The NRAO Strategic Plan

November 1, 2016

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

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Foreword

The National Radio Astronomy Observatory (NRAO) is the preeminent radio astronomy organization in the world, and the primary U.S. observatory accessing this astrophysically-important wavelength regime. For more than half a century, the NRAO has pioneered the science and technology of radio astronomy. The NRAO collaboration with the U.S. and international research communities has transformed our understanding of the Universe, and driven numerous important discoveries. 'The NRAO's capabilities are unique in the radio spectrum, and will remain so for the foreseeable future. The JVLA and ALMA have established themselves as cornerstone facilities in the suite of 21st century state-of-the-art telescopes, ranging from X-ray through radio wavelengths, and now gravitational waves, that power discovery in modern multi-messenger astronomy. Our commitment to excellence in science and engineering has made us a key partner for the U.S. and global astronomy community in exploring the Universe on all scales.

This document describes our strategies and goals for the future, focusing on the coming decade leading to the 2030s. The U.S. Decadal Survey process will begin again in 2018, and aligning the NRAO's mission, abilities, and initiatives to bridge the Astro2010 outcomes and Astro2020 aspirations is a challenging task. The initiatives in this Strategic Plan have been developed to focus the Observatory on issues of vital importance to the research community. Detailed planning is underway along parallel paths to implement these initiatives effectively and efficiently, consistent with our understanding of future funding from our federal sponsor, the National Science Foundation – Division of Astronomical Sciences (NSF-AST). The NRAO also obtains additional funding from various U.S. and international sources when such funding opportunities are consistent with the Observatory's mission and vision.

The strategic plans, goals, and initiatives proposed here have been developed with input from funding agencies, our management organization Associated Universities, Inc. (AUI), the U.S. research community, and the NRAO staff. As the scientific, funding, and collaborative environment continues to evolve, we too will continue to evolve our strategies to deliver excellence. The audience for this document includes our federal sponsors, the research community we serve, the general public that supports our endeavors, and the NRAO staff itself. As indicated in Figure 1, the NRAO Strategic Plan is a key component of a suite of Observatory foundation documents, which connect the Observatory mission to other Observatory planning activities. The goals and initiatives in these high-level documents are adopted by the departments, and ultimately drive the individual tasking and performance priorities of the staff. Additional supporting and reporting information informs the decisions and assesses progress towards the strategic initiatives.

By linking the Observatory's mission, vision, goals and initiatives, investment priorities can be clearly evaluated, effective and mutually beneficial partnerships can be established with the research community, and the NRAO staff can readily develop personal performance objectives that align with Observatory strategies.

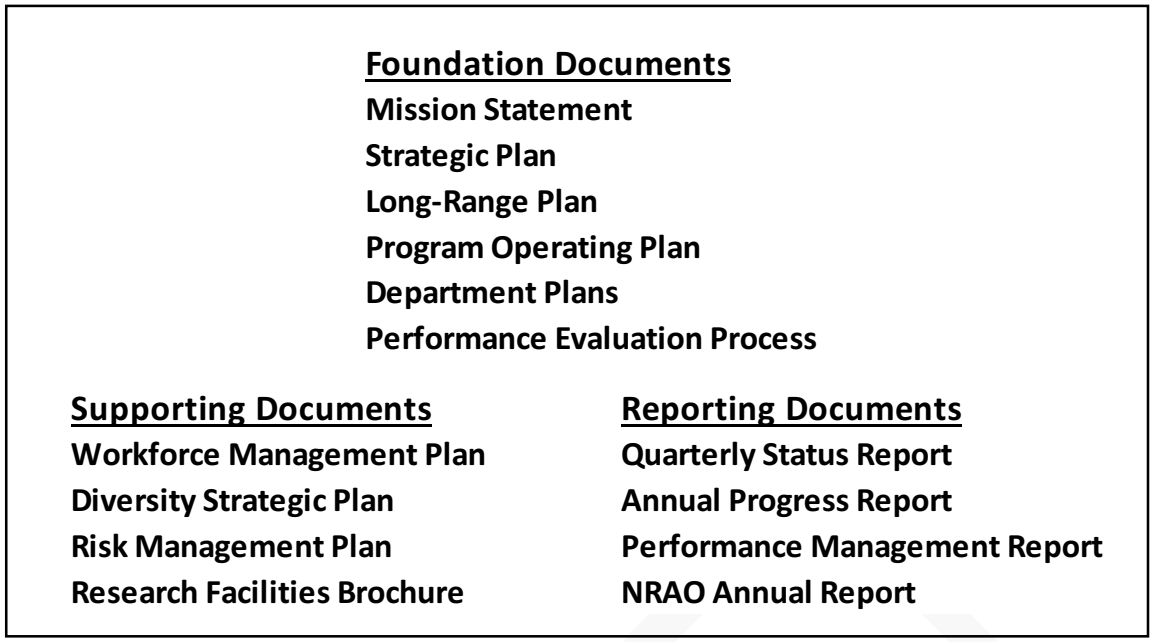

Figure 1 – Strategic Document Hierarchy, including Foundation/Supporting/Reporting Components

Our 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,***
- ***train the next generation of scientists and engineers, and***
- ***promote astronomy to foster a more scientifically literate society.***

The NRAO mission derives from and builds upon the mission of the Observatory's management organization, AUI:

> *AUI collaborates with the scientific community and research sponsors to plan, build, and operate cutting-edge facilities. We cultivate excellence, deliver value, enhance education, and engage the public.*

and the NSF mission:

> *To promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense; and for other purposes.*

The NRAO Organization

From a strategically placed location in Charlottesville, Virginia, the NRAO supports a complementary suite of powerful telescopes for exploring the Universe. The NRAO Headquarters has been located in Charlottesville since December 1965, and provides proximity to our funding and managing organizations (NSF and AUI) in Washington, D.C. The NRAO Headquarters are on the grounds of the University of Virginia, a renowned astronomy, chemistry, physics, and engineering research environment with which the NRAO staff interact. The Charlottesville facilities include the Director's and administration offices, the North American ALMA Science Center (NAASC), and the NRAO Central Development Laboratory (CDL). The NAASC supports community preparation, observing, and data reduction for ALMA observations, and CDL / NAASC support maintenance and development of key ALMA hardware and software.

In New Mexico, the NRAO operates the Karl. G. Jansky Very Large Array (JVLA) on the plains of San Agustin, southwest of Albuquerque. In Socorro, NM (45 miles from the JVLA) the Pete V. Domenici Science Operations Center (DSOC) on the campus of the New Mexico Institute of Mining and Technology provides a base for scientific, technical, and administrative support for the JVLA.

In Chile, NRAO is a major partner in the Atacama Large Millimeter/submillimeter Array (ALMA), an international collaboration to operate the world's most advanced, large-scale millimeter/submillimeter telescope in the high-altitude Atacama Desert of northern Chile. ALMA scientific and technical operations are based at the telescope site, in offices in Santiago, and are distributed throughout the ALMA partner regions in North America, Europe, and East Asia.

ALMA is funded in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan, in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), and in North America by the U.S. NSF in cooperation with the National Research Council of Canada (NRC) and the Ministry of Science and Technology (MOST) in Taiwan. In North America, activities supporting ALMA are carried out at several NRAO facilities.

The NRAO also partially supports other radio observatories used by the scientific community, including the Green Bank Observatory (GBO) in Pocahontas County, West Virginia, which operates the Green Bank Telescope, and the Long Baseline Observatory (LBO) which operates the Very Long Baseline Array (VLBA) that spans the western hemisphere from Hawaii to St. Croix in the U.S. Virgin Islands. Collaborations with other observatories around the world are listed in the "Partnerships" section below.

The NRAO is the preeminent radio astronomy organization in the world and stands unrivalled on a platform of organizational stability, science management experience, and broad community interfaces provided by AUI. NRAO and AUI have faced many challenges, learned from successes and failures, supported remarkable science and people, and built and operated one of the world's great observatories while playing a leading role in a global partnership to build and operate ALMA.

Core competencies of the NRAO include:

- **Astronomical Research** – To promote leading-edge research with our instruments, NRAO collaborates extensively with the U.S. and global scientific and technical community. Having a world-class active scientific staff engaged in the research areas addressed by our instruments is critical to ensure that we understand the needs of the community, and that we are focused on the most important scientific challenges of the age. A cutting-edge science and engineering staff, acting in close collaboration with the community, pushes the boundaries of instrumental capabilities, thereby enabling the full science return for the community on the major infrastructure investment by the NSF. The NRAO expert staff work in concert with the community to foster the long-term development of radio astronomy, thereby keeping the U.S. a global leader in the field. The research carried out by the NRAO scientific staff, and their collaborations with scientists across the world, establishes our relevance and excellence in the field of astronomy, and demonstrates the sense of exploration and wonder about the Universe at the foundation of our Observatory culture. Our research enhances our service to the community, and sustains our excitement and enthusiasm for radio science.

- **Technology** – NRAO pursues new methods and technologies across many disciplines (e.g. radio and digital engineering, software, computing and algorithmic research) to keep the organization and field of astronomy vital and evolving in capabilities. NRAO delivers world-class instrumentation for the detection, processing and analysis of electromagnetic waves at radio frequencies extending from 70 Megahertz to a Terahertz. It is a world leader in signal processing and imaging software and astronomy-related computing, including data management.

- **Operations & Project Management** – Over the course of five decades, the NRAO has successfully built, operated and upgraded a suite of world-class research instruments and astronomy facilities both domestically and internationally, spanning most areas of radio astronomy endeavor. Our demonstrated strength and global reputation is based upon our success in building major instruments with cost-effective facility operations for use by a broad U.S and international community of professional astronomy researchers, delivering outstanding science.

- **Administration & Human Resources** – Efficient scientific and technical operations require a high-quality framework of supporting administrative and consultant services, including financial and budget services, performance tracking, human resource activities, procurement, facility maintenance and environmental/safety compliance. NRAO applies a distributed services model, with key and support personnel in administrative services and human resources assigned to the operating sites.

- **Education and Public Outreach** – NRAO provides world-class education and public outreach activities that address diversity and reach out to underrepresented populations across the U.S. and throughout the world.

Our Core Principles

NRAO staff contributions have enabled innumerable past successes, form the foundation of our current competencies and strengths, and will be critical to realizing our vision for the Observatory's future. An organizational culture that amplifies and rewards excellence supports our staff and these efforts and arises from a set of closely held core principles. These principles are visible at all levels of the organization, and guide our actions and decisions.

- **We Are Science-focused, Curiosity-driven** – As an Observatory, we align our scientific, technical, and administrative activities to produce the best outcome for the research community. We follow our instincts into new areas passionately. The NRAO supports an active and vibrant scientific staff, and involves them across the Observatory to ensure that we simultaneously see the big picture, the details, and the path forward associated with leading-edge science, and new technologies of interest to astronomy and society.

- **We Are Committed to Excellence and Innovation** – Our goal is to lead the world in radio astronomy research and instrumentation, in the training of scientists and engineers, and in the broad dissemination of scientific knowledge and discovery. We define the leading edge of our field.

- **Communications and Collaboration Guide Us** – We work closely with the research community and other interested parties to understand their needs and desires, and use a variety of methods to choose the right investment priorities and to determine the quality and effectiveness of our investments throughout their lifecycle. Expert evaluation and external reviews and assessments provide important guidance for continuous improvement, as do expert external advisory committees. Increasing the research community's awareness and understanding of our capabilities is another key goal. Additional guidance and oversight is provided by AUI. For more than six decades, we have worked with domestic and international partners to pursue compelling science initiatives, support state-of-the-art technical development, and develop human capital to its maximum potential.

- **We Support Open Skies** – The NRAO operates its telescopes under Open Skies, a core principle which provides qualified scientists access to our research facilities solely on the basis of scientific merit, regardless of institutional or national affiliation. We believe this is an important element of maximizing the scientific impact achieved from NRAO's telescopes. Historically, NSF has required that this policy be followed at the national astronomy centers: the National Optical Astronomy Observatory, National Solar Observatory, the National Astronomy and Ionosphere Center (NAIC), and the NRAO. The U.S. share of ALMA observing time is administered under the Open Skies policy. We support national initiatives led by the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE) and NSF to reframe Open Skies in a way that balances the policy's fundamental idealism with the need to optimize the partner-based investment strategies critical to making the next large U.S. radio astronomy project a

reality. Such a reformulation must allay the tensions within the U.S. astronomy community that have arisen over the support of facilities that are heavily used by non-U.S. researchers.

- **NRAO Creates Safe Working Environments** – The NRAO is committed to the protection of the environment, and to providing a safe and secure workplace. This commitment is an essential part of our endeavor. Creative and cost-effective environment, safety, and security solutions are necessary for our long-term success. Meeting this commitment is a responsibility shared by the entire NRAO staff.

- **Increasing Our Internal and Community Diversity is Critical** – We believe that a diverse staff is critical for our mission to enable world-class science with cutting-edge radio facilities for the scientific community, to train the next generation of scientists and engineers, and to foster a scientifically literate society. The NRAO is committed to a diverse and inclusive work place culture that accepts and appreciates all individuals regardless of race, gender, gender identity/expression, age, ethnicity, ability, sexual orientation, socioeconomic status, religious affiliation, or national origin and culture.

- **Broadening Participation is our Responsibility** – The NRAO endeavors to bring the benefits of radio astronomy and our technical accomplishments to the public, to support science and technology education at all levels, and to broaden participation in these fields. Through targeted programs, we seek to increase the participation of traditionally under-represented and under-served communities in the mission of the Observatory, helping to grow an inclusive scientific and technical workforce. To ensure an enduring ability to do forefront research, the NRAO must cultivate a pipeline of new scientific and engineering talent, and help the public becomes increasingly scientifically literate. It is imperative that astronomy attract talents to the Observatory from around the globe and across social spectra.

- **We Demand Ethics and Integrity from our Staff** – The NRAO staff is committed to the highest standards of ethical conduct across all areas of activity. Ethical conduct includes embracing honesty, fairness, respect for others, honoring commitments, displaying compassion, possessing integrity, taking responsibility for actions, and seeking excellence. All staff members have a responsibility to: support ethical behavior; comply with applicable laws and regulations; support the rights of the others in the work place; promote conditions of free investigation and inquiry; follow legal, equitable, and fair employment practices; and further understanding. NRAO is a careful steward of the National Science Foundation funding – we believe that it is our responsibility to use the funding we are provided for priorities identified by our customer and the scientific users of our facilities.

- **We Engage our Staff –** NRAO engages its employees in a variety of manners. The Director holds face to face all hands meetings at all locations three times a year. One hundred percent of employees receive an annual Performance Evaluation Plan. Employee climate surveys are cyclically performed on a variety of subjects. Recent examples include:

"Climate for Women at NRAO survey;" "NRAO Employee Climate Survey;" "Employee Safety Culture Survey;" and "Benefits Awareness and Satisfaction Survey."

- **Scientific training, literacy and interest** – NRAO works to provide and foster scientific training of staff and of graduate students in astronomy, and to foster and facilitate scientific interest and knowledge in the broader community and public. We contribute to these ends through the distinct but connected threads of astronomy, computing and engineering, and see the importance of maintaining interest and knowledge in the STEM disciplines as fundamentally important for the future well-being of society.

The NRAO Vision

The NRAO vision is to further grow our role as the world's premier radio astronomy observatory, enabling astronomers to pursue answers to the outstanding questions in astronomy, astrophysics, and other sub-disciplines in innovative and creative ways using techniques at radio wavelengths, and to drive the field of astronomy toward new capabilities and discoveries. In the next decade, the NRAO will be operating two leading-edge interferometer telescopes, ALMA and the JVLA, enabling scientists to observe from meter to sub-millimeter wavelengths with world-leading resolution, sensitivity, frequency coverage, spectral line capabilities, and field of view. These telescopes will operate with great technical and operational synergy, providing the resolution and sensitivity necessary to image structures ranging from milliarcsecond to degree scales, and will complement major observatories at other wavelengths as essential tools for discovery in all areas of modern astrophysics. NRAO's vision further includes working with the community to define, plan for and enable the next generation of forefront radio astronomy facilities.

To achieve this vision, the NRAO must focus on providing the community engagement and user support necessary to maximize the scientific utilization and the science impact of its facilities by the broader astronomy community. This will be provided through state of the art instrumentation producing data products ready for scientific analysis via a suite of powerful analysis tools, accessed from high-quality, easily-explored data archives, inside a user-friendly research environment that facilitates scientific productivity. NRAO believes that a contingent of outstanding engineering staff who can extend the technical limits of the instruments, computing staff who continually innovate and extend the processing capabilities of the software and the hardware, and a scientific staff whose creativity and expertise can inform and enhance the user experience, are critical to best serve the community and push the boundaries of the NRAO telescopes. Developing the human capital required to maintain NRAO's preeminent role is an important challenge.

Through the ambitious goals and initiatives outlined in this Strategic Plan, the NRAO will seek to achieve its vision for the Observatory and the science of astronomy, aiming to preserve and amplify the U.S. core competency in radio astronomy. This portfolio of technical and operational developments, key scientific projects, new university partnerships, and advanced technology development will carry our telescopes, and the astronomers and educators they serve, into the next decade and beyond. In parallel, we seek to broaden the use and appreciation of our facilities, and increase diversity at all levels, creating engaged and excited partners in scientific exploration.

Strategic Goals & Initiatives

We identify the following high-level strategic goals for the Observatory to fulfil the NRAO mission:

- Increase the scientific impact of the NRAO, including operating forefront telescopes with enhanced user support. Work with other observatories, including those outside the radio waveband, to provide balanced and simplified research support across the electromagnetic and multi-messenger spectra.
- Advance the state-of-the-art in mission-related technology, and play a leading role in developing next-generation of instrumentation, data processing and computing techniques in collaboration with the university community.
- Continue to work with the radio astronomy community and the NSF to achieve the best possible facilities for astronomical science consistent with the available resources, be an effective steward of federal funds, and create an exciting, diverse, challenging, positive working environment for the NRAO staff.
- Be an expert resource for professional scientists and the public.
- Provide and foster outstanding scientists, data and computing experts and engineers as resources for both NRAO and the broader scientific, technical and educational communities.
- Broaden participation in our research endeavors, and increase diversity at all levels, engaging students and the public in the excitement and importance of radio astronomy and NRAO's work, and improving our visibility in the national decision-making arena.
- Be a model for integrity and ethics in the workplace.

Achieving these goals will assure the scientific community has the best possible radio astronomical facilities to address outstanding astronomy problems and to make new discoveries, and create vibrant national radio astronomy programs in the U.S. university community, far into the future. These strategic goals also directly reflect the goals and vision of the National Science Foundation that led to the creation and long-term support of the NRAO.

The following major strategic initiatives will play a key role in enabling the NRAO to achieve its strategic goals:

Developing ALMA Capabilities

Discoveries are already being made with ALMA that are motivating the design and creation of new instrumentation and analysis techniques, and the march of technology is rapid. The focus in the next several years will be on completing and extending ALMA capabilities, and developing new analysis tools to enable and expedite Principal-investigator science. The ALMA Science Advisory Committee is developing priorities and themes to guide this ALMA development, and

North American ALMA Development funding will continue to be openly competed to promote new ideas. Development funding will be an important enabler in sustaining U.S. university development groups. The NRAO will convene workshops to engage key community instrumentation groups, and provide in-kind science support to approved development projects and external projects.

In coordination with the North American community, its international partners, and ALMA science advisory committees, the NRAO will propose an innovative upgrade plan for ALMA for the National Academies 2030 Decadal Survey. This program will be based on the scientific experience of the first two decades of ALMA scientific operation and the progress of technology development. We anticipate an upgrade focusing on major capability extensions, such as multi-beam receivers, wider frequency bands and/or more frequency channels (and the greater data rates that result), longer baselines, enhanced VLBI, and receiver bands above 1 THz, as well as advanced software tools for improved imaging, analysis, visualization, and data mining. Capabilities that improve ALMA synergy with relatively new and planned state-of-the-art facilities, such as ngVLA, JWST, LSST and large optical/infrared facilities (e.g. TMT/GMT/EELT) will also likely be strongly supported by the community.

Renewing JVLA Infrastructure and Developing a next-generation VLA – ngVLA

We are implementing a "3+7" initiative beginning with a three-year JVLA infrastructure renewal, and followed by a seven-year period of planning and prototyping, in collaboration with the US university community, exploring the science case and technology of a next-generation centimeter-wave facility with the JVLA at its core – a next-generation VLA (ngVLA), centered on the existing JVLA site.

As the JVLA approaches its fourth decade of continuous operations, a number of larger infrastructure needs must be addressed going forward. Engineering lifetime studies have identified the most urgent needs as the electrical system, the antennas, and the rails. Over the next three years we will replace key components of these subsystems; the payoff will be in extended lifetime, greater safety during antenna moves, and lower maintenance costs. Infrastructure renewal is ultimately tied to reducing annual operating costs. These improvements comprise an operations model of "best practices" that can be adopted by other existing or planned facilities looking to reduce lifecycle cost. This initiative will support the effective use of the JVLA through the end of the next decade.

In parallel, the JVLA development program will focus on the planning and technologies required for a next-generation millimeter and centimeter-wavelength facility. The ngVLA development program will define the most compelling science case and technical requirements for an affordable next-generation telescope system capable of achieving the community's most ambitious scientific goals. Given the existing large investment, the JVLA is a natural nucleus from which to explore what scientific opportunities exist in centimeter astronomy.

The NRAO is engaging the U.S. and international community in the discussion of this next-generation mega-radio facility, building on the legacies of ALMA and the JVLA. Community science working groups, along with community-led science and technical advisory councils, are considering the future of astronomical discovery space and identifying the role that radio astronomy can and will play in the coming decades. The goal over the next 3 years is to develop a compelling, community-driven science case, and a quantified technical design, for presentation at the up-coming decade survey.

The basic ngVLA design emerging from the initial discussions involves an interferometric array with ten times larger effective collecting area and ten times higher spatial resolution than the JVLA and ALMA, optimized for operation in the wavelength range 0.3cm to 6cm. The ngVLA opens a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milli-arcsecond resolution, as well as unprecedented broad-band continuum polarimetric imaging of non-thermal processes and time-domain science. The design remains under active consideration and revision, both scientifically and technically, and the broader community is fully incorporated in setting the design goals of the ngVLA.

We are carefully monitoring progress with the SKA project. The ngVLA design currently focuses on exploiting the frequency range between the future SKA, which will be a superb instrument at decimeter and longer wavelengths, and the ever improving ALMA as the state-of-the-art facility at sub-mm wavelengths. The ngVLA could be considered the 'high-frequency component' of the SKA program, and possibly provide a viable way for the U.S. to participate in the global SKA project, while retaining key domestic infrastructure and intellectual investment. The envisioned system of telescopes operating from meter to sub-mm wavelengths will lead astrophysical discovery well into mid-century. At the core of any plan is the realization that the U.S. university community must take a leadership role to help define the final science case and carry out significant pieces of the required development work.

A VLA Sky Survey – VLASS

The NRAO is undertaking a new survey of the radio sky, the Very Large Array Sky Survey - VLASS. This is an important Observatory science initiative, designed and implemented in partnership with the U.S. and global science communities. The survey will take ~6000 hours to execute, spread over seven years starting in October 2017, with a pilot survey carried out in summer 2016.

The VLASS will deliver the sharpest view of the whole radio sky visible to the JVLA, enabling data-driven science connecting the radio to optical, infrared, and X-ray/gamma-ray wavelengths. The unique ability of the JVLA to collect data over an entire octave in frequency (2-4 GHz) in a single observation will determine the spectra of hundreds of thousands of radio sources and the properties of the intervening plasma along the line-of-sight between the radio sources and the observer to be characterized in a way that has not been previously possible. By carrying out the survey in three passes over the whole sky visible to the JVLA, with half the sky being imaged every 16 months, each time the B-configuration is available—the JVLA will be able to find transient

sources during the survey period. In total, the VLASS will detect nearly 10 million radio sources, about four times more than currently cataloged.

The VLASS will serve as a portal for students, educators and citizen scientists to access the world of radio astronomy. VLASS will produce high-quality data products that can be used to involve the public and stimulate their curiosity in astronomy and science. The NRAO is looking to leverage community efforts to make and store enhanced VLASS data products. The VLASS is designed to complement, rather than compete with, surveys planned by two SKA precursors, the Australian SKA Precursor (ASKAP) and the Karoo Array Telescope (MeerKAT). By observing at a higher frequency and with higher angular resolution, the JVLA will be able to study source details that are inaccessible to lower frequency surveys, but researchers will be able to use those other surveys to obtain accurate flux densities for the few percent of large radio sources that will be partially resolved by the VLASS.

Central Development Laboratory: New Focus and Growth

The nearly simultaneous completion of the JVLA and ALMA construction projects recently led NRAO to reduce the Central Development Laboratory (CDL) staff in several important technical areas. To address the significant technology development required for upgrades of our existing instruments, and development a next-generation U.S. radio telescope system, the CDL will reinvigorate its staff and infrastructure in the coming decade. New engineers and technicians will be hired to support the NRAO initiatives, and CDL will reestablish its global importance in radio astronomy technology development.

As radio receiver technologies have essentially reached their quantum limits for frequencies up to ~200 GHz, new projects requiring high sensitivity will require CDL engineers and scientists to develop novel approaches to antenna design and fabrication that offer drastically reduced cost per unit area and employ low-maintenance, lightweight mounts with inexpensive precision encoders. Radically new low-noise detectors with reduced cooling requirements will be required, including coherent and incoherent devices and associated down-conversion technologies. Ultra-wide band front ends (feeds and multi-octave receiver systems) that consume significantly less power will be required, along with novel dewar materials and refrigerators.

This CDL initiative envisions developing hybridized correlator designs and technologies that focus on flexible chip and system architectures based on new integrated circuit designs that limit power consumption. Technology development will be required to support the anticipated massively increased system data throughput of a next generation telescope, including highly integrated and fully digital front-end systems that are supported by the high-speed digital processing systems that will be needed for multiple beam throughput.

CDL will proactively nurture the community by enhancing undergraduate and graduate mentoring and exchange programs will be developed with sister laboratories in the U.S. and abroad, enabling staff to sharpen their technical skills and broaden their understanding of ongoing advances. CDL staff will be encouraged to increase cooperation with teaching and lab-based instrumentation

programs in the UVa Electrical Engineering and Astronomy Departments, and will maintain the NRAO collaboration with the UVa Materials Laboratory. CDL will continue collaborations with domestic laboratories such as NASA-JPL, and will expand existing programs with international partners, for example Canada's National Research Council-Herzberg radio astronomy technology program at Dominion Radio Astrophysical Observatory, the South African SKA project and China's Shanghai Astronomical Observatory.

This personnel development initiative will be complemented by infrastructure modernization, including the replacement and updating of critical equipment, such as high-precision Computer Numerical Control machines, high-speed digital oscilloscopes, and other appropriate research equipment.

Science-ready data Products

The NRAO has a long-standing design priority to provide Principal-Investigator teams with fully calibrated and imaged data cubes that can be used immediately for scientific analysis, i.e. Science-Ready Data Products (SRDPs). Producing SRDPs for investigators is an AUI goal for both ALMA and the JVLA. SRDPs are a key mechanism for expanding the NRAO user base and making radio astronomy accessible to all astronomers. The availability of SRDPs will improve accessibility and eliminate the considerable hurdles of interferometer calibration and large datasets, and the complications of imaging and de-convolution that occur, e.g., with the wide fractional bandwidths of the JVLA.

Associated with SRDPs are several key software/computing initiatives, including

- CASA Revitalization – CASA is the NRAO flagship post-processing package for the JVLA and ALMA. CASA is also the development base for several initiatives. An active forward-looking CASA development path is critical for leveraging the NRAO investments and moving our community forward.
- Visualization – The NRAO is actively exploring the development, implementation, and delivery of new visualization and analysis software. The objectives of this initiative include the definition and creation of a common software platform for the visualization, manipulation, and analysis of the large-scale data cubes / hyper-cubes output by ALMA and JVLA/ngVLA.
- Distributed Data Access – This initiative will enable the community to access and process NRAO data and data products from distributed centers and the cloud. This capability will be critical to delivering large data volumes and high-end processing capabilities to users without the NRAO becoming a high performance computing (HPC) center.
- Advanced Algorithm Development – This initiative will develop the algorithms and next generation software and firmware that will enable data processing for NRAO telescopes and programs. Key JVLA scientific drivers, with applications to SKA, require very wide-field, ultra-deep imaging in full-polarization.
- High Time Resolution Processing – This initiative will deliver the hardware, software, networking, computing infrastructure, and algorithms to acquire ALMA and JVLA data at high data rates and volumes. This includes "Burst Mode" observing at extremely high data rates, as well as support for long-term observing at more modest rates but high overall

volume. This capability will be of increasing interest in the Large Synoptic Survey telescope era.

Expanding Education & Public Outreach, Broadening Participation

The NRAO endeavors to bring the benefits of radio astronomy and our technical accomplishments to the public at large, to support science and technology education at all levels, and to broaden participation in these fields. Through targeted programs we seek to increase the participation of traditionally underrepresented and under-served communities in the mission of the Observatory, helping to grow an inclusive scientific and technical workforce.

The NRAO will conduct vigorous programs of public outreach and Science, Technology, Engineering, and Mathematics (STEM) education that incorporate our knowledge and discoveries to strengthen education and public awareness of radio astronomy science, engineering, and technology. To promote and support these activities, the NRAO will develop alliances with local, national, and international organizations that build on existing programs and infrastructure and develop innovative approaches that increase NRAO's educational and media impact.

To ensure the NRAO has an enduring ability to do forefront research, we must cultivate a pipeline of new scientific and engineering talent, and to help the public become increasingly scientifically literate. It is also imperative that the NRAO continues to draw scientific and technical talents to the Observatory from around the globe.

Improving diversity and broadening participation in NRAO's activities are important elements of NRAO's mission. The NRAO National and International Non-Traditional Exchange (NINE) Program's primary objectives are to:

- provide supported short programs (typically nine-weeks duration) designed to teach sustainable skills in any STEM functional area associated with radio astronomy that can ultimately be applied in the home location,
- to form long-term mentor/mentee relationships with staff at the NRAO, and
- position the participant to successfully develop a NINE Hub, capable of providing training in the STEM field of experience to their local communities.

Expanding this program is a key initiative of the Observatory.

In parallel, the NRAO National Astronomy Consortium (NAC) led by the NRAO in collaboration with the National Society of Black Physicists (NBSP) and a number of minority- and majority-serving universities and observatories, has the goal to build a pipeline of students from underrepresented and underserved groups to STEM fields that support 'full-spectrum' astronomy. The NAC uses a cohort model, multiple mentors, professional development, and lifelong career mentoring to increase participation of underrepresented groups in astronomy-related careers. The NAC will host an annual fall conference. This workshop is designed to maintain and increase participation from Minority-Serving Institutions and Majority White Institutions and Universities, and to build and sustain an enduring pipeline of underrepresented future STEM leaders.

Square Kilometer Array Engagement

To play a leading role in the development of next generation facilities on a global scale, the NRAO will participate in relevant SKA technology research and development, in collaboration with the U.S. and international communities. The SKA project represents the current plan by a number of countries for the next international radio facility; the plan is for a set of meter- and centimeter-wave interferometers to be located in South Africa and Australia, with a collecting area of a million square meters. The International SKA Organization is currently working on "Phase I" low- and mid-frequency arrays representing roughly 10% of the hoped-for final collecting area.

The NRAO will explore possible synergies with SKA development through continual development of its facilities and technologies, and consideration of ngVLA as an implementation of SKA-High. We will use our current facilities to perform unique scientific programs that inform the design, techniques, and science of the SKA, such as pushing to sub-uJy sensitivities at high spatial resolution. It remains to be seen how the international SKA project will evolve; the NRAO will continue to engage with the SKA on behalf of the U.S. astronomy community, seeking balanced opportunities for collaborations and involvement.

Partnerships

In the coming decade, NRAO will continue to grow a portfolio of national and international partnerships with universities, research laboratories, key industries, and private sector research facilities that will assist NRAO in achieving the strategic goals in this plan. These partners will invest substantial intellectual and financial resources toward high priority NRAO activities and will work collaboratively with AUI and the NSF to ensure NRAO fulfills its mission.

The NRAO participates in several important instrumental developments arising from the U.S. community, including NANOGrav (the NA NanoHertz Observatory for Gravitational Waves), HERA (the Hydrogen Epoch of Reionization Array), the LWA/VLITE (Long Wavelength Array/ VLA Low Frequency Ionosphere and Transient Experiment), and NRAO scientists are connected to efforts to build a next-generation radio-heliograph. In all cases, NRAO technical, operational and administrative resources are made available to support our partners.