescope usage statistics, and top-level science metrics. More detailed information can be provided upon request

Table 2.1. Usage Statistics

Year	Total Users	Student Users #	Science Telescope Hours	Proposals Received ^	Refereed Telescope Publications %	Refereed Citations *	All Telescope Publications
2004	1074	103	17,190	785	262	4031	377
2005	1115	102	17,828	742	263	3250	433
2006	1157	143	18,822	737	303	3075	381
2007	1106	169	16,028	717	358	2701	537

*Notes: # - Student users include graduate and undergraduate, although the majority (>95%) are PhD students. % - Includes only peer-reviewed papers using NRAO telescope data. ^ - Does not include joint NASA/NRAO proposals with Chandra, Fermi, and Spitzer. *- ADS citations are preliminary and underestimate the total citation count. Statistics for 2008 were not yet available.*

NRAO is committed to fostering the next generation of astronomers and engineers as a core element of its mission. Existing programs include opportunities at the undergraduate (NSF REU program, Internship program, NRAO Summer Student program, and the Engineering Co-Operative program), graduate (Summer Student program, Internship program and Pre-Doctoral Fellows) and post-graduate levels (Jansky Fellows, NRAO Postdoctoral Fellows, and Research Associates). For example, 2009 is the 50th anniversary of the NRAO Summer Student Research Assistantship program, which has engaged 1,000 summer students in scientific research. Former

NRAO summer students include women and men representing a wide range of careers, research interests, geographic locations, and ethnic backgrounds, including many with distinguished accomplishments such as Steven Chu, Physics Nobel Laureate and current Secretary of the Department of Energy. For details of the NRAO summer student program, please see http://www.nrao.edu/students/summer-students.shtml.

In Table 2.2 below we provide numbers of undergraduates, graduates, and postgraduates that are directly funded by NRAO through these various NRAO programs. The individual programs are described in greater detail at http://www.nrao.edu/admin/dsaa/. The total number of students using NRAO telescopes for their research is listed in the third column of Table 2.1. On average, 50 PhD students worldwide use NRAO telescopes for their research each year, and one quarter of all astronomy PhD students in the US use NRAO telescopes for some or all of their research. NRAO provides other student funding and training not included in these tables, including paid travel to the telescope, full page charges, and computing support. NRAO research staff have created a one-semester course called "Essential Radio Astronomy" (ERA), intended for astronomy graduate students and advanced undergraduates. ERA is available at no cost; see http://www.cv.nrao.edu/course/astr534/ERA.shtml.

NRAO pioneered development of portable software (Astronomical Image Processing System=AIPS) that astronomers could use to analyze data at their home institutions; AIPS is downloaded by over 1000 individual IP addresses each year, and used for almost all VLA and VLBA data analysis. Further, the NRAO on-line data archive (http://archive.nrao.edu) provides 30 years of VLA data and more than a decade of VLBA data, with an ever-increasing amount of calibrated data and images.

Table 2.2. Student Programs

Year	NSF REU ^	NSF RET ^	NRAO Summer Students & Interns	Eng Co-Op Training	Pre-doctoral Fellows	Student Observing Support	Jansky Fellows	NRAO Postdoc Fellows & Research Associates
2004	14	3	11	4	6	12	7	3
2005	18	3	10	4	7	10	10	2
2006	14	3	9	2	7	12	12	4
2007	15	1	21	4	8	21	14	7
2008	16	4	18	4	7	12	13	11

^ *REU=Research Experiences for Undergraduate, RET=Research Experiences for Teachers.*

For 25 years, NRAO has held the biannual Synthesis Imaging Workshop. These popular summer schools are designed to introduce graduate-level researchers to synthesis imaging techniques. The NRAO scientific staff runs the workshop and the majority of lectures are drawn from the staff. The synthesis workshop has educated 1,450 participants within the US and worldwide since its inception. Its style and format have been widely emulated by other National centers, including in the Single Dish school partnered by NRAO.

2.2 Engineering Impact

The Central Development Laboratory (CDL) of the NRAO has led the development of radio astronomy instrumentation in many areas, providing equipment to other observatories and strongly influencing R&D efforts at other observatories and universities. In particular, the CDL has been a world leader in the development of low-noise cryogenic amplifier technology. The CDL designs are being used in radio astronomy observatories worldwide. Notably, CDL designed and built all 80 low-noise amplifiers used in the very successful WMAP mission to measure the anisotropies in the cosmic microwave background. They are also used in CBI, DASI, and space communications systems for NASA and ESA.

NRAO engineers pioneered the change of Superconductor-Insulator-Superconductor (SIS) mixers from unreliable Pb-based junctions to reproducible, robust Nb-based junctions. Universal adoption of this new technology resulted in a great improvement in sensitivity at all mm and submm telescopes. NRAO improvements in SIS mixer design techniques have been universally adopted and made possible the sensitive ALMA receivers.

The NRAO pioneered the development of digital correlators after the initial invention at MIT in 1960. Used first for single-dish spectroscopy in 1963, further development led to construction for the VLA of the first large array cross-correlator and to other large systems including the ALMA correlator, capable of 1.7×10^{16} calculations per second. This work strongly influenced the universal adoption of the digital correlation technique at almost all other radio observatories. In 2009, NRAO will complete implementation of a software correlator at the VLBA, making it the first full-time, general-purpose radio interferometer to take this step.

NRAO engineers are engaged in R&D for the next generation of devices and instrumentation, including those important to the SKA, such as beam-forming arrays, which are also important to the GBT in the near term. University of Virginia and CDL engineers are developing NbTiN SIS devices, which are needed for best performance of ALMA receivers in the 1 THz bands. CDL R&D often has broad applications beyond radio astronomy. For example, a filter recently designed for a frequency down-converter is being patented for its broad commercial applications as a nearly reflection-less stop-band filter.

2.3 Community Collaborations

NRAO actively collaborates with the university and international community on a variety of instrumentation developments and scientific and educational initiatives. For example, New Mexico Operations and the VLA site host the Long Wavelength Demonstrator Array and have worked closely with the LWA consortium. Many of the VLBA antenna stations host geodetic GPS receivers that are used for long-term Earth science research. NRAO staff has supported the PAPER Epoch of Reionization demonstrator project, including engineering development and prototype deployment in Green Bank. Several instrumentation projects for the GBT have been led by or developed in collaboration with universities, including the MUSTANG bolometer camera, the Zpectrometer wideband spectrometer, the Caltech Continuum Backend, the Pulsar Spigot, and others. In fact, most of the GBT observing instruments released after initial telescope commissioning have been constructed through university collaborations. The development of FASR, the Frequency Agile Solar Radiotelescope, has been led by an NRAO staff member on behalf of a university consortium. Joint educational outreach projects include the Pulsar Search Collaboratory.

2.4 Education and Public Outreach

NRAO uses its visible and attractive radio telescopes to draw the public to a variety of outreach programs. These programs are organized around the Green Bank Science Center and the VLA Visitor Center, which receive 45,000 and 20,000 visitors per year, respectively; an ALMA Visitor Center also is planned for Chile. The Green Bank Science Center is fully staffed, and has been very successful in attracting additional funding for activities such as the Pulsar Search Collaboratory, where teachers and students work with a worldwide team of astronomers in discovering new pulsars. NRAO has developed plans to replace the VLA Visitor Center, based primarily on static exhibits and a self-guided walking tour, with a more modern educational facility; funds for this new facility are being sought from the New Mexico State Legislature.

The Observatory continues to seek funding for and to expand its range of residential programs for teachers, including the Chautauqua Program, Master of Science Teaching Class, and the Research Experience for Teachers program. NRAO will seek funding to transition its *Navigators* program, begun as a pilot with the Society of Amateur Radio Astronomers, into a national program. *Navigators* train volunteers to deliver engaging presentations about NRAO and radio astronomy in their home communities. We also continue the *Sister Cities* program initiated to link and provide mutual cultural and educational benefits for Magdalena, NM, and San Pedro de Atacama, Chile. These two widely separated communities share many characteristics, both hosting world-leading high technology facilities in remote, rural environments. The *Sister Cities* initiative is part of NRAO's *Broadening Participation* program that increases outreach, services, employment, and advancement to underrepresented communities.

The News & Public Information program publicizes scientific discoveries made by astronomers using NRAO telescopes, as well as programmatic achievements, such as completing major ALMA and EVLA construction milestones. As these telescopes come on line, we expect to increase our press-release rate from ~24 per year to ~36 per year. NRAO will continue to bring radio science into more than 180 major science museums and planetariums in North America via its participation in *ViewSpace*, a free multi-media electronic exhibit developed and managed by the Space Telescope Science Institute.

3. NRAO Going Forward

3.1 Strategic Goals for the Decade 2010-2020

In the coming decade, NRAO has five principal strategic goals:

1. Complete ALMA and EVLA successfully on schedule by the end of 2012;
2. Provide effective user support for a broad, multi-wavelength community;
3. Realize the vision of the SKA, in partnership with the U.S. and international community;
4. Achieve a quantum leap in GBT science capability with next-generation camera systems;

5. Maximize the scientific impact of the VLBA by key science programs and innovative partnerships.

ALMA and EVLA are both transformative instruments that will provide the scientific complement in the radio to submillimeter range to other leading facilities such as JWST, 30-meter class optical telescopes, LSST, etc. Both construction projects are international partnerships and are proceeding extremely well; continued excellent progress through commissioning and early science, to full scientific operation, is essential.

At the completion of ALMA and EVLA construction, NRAO will have a complete suite of the best radio telescopes in the world, including also the GBT and the VLBA. As a strategic goal, NRAO is enhancing user services for all its facilities, including delivering images as data products, and an integrated Observatory Science Operations division that provides unified user friendly access and support services to the community for all NRAO telescopes.

The Square Kilometer Array is the next major project at radio wavelengths and promises huge scientific breakthroughs. NRAO has the necessary expertise, experience and scale to provide technical and project management to the SKA, working in full concert and cooperation with community initiatives, both within the U.S. and internationally. NRAO has offered a concept for a cost-effective North America Array that could become the high-frequency portion of the SKA.

The enormous scientific potential of the GBT can be realized through development of next-generation camera systems. Such systems would increase the scientific throughput by factors ranging from 10-1000, enabling truly wide-field radio and mm-wave research into star-formation, high-Z galaxies, the S-Z effect, and other areas. The science is complementary to ALMA and EVLA, and the focal-plane array technology is highly relevant to the SKA.

Following the recommendation of the NSF Senior Review, NRAO is converting the VLBA to a subscriber facility in which external institutions provide approximately one-half of the annual operating funds and receive a commensurate proportion of the observing time. For open community time, NRAO will increase the science impact by emphasizing key science projects. This transition in VLBA operational mode will be completed in the early part of the next decade.

3.2 Operations & Facilities

To optimize the scientific impact of its facilities by making them easy-to-use by the broad, multi-wavelength community, NRAO is creating a new, integrated support division known as Observatory Science Operations (OSO) that will serve users of all NRAO telescopes and the common data archive. OSO services will include web outreach for the science community, web-based user portals, helpdesks, proposal preparation and submission, proposal review process, observation preparation support, observing usage and publication metrics, data processing, automated data pipelines, data archives and Virtual Observatory access, user training, advanced algorithm R&D, science user outreach, and community support programs.

In early 2013, ALMA will enter full scientific operation. This joint observatory with our international partners will have transformative capabilities in the mm/submm wavelength range, providing 10 to 100 times improvement over current sensitivity and a resolution that can be 10 times better than the HST. It is capable of imaging the tidal gaps in planetary formation disks in the nearest star formation regions (out to ~150 pc) and the molecular ISM in galaxies and quasars at redshifts up to z=12. ALMA will continue to enhance its capabilities through an ongoing instrumentation development program. Future development will include coverage of the 1 THz bands, as well as other planned ALMA receiver bands that were not populated as part of the initial generation of frontends.

The EVLA, with scientific capabilities comparable to ALMA in the adjacent mm and cm wave range, will also be completed at the end of 2012. It provides a 10-fold improvement in continuum sensitivity and greatly enhanced spectral capability compared to the VLA. The EVLA will have 1μJy/beam continuum sensitivity and 1mJy/beam line (1km/s) sensitivity in 9 hours of observation, and an angular resolution as small as 30 milli-arcsecond. The EVLA has four, primary science themes: measuring the strength and topology of the cosmic magnetic field, imaging young stars and massive black holes in dust-enshrouded environments, following the rapid evolution of energetic phenomena, and studying the formation and evolution of stars, galaxies, and AGN. Follow-on development includes a compact E-array and the North America Array build-out, as a pathfinder to SKA-High.

The GBT is in mature operation with first-generation instrumentation and working toward a second generation of focal plane arrays (cameras). The GBT has comparable collecting area to ALMA and EVLA, and thus similar point-source sensitivity. When properly equipped with camera systems, the GBT will provide the sensitive, wide field complement to ALMA and EVLA for Galactic and extragalactic research. In addition, the GBT has unique capabilities for pulsar studies and will be enhanced for key science projects in gravitational wave detection.

The VLBA remains the foremost astrometric observatory in existence, capable of measuring to the ~10 μarcsec level. Key science projects include the Megamaser Cosmology Project, that aims to determine the Hubble Constant to ~3% accuracy as a first step toward the ultimate 1% goal, and precision measurements of the structure of the Milky Way, which recently determined that the mass of the Milky Way is about 50% greater than previously believed, comparable to that of the Andromeda Galaxy. The VLBA is undergoing a significant upgrade that will increase its sensitivity by a factor of ~16, making its resolving power available for addressing many more astronomical problems.

3.3 Future Telescopes

The EVLA and ALMA increase by orders-of-magnitude the discovery space in centimeter- and millimeter-wave astronomy in the upcoming decade. Results from these and other next-decade telescopes such as JWST will have a huge impact on plans for telescopes in 2020-2030. Thus, NRAO will remain flexible so that we can respond to the scientific opportunities revealed in the next decade. An organizing framework of future centimeter/meter-wave telescopes is the SKA Program, which incorporates components at "low" (up to a few hundred MHz), "mid" (a few hundred MHz to a few GHz), and "high" (a few GHz to 25-50 GHz) frequencies. NRAO endorses a science-based approach to this program, with component projects led by the US and international communities.

At the lowest frequencies, probing the universe at the Epoch of Reionization (EoR) is a clear science driver, while radio transients will provide a window into the unknown. NRAO scientists and engineers will continue to collaborate on developmental telescopes (MWA and PAPER) aimed at first detection of redshifted HI from the EoR. We will support the Reionization and Dark Ages Radio experiment (RADARe), the next step toward SKA-low.

At frequencies up to a few GHz, construction funding is being sought for an SKA-mid telescope in Australia and/or South Africa. A prime science goal is to understand the formation of structure in the Universe by studying the evolution of the HI content of galaxies, and measuring Baryon Acoustic Oscillations out to redshift z~2. Cost-effective paths to SKA-mid are under development, and should lead to construction readiness in the second half of the decade. With ALMA and EVLA construction winding down, the NRAO will increase its participation in SKA-mid design efforts. It is also providing assistance in the development of the precursor and path-finding telescopes for SKA-mid, notably MeerKAT in South Africa and the Allen Telescope Array in California.

The frequency range from a few to 50 GHz is exemplified by SKA-high, to be built after 2020 and likely to replace the EVLA and VLBA. This telescope would have at least 10 times the sensitivity of EVLA, and resolution similar to the VLBA. SKA-high requires a high, dry location, and is naturally centered at the EVLA site. The prime long-term goal is "cradle of life" astrophysics, carrying forward the ALMA and EVLA results on planet, star, and galaxy formation. In the coming decade, there will be a detailed investigation of the structure of our Galaxy by high-bandwidth VLBA astrometry. Tests of cost-effective technology will prepare NRAO for the construction of the North America Array (http://www.nrao.edu/nio/naa), as the implementation of SKA-high after 2020. A separate white paper on this plan is being submitted to the Program Prioritization Panel.

4. Summary – NRAO and Astronomy: 2010-2020

The NRAO is dedicated to its mission of enabling astronomers to explore the Universe and to pursue the outstanding questions in Astronomy and Astrophysics by providing cutting-edge astronomical facilities at radio wavelengths and related resources for the entire astronomical community. As a cornerstone of the current and future multi-wavelength suite of key ground- and space-based observatories, its radio telescopes carry out a broad program of astronomical observations in response to the research proposals submitted by its diverse user base. In this era of big science, NRAO is also committed to facilitating the individual scientist's pursuit of novel and unexplored research, by sharing its scientific and technical expertise in radio astronomy beyond simply providing telescope time. Through the ambitious new initiatives outlined in this white paper, the NRAO aims to preserve the US core competency in radio astronomy via a portfolio of proposal-driven, key scientific projects, university partnerships, education and outreach, and advanced technology development that will take its telescopes, and the astronomers and educators they serve, into the next decade and beyond.