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Final
Long Range Plan for the
National Radio Astronomy Observatory
FY2019–2023

PREPARED BY	ORGANIZATION	DATE
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Change Record

VERSION	DATE	REASON
Final	2017-12-19	NSF approved preliminary report at December Program Review – report is now final
1.2	2017-09-30	Preliminary version to NSF
1.1	2017-08-29	Proofread & edits
1.0	2017-08-08	Edits from ADs

Final
Long Range Plan for the National Radio Astronomy Observatory

FY2019 – 2023

12-19-2017

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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1. OVERVIEW

This Long-Range Plan (LRP) describes Fiscal Year (FY) 2019–2023 activities, operations, and initiatives that support the National Radio Astronomy Observatory (NRAO) Strategic Plan, which provides a compelling, long-term vision for NRAO and strategic guidance for Observatory initiatives. This is the second NRAO LRP crafted within the framework of the new Cooperative Agreement established by the National Science Foundation (NSF) with Associated Universities, Inc. (AUI) for the operation of the NRAO up to FY2026.

During FY2019–2023, the NRAO will deliver transformational scientific capabilities that will enable the astronomy community to make new discoveries and answer outstanding fundamental astrophysical questions. The NRAO will operate the international Atacama Large Millimeter/submillimeter Array (ALMA), and the Karl G. Jansky Very Large Array (VLA), each the world leader in its observing domain. These telescopes acquire observations from sub-millimeter to meter wavelengths with unprecedented resolution, sensitivity, frequency coverage, and field-of-view.

Used individually or in combination, the NRAO telescopes provide the novel capabilities required to address many of the science objectives described in the Astro2010 Decadal Survey report, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH), such as placing constraints on the nature of Dark Energy, imaging the first galaxies in the epoch of reionization, and directly observing the formation of planets in proto-planetary disks.

ALMA is providing, for the first time, detailed images of stars and planets in formation, young galaxies being assembled throughout the cosmic history of star formation, and opening new windows into the cold Universe via its tremendous increase in sensitivity and resolution at millimeter and submillimeter wavelengths. Early science was initiated at ALMA in September 2011, Steady State Operations achieved at the beginning of Cycle 5 (FY2018), and full ALMA Operations will begin no later than Cycle 7.

At the adjacent centimeter-wavelength range, the upgraded VLA is in full science operations as the world's most capable and versatile centimeter-wave imaging array and has scientific capabilities comparable to those of ALMA.

To maximize the usage and science impact of its research facilities, NRAO is working to broaden accessibility to all astronomers by the development of uniform and enhanced user support services. These services are closely coordinated by the NRAO Science Support and Research (SSR) department and are provided by the North American ALMA Science Center (NAASC) in Charlottesville and the Domenici Science Operations Center (DSOC) for the VLA in Socorro.

At the same time, NRAO is focusing on developing forefront technology to continuously improve the capabilities of existing facilities and to realize next generation facilities. Taking advantage of the outstanding technical expertise across NRAO, the Central Development Lab (CDL) oversees a science-driven research and development program that will help realize the NRAO Strategic Plan and key *NWNH* science goals, including: the detection of gravitational waves via pulsar timing and the North American NanoHertz Observatory for Gravitational Waves (NANOGrav); studying the early Universe via the highly redshifted 21 cm Neutral hydrogen (HI) line with the Precision Array to Probe the Epoch of Reionization (PAPER) and the development of a Hydrogen Epoch of Reionization Array (HERA).

To engage the community in an ongoing discussion and planning of long-term (10+ year horizon) developments, NRAO will continue to sponsor a series of workshops on future science and technology for the next-generation meter and centimeter-wave facilities, but in the context of a multi-wavelength and time domain approach to addressing outstanding scientific questions.

To broaden the impact on society, the NRAO will continue to engage the American public in the adventure of radio astronomy and the wonders of the Universe through our Education and Public Outreach (EPO) program. The education components of that program connect a diverse range of learners and teachers to role models who are passionate about science and engineering, give them privileged access to the resources and milieu of professional science, and enable them to accomplish projects of true significance. Astronomy is an appealing gateway by which learners of all ages can be drawn to science, technology, engineering, and mathematics (STEM). Our STEM education programs aim to build the skills and confidence of young men and women, attract them to STEM careers, enhance their appreciation of STEM fields, and thus contribute to our national competitiveness. Internally, NRAO will continue to foster a multi-faceted culture and environment via initiatives designed to attract, nurture, and retain a diverse workforce that will serve as a role model to other research facilities.

As described in this LRP, the NRAO is fulfilling its commitment to deliver transformational facilities to the U.S. as well as the international astronomy community. The VLA is demonstrating its broad capabilities with numerous new scientific results, including gas excitation studies at redshift z=6, characterization of the spectral energy distributions of nearby Ultra Luminous Infrared Galaxies (ULIRG), and studies of trans-Neptunian objects. The community's engagement with ALMA is demonstrated by the substantial science observing time oversubscription in every proposal Cycle, and the numerous impressive science results published in the literature.

1.1 Strategic Goals

The **NRAO Strategic Plan** outlines a set of ambitious initiatives seeking to enhance NRAO's role as the nation's core competency in radio astronomy research infrastructure and techniques, and an invaluable resource for astronomy in the U.S., and indeed the world. The NRAO strategic goals over the next several years are:

- **Developing ALMA's capabilities.**
- **Renewing JVLA Infrastructure and Developing a next-generation VLA – ngVLA.**
- **A VLA Sky Survey – VLASS.**
- **Central Development Laboratory: New Focus and Growth.**
- **Science-Ready Data Products from NRAO instruments.**
- **Expanding Education & Public Outreach, Broadening Participation.**
- **Square Kilometer Array Engagement.**

Details on these activities can be found in subsequent sections. To achieve these important goals, we identify the follow key actions:

1. Enhance User Support to Maximize Scientific Impact

To ensure the astronomy community will make optimal scientific use of the remarkable capabilities of the Observatory's forefront facilities, the NRAO will focus on providing easier access to all NRAO telescopes and enhanced support for astronomers from all sub-disciplines in a uniform and coordinated interface. The goal is to maximize the Observatory's science impact, especially along the scientific directions highlighted by the Astro2010 Decadal Survey *NWNH* report and the NRAO Strategic Plan, and to be accessible to the broadest cross-section of the U.S. astronomy community.

2. Develop State-of-the-Art Instrumentation for Current and Future Facilities

The NRAO has a long tradition in leading the development of state-of-the-art technology and telescope design in radio astronomy for the benefit of the astronomy community. For the future of the field, a forward-looking, prioritized, Observatory-wide research and development (R&D) program that is aligned with the NRAO Strategic Plan and recommendations of the *NWNH* report will be carried out.

NRAO will continue developments for its operational facilities, novel experiments, and next generation facilities, with the activities determined by an annual science-driven prioritization process across the Observatory. NRAO will continue to play an important role to help develop and realize the mid-scale projects recommended by *NWNH*—such as HERA and NANOGrav—in the coming decade.

Importantly, this work will be done in collaboration with research groups at universities and colleges throughout the country, leveraging NRAO staff efforts in support of the university community, and providing a valuable training ground for students and young scientists to become future instrument builders.

3. Develop NRAO's Outstanding Scientists and Engineers: A Key Community Resource

The NRAO embodies a wealth of staff expertise and experience built up over 50+ years that is unrivalled among radio astronomy observatories or groups in the world. As a strategic goal, NRAO aims to deploy this invaluable resource for the benefit of the U.S. and international community, helping to realize major new facilities that are aimed at important scientific objectives, especially those recommended by *NWNH* and adopted by NRAO.

1.2 Introduction to the Plan

The LRP serves as primary NRAO document for communicating the vision, mission, strategy, and initiatives that will best serve the user community and deliver the best science results. The LRP is updated annually to incorporate the latest scientific, technical and budgetary developments. The financial basis of the projected budget and staffing levels is the established President's Request Level projection. NRAO has multiple sources of funding incorporated into this Plan including NSF-AST Cooperative Support Agreement (CSA) funds and other awards. NRAO targets non-CSA sources of funds to overcome some challenges in the NSF funding allocation, but only sources of funding that are established, or committed through a formal Memorandum of Understanding (MOU) at the time of writing, are included in the LRP.

This LRP covers FY2019–2023. NRAO develops its LRP by proactively assessing which activities should be pursued in addressing the needs of the user community in a constrained fiscal environment. NRAO has developed this Plan to represent a budget-balanced program. The LRP describes the tasks and resources that will be used to accomplish the following high-level goals:

- Continued successful operations of telescope facilities.
- Focus on improving the community's optimum scientific utilization of NRAO facilities.
- Research and development to evolve the NRAO facilities based on the most scientifically promising projects to help realize mid-scale facilities recommended by NWNH.

Fitting the planned activities within the given budget profile will be accomplished by a well-established Observatory-wide, science-driven prioritization review, carried out annually to ensure an optimum and feasible Program Operating Plan (POP) is formulated.

1.3 Structure of the Long-Range Plan

Section 2 describes the key community-driven science goals, outlining a new vision for research built upon science produced since the 2010 decadal survey, and how the new capabilities of NRAO facilities allow the astronomy community to address the outstanding questions of *NWNH*. It then addresses the topics of science in the next half decade, general development initiatives, and longer term developments.

Section 3 describes Observatory science operations that will be coordinated by the Scientific Support and Research (SSR) department. Through SSR, NRAO provides access to all its facilities, expands access to new users, enhances services to users in order to facilitate achievement of their scientific objectives, and optimizes operational efficiencies across the Observatory. Significant new initiatives have been launched to expand and enhance user support at NRAO facilities in FY2019–2023. Topics include Telescope Time Allocation (TTA) process improvements, the commitment to deliver Science Ready Data Products (SRDP), Scientific User Support (SUS) and Student Programs, reference services, scientific staff, and Jansky Fellows.

Section 4 details the telescope operation structure and plans for ALMA and the VLA in FY2019–2023. The North American ALMA strategic objectives and implementation plans are described, as well as the overall operations plans for the ALMA divisions. ALMA will achieve full operations no later than Cycle 7 (FY2020). New VLA capabilities will open additional discovery space, such as the ability to respond quickly to an external fast transient trigger, and the ability to detect very fast transients and generate those triggers for other observatories. The seven year VLA Sky Survey (VLASS)—a multi-epoch, all-sky, 2–4 GHz survey with the highest spatial resolution for an all-sky radio survey—will be underway, with the potential of vastly increasing access to radio data products outside the traditional radio astronomy community.

Section 5 describes the NRAO research and development activities: continually developing critical capabilities for upgrading existing NRAO facilities and for next generation facilities; helping the community realize mid-scale projects recommended by NWNH; and identifying and pursuing collaborations that lead to new scientific initiatives, advancements in the state-of-the art technology, as well as possible additional funding opportunities. Central Development Laboratory activities are described in Section 5.1; ALMA Development in 5.2, and VLA Development in 5.3.

Section 6 describes the activities and programs of the NRAO EPO Department, which will work to achieve the public recognition and understanding for NRAO facilities, science, achievements, and people and to engage students in our evolving educational opportunities. The NRAO EPO programs contribute to the fulfillment of the NSF mandate for the achievement of Broader Impacts.

Observatory-wide services include headquarters, as well as dispersed activities housed at each NRAO site, that support the overall Observatory including: Data Management and Software (DMS, Section 7.1), Program Management (PMD, Section 7.2), Administration (ADMIN, Section 7.3), Human Resources (HR, Section 7.4), the Office of Diversity and Inclusion (ODI, Section 7.5), Computing and Information Services (CIS, Section 7.6), and the Director's Office (DO, Section 7.7).

Section 7.1 describes the Data Management and Software (DMS) Department roles in the evolution of NRAO user services, improving user interfaces, and the Common Astronomy Software Applications (CASA) package.

Section 7.2 describes the activities of the Program Management Department (PMD). PMD provides processes, templates, and training, as well as project management and systems engineering services, to ensure that projects on all scales are initiated and led with the appropriate level of integrated Project Management and System Engineering in order to obtain quality outcomes that meet stakeholder expectations.

Section 7.3 details the Administration (ADMIN) Department plans for Observatory Business Services, Budget Office, Environmental Safety and Security, Contracts and Procurement, Management Information Systems, and the Technology Transfer Office.

Section 7.4 describes how the Human Resources (HR) Department will take a leadership role in FY2019–2023 and provide services that promote the concept that employees are NRAO's most valuable resource.

Section 7.5 details the Office of Diversity and Inclusion (ODI) Department efforts that will focus on broader impacts, new and on-going pipeline initiatives, workforce hiring, retention, training, and workplace culture. As a national laboratory, NRAO recognizes its responsibility to reflect, to the greatest extent possible, the U.S. population.

Section 7.6 describes the unprecedented Computing Information Services (CIS) staff and infrastructure demands that will be met by a close partnership with DMS for provisioning and supporting critical science support services.

Section 7.7 describes the Director's Office activities for FY2019–2023, including providing executive management and leadership for the Observatory, scientific research, and community relations. The Director's Office includes the Director, Chief Scientist, the Scientific Communications Office, and Spectrum Management.

Four appendices describe: Appendix A - the relevant resource projections for FY2019–2023; Appendix B - the major milestones; Appendix C - planned infrastructure progress; and Appendix D - the acronyms used in this LRP.

1.4 Financial and Budget Considerations

The LRP budget assumes 3% annual increments in NSF allocated funds as well as continuing increments to and the availability of ALMA NA partner contributions from Canada and Taiwan. In addition, the budget assumes the ability to carry-over funds from year to year. The importance of this assumption will be seen below.

NRAO continues to experience significant pressure from the cost of compensation. It is expected that significant choices with regard to the employee benefits program as well as the tradeoff between salaries and benefits will need to be made over the course of this plan. Key competencies are also becoming more expensive to recruit and retain which may, again, force the Observatory to opt for a smaller, more expensive work force.

NRAO has assumed responsibility for managing the North American risk associated with the cost of the Joint ALMA Observatory (JAO) in Chile. This brings significant risk to the budget from exchange rate fluctuations, fuel price volatility, and JAO outyear budget growth owing to evolving maintenance and equipment overhaul requirements. Current conditions suggest that some of that risk associated with currency fluctuations may occur in the next year as the Chilean peso strengthens.

While the NA responsibilities to the ALMA development program are expressed in annual terms, the actual delivery of the development program means that the outlays are not linear through fiscal years. In addition, awards may be made for periods longer than a year and NRAO cannot govern the spend rate of awardees within the award period.

For the reasons noted in the above paragraphs, it is vital that the ALMA program be able to retain unspent funds during the period of the plan.

The plan also assumes that a certain fraction (~50%) of ALMA development awards are competitively awarded to the CDL either as the Principal Investigator (PI) or through a subcontract. This is important to maintaining strategic and core competencies at the Lab. Shortfalls or overages in the awarding of these funds to the CDL will produce stresses on maintaining a steady state staff. However, since ALMA development awards are competitively funded and selected through an independent process, this funding is not guaranteed.

The NRAO plan includes significant infrastructure maintenance expenditures at the VLA. As NRAO moves through the list, attempts to provide early funding for ngVLA activities, and experiences unanticipated failures or longevity, the plan will continue to evolve. NRAO is committed to tracking the infrastructure renewal program through the mechanism of this plan (see Appendix C). Again, with the highly variable expense of certain elements of the plan, it is critical that NRAO be able to carry-over funds from one year to the next to enable the accomplishment of important on-going maintenance items such as the VLA track.

NRAO is entering its second year with a Negotiated Indirect Cost Rate Agreement (NICRA) providing recovery for its Internal Common Cost (ICC) activities. The rates cover a larger base than just the NRAO award covered by this plan. Should the base change materially, e.g. if Green Bank Observatory (GBO) and/or Long Baseline Observatory (LBO) were to exit AUI or stop being covered by the ICC, this would have a material effect on the rates and subsequently on the budget—especially on the latter years of the plan. No assumption to this effect (GBO/LBO exit) has been made.

1.5 NRAO Telescope Facilities

Atacama Large Millimeter/submillimeter Array

ALMA is transformational in its scientific concept, engineering design, and organization as a global scientific endeavor. It represents one of the largest advances in observational capabilities in ground-based astronomy ever made. At construction completion in FY2014, it provided an order of magnitude or more improvement in sensitivity, frequency coverage, resolution, imaging, and spectral capabilities. In full science operations, ALMA will provide precise images of forming galaxies back to the epoch of "first light" in the Universe; reveal the physical conditions and chemical composition of stars and planets during their earliest formative stages; and provide an accurate census of the sizes and motions of the icy fragments left over from the formation of our own Solar System that are now orbiting beyond Neptune.

Located at 5000m altitude in northern Chile, ALMA is an interferometric array of fifty 12m radio telescopes in extended configurations, plus twelve 7m and four 12m radio telescopes in a compact array, operating at frequencies from 30 to 950 GHz (10 to 0.3 mm wavelength). ALMA Early Science Calls for Proposals were issued on 30 March 2011 and 31 May 2012, respectively. Each attracted enormous community interest, resulting in oversubscription rates exceeding 9:1, comparable to the typical oversubscription of the Hubble Space Telescope. Cycle 0 Early Science observations began 30 September 2011.

ALMA's enormous collecting area and superb site make it a singular instrument for the exploration of the most distant parts of the Universe, and measuring spectral lines from distant galaxies is the first of ALMA's primary science goals. Fortuitously, at the redshifts $6 < z < 15$ at which the first stars created the first metals, the strong forbidden lines of the most abundant of those elements migrate through the ALMA bands. Oxygen and carbon are the most abundant metals produced by these first stars and both have lines detectable in this redshift range:

- The 157μm [C II] line is among the brightest lines in the Universe, carrying ~1% of the luminosity of the Milky Way.
- Other carbon carriers will also be detectable by ALMA, including [C I], CO, CH and CH+.
- Strong atomic oxygen lines occur at 63μm and 145μm (from [O I]), and 52μm and 88μm (from [O III]); these lines may be detected in several-hour integration times up to redshifts which reach the near edge of cosmic reionization.

Together with OH and H_2O lines detectable at moderate redshift, these lines chronicle the production of metals over the course of the history of their creation. The metals also form dust, and thermal dust emission provides an essentially distance-independent means of measuring galaxies to $z\sim10$.

The second of ALMA's primary science goals, to image proto-stellar and proto-planetary disks, addresses the origins of stars and planets, the fundamental objects of our Universe. A cloud may have many cores within it, some of which will collapse to form stars while others find collapse impeded, perhaps by magnetic fields lacing the gas or by turbulence. High resolution, sensitivity and excellent capability for measuring polarization endow ALMA with the potential to distinguish the roles of these factors in accelerating or retarding star formation. High-resolution studies of the emission distribution of various molecules reduce "spectral confusion" and serve to relate molecular distributions to local physical conditions in order to elucidate molecular formation and destruction mechanisms. Images also show how the gas temperature varies across the region, highlighting the roles of shocks.

Karl G. Jansky Very Large Array

The VLA is a centimeter-wavelength telescope array of unprecedented sensitivity, frequency coverage, and imaging capability created via a comprehensive modernization of the VLA. Located at 2140m altitude on the Plains of San Agustin in west-central New Mexico, the VLA is an interferometric telescope array of twenty-seven 25m radio telescopes in an extended, reconfigurable array operating at frequencies of 1-50 GHz (30cm–6mm). Full science operations of the upgraded array were achieved in 2013.

The primary science goals of the VLA can be summarized as follows:

The Magnetic Universe: Magnetic fields are important in most astrophysical contexts, but are difficult to observe. The sensitivity, frequency agility, and spectral capability of the VLA allow 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 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 to image the densest regions in nearby starburst galaxies.

The Evolving Universe: The formation of stars and galaxies, and the evolution of the gas content of the Universe, are exciting topics for scientists using the VLA. Radio data 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 can distinguish dust from free-free emission in disks and jets within local star-forming regions, and can measure the star-formation rate, irrespective of dust extinction, in high-z galaxies.

1.6 Services Provided to Other Observatories

NRAO established Service Level Agreements (SLAs) with the GBO and LBO for the period of FY2017 and FY2018, and extended those SLAs by mutual agreement.

The purpose of the SLAs is to document services that NRAO will provide to the GBO and LBO and vice-versa. Several independent statements of work, each with its own point of contact, are specified within a common framework. The SLAs are established with the understanding that in all cases, for identified work packages, GBO/LBO will be provided with a level, quality, and responsiveness of service that is consistent with and undifferentiated from that provided within NRAO.

The SLAs document areas in which shared services provide either clear advantages to both the NRAO and GBO/LBO or areas in which shared services have significant cost savings or other advantages for the GBO/LBO. As of the beginning of 2018, all services to GBO have been further rationalized, the ICC pools redefined, and interactions among the Observatories should be in a steady state.

It should be noted that, as sister organizations within AUI, the NRAO and the GBO/LBO will continue to share resources and services beyond what is described by the SLAs as feasible and through the use of direct cost reimbursement. Such shared services will be handled on a case-by-case basis.

The following NRAO divisions and programmatic activities are staffed, from a skills and force perspective, to provide services to GBO/LBO. Requisite incremental funding in support of the SLA effort is provided by GBO/LBO either directly or through the Internal Common Cost pool:

Science Support and Research
Student Programs & Training
Conferences, Workshops, Colloquia, and Lectures
Data Management & Software
Computer and Information Services
Education & Public Outreach
Communications

Spectrum Management
New Mexico Operations, Scientific Services
New Mexico Operations, Operation of the VLBA
Central Development Lab

In addition to the operations noted above, GBO/LBO participate in the NRAO Internal Common Cost pool which provides support for a large package of common administrative and programmatic activities. The ICC pool is described in other NRAO documents.

NRAO, GBO, and LBO expect the SLAs to evolve over the LRP period based on the status and needs of each Observatory.

2 COMMUNITY-DRIVEN SCIENCE GOALS

In the first two years of this LRP, the astronomical community will perform a new Decadal Survey, updating the overarching *NWNH* document and conceiving a new vision for research on the physics, chemistry, and biology of the Universe. This vision will build on the remarkable progress in our understanding of the cosmos that has developed through the use of major new astronomical instrumentation since the last Decadal Survey. Time domain astronomy has demonstrated the richness of the variable and explosive Universe, and the Large Synoptic Survey Telescope (LSST) promises to revolutionize this field. Large, spectroscopic sky surveys are tracing out cosmic structure on the largest scales to determine the nature of Dark Energy. The study of exoplanets, and the search for life beyond the Earth, has taken center stage in modern astrophysics. The study of galaxy formation has reached back to the epoch of cosmic reionization and the first galaxies in the Universe, some few hundred mega-years (Myr) after the Big Bang, and the advent of the James Webb Space Telescope (JWST) and 30m-class ground-based optical telescopes will afford a full characterization of the stellar content of galaxies throughout cosmic time. The Laser Interferometer Gravitational-wave Observatory (LIGO) is routinely detecting gravitational waves from cosmic sources, opening a window on the non-electromagnetic cosmos, and prompting follow-up observations at other wavelengths including radio..

The VLA and ALMA represent unique and powerful components of the arsenal of astronomical facilities that power discovery in modern multi-messenger astronomy, impacting a remarkably broad range of problems in modern astrophysics, in environments ranging from the Earth's ionosphere to the first galaxies. The VLA remains the world powerhouse in radio astronomy, receiving a steady 400 proposals a year, with a publication rate that rivals the most advanced optical 10m-class telescopes and the great space observatories. ALMA has eclipsed even the Hubble Space Telescope (HST) in demand, consistently receiving over 1600 proposals per year.

In the coming years, the NRAO will exploit the power and synergies between the ALMA and VLA interferometers—in terms of techniques, science, and design—to perform ground-breaking science at centimeter to sub-millimeter wavelengths. The Common Astronomy Software Applications (CASA) package provides a unified software environment for advanced interferometric data analysis. The NRAO is implementing a Science Ready Data Products (SRDP) program across both the VLA and ALMA that will facilitate usage of these complex instruments by an ever-growing astronomy and physics community. These facilities are pushing the envelope of science applications and observational techniques required to inform and inspire the design of the next generation large facilities in U.S. radio astronomy, the next generation Very Large Array (ngVLA) and ALMA 2030.

The following sections outline the broad range of science potential of the VLA and ALMA in the coming five years, and the fundamental role these programs will play in modern multi-messenger astronomy. The development programs that will enable substantial improvements to VLA and ALMA capabilities in the near term, and into the next decade and beyond, are also described.

2.1 Science in the Next Half-Decade

Time Domain and Fundamental Physics

Study of the temporal variations of cosmic objects has become a dominant branch of astronomy, and radio astronomy remains front-and-center in this field. These studies range from investigations of fast transients, such as the enigmatic Fast Radio Bursts (FRBs), to long-timescale transients, such as novae, tidal disruption events (TDEs), and gamma-ray bursts. The VLA and ALMA have already played major roles in explaining the physics of these transient phenomena, and users of these facilities are exploring various new techniques to unveil this exciting growth area in astronomy. Large multi-wavelength studies of the variable sky are in progress using NRAO facilities in collaboration with the Panoramic Survey Telescope & Rapid Response System (PanStarrs), the Zwicky Transient Factory, and eventually the LSST.

The most impressive result to date has been the first ever localization of an FRB, which was achieved with the VLA. Using a new fast sampling and imaging mode, the repeating FRB 121102 has been localized to 0.1" accuracy, showing that it is situated at the center of a dwarf galaxy at z ~0.1. Models for the system include a neutron star or magnetar enveloped by supernova ejecta, or a new Active Galactic Nucleus (AGN) jet-related phenomenon. The discovery that FRBs are at cosmological distances raises the potential to use FRBs as unique probes of the physics of the intergalactic medium at extreme energies. The current result has already inspired numerous theoretical papers on the physics of the intergalactic medium and degenerate stars.

The VLA has demonstrated a fast, triggered response mode that enables the transition from identification of an external trigger event to on-source VLA observations to be accomplished in ~10 minutes. With the discovery of radio emission from TDEs, the VLA has opened up a new window in the study of accretion onto supermassive black holes (SMBHs) at the center of galaxies. ALMA and VLA observations of TDEs enable the study of the initial formation and cessation of jet activity at early and late times, respectively, as well as probing the density structure of the immediate circumnuclear black hole environment.

LIGO is now regularly detecting gravity waves from space. Events associated with black hole-black hole mergers are now commonly detected, and the system is pushing toward the detection of neutron star mergers. In the coming years, new gravitational wave detectors distributed across the globe will dramatically narrow the search zone for electromagnetic counterparts. There are good physical reasons to expect these mergers to generate both radio bursts and long-duration radio afterglows. The VLA has undertaken a pilot observational program to detect this radio emission, and thereby transform the emerging field of gravitational wave astronomy. The VLA will undoubtedly be a core element in the study of gravity waves over the coming years.

The next five years promise to be a golden age of time domain astronomy, with the advent of the LSST, Euclid, the next generation X-ray and gamma-ray telescopes, and the ever-improving LIGO. The VLA and ALMA are well positioned to lead radio astronomical studies of the variable cosmos into the new decade.

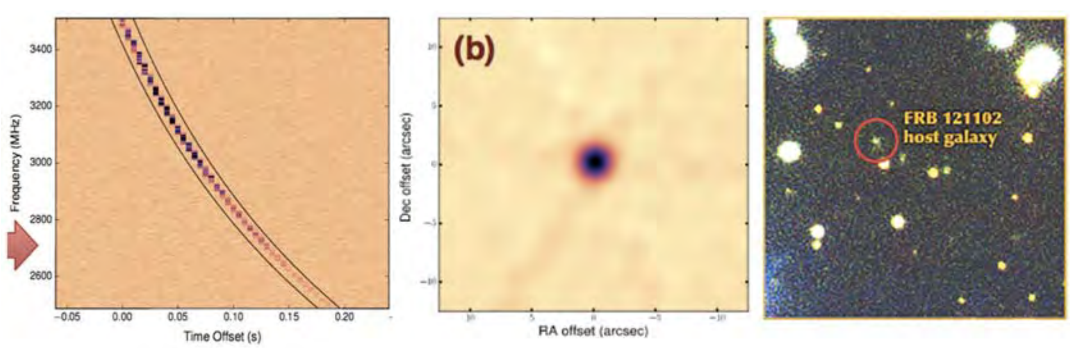

Figure 2.1.1: FRB 121102 observations. [Left] Dispersed burst seen by the VLA. [Center] The persistent weak radio source imaged by the VLA. [Right] Near-infrared image of the host dwarf galaxy (Chatterjee et al. 2017, Nature)

In the realm of basic physics, the VLA and ALMA have implemented pulsar observing modes. For the VLA, the primary science goal is a search for pulsars orbiting the SMBH at the Galactic Center. Such a discovery would provide the ultimate laboratory for the study of strong-field General Relativity.

The phased array mode at ALMA is now the anchoring element in global millimeter Very Long Baseline Interferometry (VLBI). The primary science driver for these experiments is to image the event horizon of the supermassive black holes in the Galactic Center and in M87. VLBI at submillimeter wavelengths has the potential to perform the most fundamental, and as yet unrealized, measurement in black hole theory, potentially differentiating between static and spinning black holes. The first images incorporating ALMA into global VLBI networks have been produced in the last year. Major discoveries in this field seem highly probably in the near-term future.

Solar System

Studies of our Solar System have assumed renewed attention, with keen interest in understanding the origin of the Solar System, and the life within it. Likewise, space weather has become a major issue in the consideration of the development of life in our Solar System and exo-planetary systems, and a practical challenge to our everyday lives. ALMA and the VLA provide unique insights into Solar System physics and maintain a healthy demand for observing time in this field.

ALMA has released its first images of the Sun, showing a giant sunspot observed at 250 GHz, as well as a large-scale image of the Sun made using total power scanning. These images dramatically demonstrate the remarkable potential for ALMA in Solar studies. Sunspots are low-temperature, transient features that occur in regions of strong magnetic field. ALMA measures the temperature of the chromosphere just above the optical photosphere. Understanding the heating and dynamics of the chromosphere is key to understanding the active Sun and the origin of space weather.

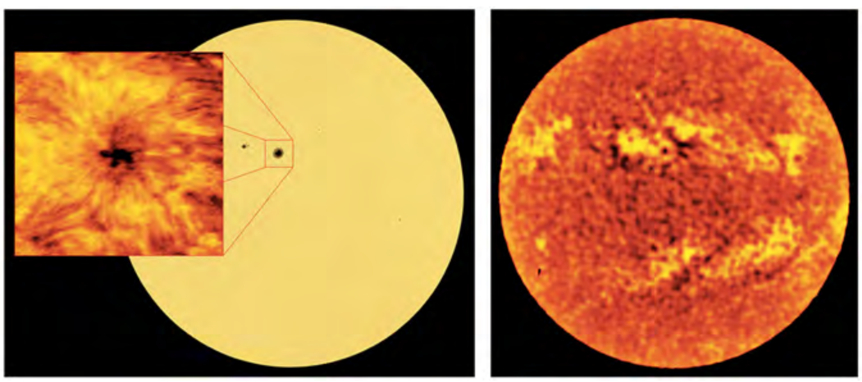

Figure 2.1.2: First ALMA images of the Sun at 250 GHz (ALMA solar commissioning team).

Coronal Mass Ejections (CMEs) represent the most violent form of space weather, with the potential to severely impact the Earth. However, their physical properties remain obscure. The VLA has made by far the best measurement of the Faraday rotation through CMEs to date, using a cluster of background sources at projected distances of 6–15R_{sun}. Combined with optical observations acquired with the Large Angle and Spectrometric Coronagraph (LASCO) and Solar Terrestrial Relations Observatory (STEREO), the observations determine the density and magnetic field strength and topology in CMEs. Working in concert with current and future missions to the Sun, such as the Parker Space probe, ALMA and the VLA will remain leaders in the study of Solar activity, and its impact on Earth.

The micro-Jansky (micro-Jy) sensitivity of ALMA has proven to be a powerful new tool in the study of dwarf planets. ALMA has determined the properties of a new trans-Neptunian dwarf planet called DeeDee at 92 astronomical units (AU), with an orbital period of 1140 years. ALMA observations, coupled with Dark Energy Survey optical observations, determine both the surface properties (albedo), and the size of the objects. Dwarf planets hold the clues to the early Solar System, and will remain targets of intense study over the coming years.

The VLA and ALMA observations are unique and complementary elements in the ambitious program of ground and space missions dedicated to Solar System science. The VLA has recently performed important radio observations in concert with the Juno Jupiter flyby mission which determine the dynamics of the lower Jovian atmosphere.

Solar System science will likely continue to expand in scope over the coming years, with future deep space missions to the Sun and planets. ALMA and the VLA will remain the key ground-based radio astronomy facilities in support of these missions.

Star and Planet Formation and the Search for Life

The study of extrasolar planets and planet formation has become a mature field, with thousands of planets now characterized by stellar host, mass, and orbit thanks to the Kepler space telescope. The VLA and ALMA play incisive roles in the study of extrasolar planets, probing the physics of early planet formation in dusty disks, down to solar system scales. These crucial formative zones are inaccessible to observations at other wavelengths due to the high dust opacity.

Since ALMA produced the game-changing image of the HL Tau planetary system, ALMA and VLA images of dusty protoplanetary disks around solar mass stars are becoming routine. ALMA and the VLA are undertaking large programs to characterize statistically significant samples of protoplanetary disks and older transitional disks.

In the coming years, ALMA and VLA observations of the dust, gas, and chemistry of protoplanetary systems will be used to determine the detailed processes involved in the formation of planetary systems similar to our own. The broadband systems at the VLA and ALMA provide the critical ability to image the chemistry in protoplanetary disks that potentially fosters the formation of life. ALMA has already shown chemical evidence for excessive cometary disruption in the early phases of protoplanetary disk formation, seeding the early disk with organic molecules.

With the near-term advent of the James Webb Space Telescope (JWST) to image dusty proplyds at tens of milli-arcseconds resolution in the near-infrared, planetary studies will remain a major growth area for the VLA and ALMA for the foreseeable future.

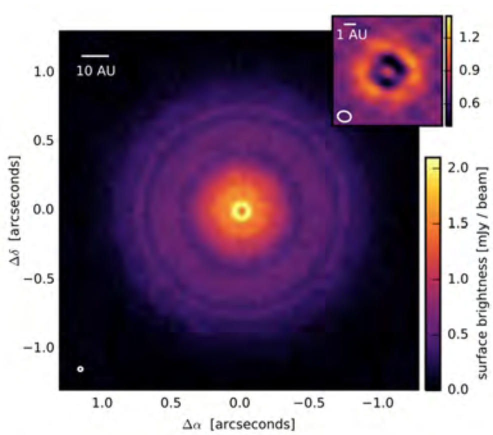

Figure 2.1.3: ALMA image of the 870 µm continuum emission from the 10 Myr old TW Hya disk at 30 milli-arcseconds (1.6 AU) and 20 milli-arcseconds resolution [Inset] Andrews et al. 2016, ApJ 840, L40).

ALMA and the VLA remain the workhorse radio telescopes for the study of star formation, with large programs underway to investigate the origin of stellar multiplicity and environmental factors driving star formation. A recent spectacular example is the ALMA image of the explosive events associated with massive star formation in the Orion Molecular Cloud. These observations provide important clues into the recycling of material from stars back to the interstellar medium. Such studies will remain at the forefront of the field of Galactic star formation as we push into the next decade.

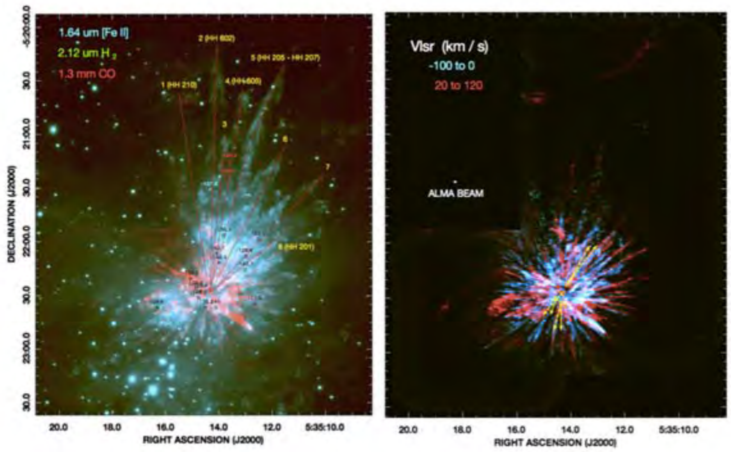

Figure 2.1.4: The Orion Molecular Cloud (Bally et al. 2017). [Left] Near-infrared molecular emission. [Right] Neutral carbon emission imaged with ALMA.

The broad band, micro-Jansky sensitivity of the VLA has opened up a new field of study of radio emission from solar and lower mass stars. Detections are now routinely made of the thermal winds and non-thermal flares from main sequence, solar-mass stars, some with known planetary systems. In analogy to the Solar System, all of these phenomena drive space weather in other planetary systems, with the obvious implications on the development of planetary atmospheres. These results have led to new consideration of the importance of space weather and planetary magnetospheres in exoplanetary systems. As more planetary systems are discovered, the VLA and ALMA promise to be the primary tools to study the nature of exospace weather, and its potential impact on the development of life in other planetary systems.

Galaxies and Galaxy Formation: The Baryon Cycle

The question of the baryon cycle—the cycling of material through the Interstellar Medium (ISM), to stars, and back—is at the center of studies of galaxy evolution. The VLA and ALMA allow for a massive step forward in our knowledge of the baryon cycle throughout the Universe, through imaging from parsec to kiloparsec scales of the molecular and atomic gas, and cold dust, from the Milky Way and nearby galaxies, to the edge of the observable Universe. The causal relationship between star formation and the various ISM gas phases is being quantified through ALMA and VLA observations of the thermal dust, plus myriad molecular gas phases, in environments ranging from typical spiral arm clouds to the extremes of dense starbursts and the formation of superstar clusters.

The COSMOS HI Large Extragalactic Survey (CHILES) is well underway at the VLA. This survey will provide a state-of-the-art measurement of the evolution of the neutral hydrogen content of galaxies to significant lookback times (z ~0.5). These studies are critical input into the science and technical directions needed to design and implement the Square Kilometre Array (SKA) in the coming decade.

One of the great legacies of the last two decades of continuum deep fields from radio through X-ray wavelengths has been a detailed delineation of the cosmic star formation rate, and the build-up of stellar mass, from the present back to the epoch of first galaxy formation a few hundred mega-years after the Big Bang. With the advent of the sensitivity and frequency coverage of ALMA and the VLA, studies of galaxy formation are now focusing on the molecular gas—the fuel for star formation in galaxies. The broad bandwidths of these facilities have enabled a new type of cosmological deep field termed spectroscopic deep fields, in which a full three-dimensional search is performed for molecular line emission from galaxies over large cosmic volumes.

The first unbiased, three-dimensional, cosmological deep fields looking for cold gas throughout cosmic time are in progress with ALMA and the VLA. The results indicate a fundamental change in galaxy properties with cosmic time, with the normal matter content shifting from dominance by gas in the earliest galaxies, to stars at later cosmic epochs. This shift is the root cause driving the star formation history of the Universe.

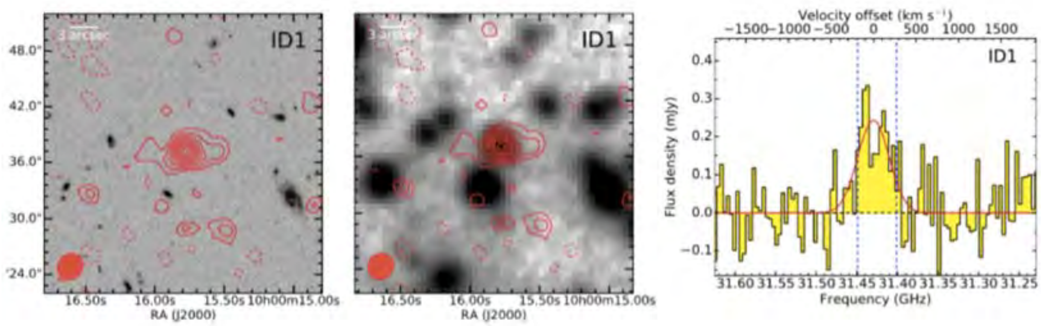

Figure 2.1.5: Sample CO 1-0 emission of a gas-dominated galaxy at z = 2.7 from the CO Luminosity Density at High Redshift (COLDz) deep field (Riechers et al. 2017).

The VLA and ALMA are pushing continuum deep fields to new levels. The VLA is now systematically achieving sub-micro-Jansky sensitivities at centimeter wavelengths, ushering in the era of nano-Jansky radio astronomy, while ALMA is routinely getting to 10 micro-Jansky sensitivity in the submillimeter. These data provide complementary views of star formation through cosmic time, via the dust and synchrotron emission, as well as pinpoint weak AGN and other exotic phenomena. Attention is being turned to detailed morphological studies of star-forming galaxies at large lookback times, using the available sub-arcsecond resolution. A growing area of interest is using polarimetry for exclusive studies of magnetic fields in the distant Universe, principally through Faraday rotation studies of polarized continuum sources.

Perhaps the most exciting prospect for the study of very early galaxies comes through observations of the atomic fine structure lines using ALMA. The [CII] 158-micron line, in particular, is the brightest emission line from star-forming galaxies from meter through far-infrared wavelengths, and promises to be an ideal tracer of galaxy dynamics and redshifts back into cosmic reionization (z ~5-8). A recent example is the ALMA discovery acting in concert with the HST, of the most distant spectroscopically confirmed galaxy at z=8.4, in the HST Frontier Field. Emission from stars, dust, and gas is seen in the ALMA and HST observations, implying a galaxy with a low stellar mass, but a substantial star formation rate and dust mass. The observations imply that the ISM in galaxies can be substantially enriched with metals and dust when the Universe was only 600 Myr old.

With the launch of the JWST and upcoming 30m-class telescopes to study stars in the first galaxies, and future missions focused on dust, such as NASA's Wide-Field Infrared Survey Telescope (WFIRST) and Far IR Surveyor, a full census of the baryonic components of galaxies over cosmic time is underway. ALMA and the VLA will remain cornerstone facilities in these efforts over the coming five years, completing our view of how the Universe converts gas to stars through cosmic time.

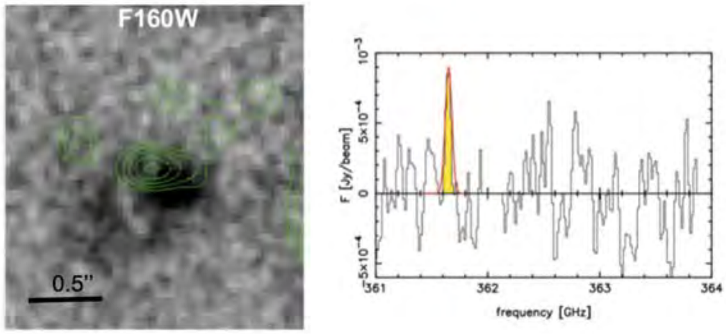

Figure 2.1.6: [Left] HST near-infrared image with ALMA dust continuum contours of a z=8.4 galaxy candidate (Laporte et al. 2017). [Right] Possible [OIII] 88 micron fine structure line emission observed with ALMA from the same galaxy.

2.2 General Development Initiatives

The programs in Section 2.1 highlight many of the innovations being implemented at NRAO facilities, including advances in time domain astronomical techniques and Solar observing. Beyond these initiatives, the NRAO, in collaboration with the U.S. and international community, is pursuing general improvements to the VLA and ALMA, and broader initiatives that promote the long-term development of radio astronomy. These efforts are described in the following sections.

VLA Sky Survey

The NRAO is undertaking a new survey of the radio sky, the VLA Sky Survey, or VLASS. The survey was planned through consultation with the astronomy community and will take ~5500 hours of VLA time to execute, with the observing spread over seven years starting in September 2017.

VLASS will deliver the sharpest view of the whole radio sky visible to the VLA, enabling data-driven science connecting the radio to optical, infrared, and X-ray wavelengths. The unique ability of the VLA 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 to be characterized in a way that has not been possible until now. By carrying out the survey in three passes over the whole sky visible to the VLA—with half the sky being imaged every 16 months, each time the B-configuration is available—the VLA 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. Specific science themes that the survey will address are as follows.

Hidden Explosions: VLASS will open up new parameter space for finding supernovae, gamma-ray bursts and mergers of compact objects (e.g. two neutron stars), even if they are hidden at optical wavelengths by dust. Mergers lead to the emission of gravitational waves that may also be detectable with instruments such as Advanced LIGO.

The Magnetic Sky: Our understanding of how and when magnetic fields arose in the Universe is very poor. VLASS will measure the Faraday rotation of the plane of polarization of radio waves that occurs when they pass through a magnetized plasma. Faraday rotation is proportional to the square of the wavelength and the line-of-sight product of the magnetic field and the plasma density. This is one of the few techniques for measuring magnetic fields in space, from the surroundings of radio sources in dense galaxy clusters to the magnetic field of our own Milky Way.

Galaxies Through Cosmic Time: Jets of radio-emitting plasma can heat the gas within and around galaxies, slowing the accretion of gas and inhibiting the formation of stars. VLASS will yield a much improved census of these radio jets, which is needed to determine whether this heating is sufficient to restrict the growth of galaxies via this feedback mechanism.

Peering Through Our Dusty Galaxy: Dust is transparent to radio waves, allowing us to see structures in the Galaxy that are hidden at other wavelengths. In addition, we will find extreme pulsars and cool stars with active coronae that are likely to be variable in the optical and radio.

Missing Physics: Whenever an astronomical survey breaks new ground in parameter space there are discoveries unanticipated by the survey team. The radio part of the spectrum in particular provides unique diagnostics for a whole range of physical processes. Combining VLASS data with ambitious new surveys in the X-ray through optical and infrared—the extended Roentgen Survey with an Imaging Telescope Array (eRosita) on Spektrum-Roentgen-Gamma, the Panoramic Survey Telescope & Rapid Response System (PanSTARRS), the Wide-Field Infrared Survey Explorer (WISE), LSST, and the Dark Energy Spectroscopic Survey (DESI)—will inevitably lead to significant discoveries.

VLASS will serve as a portal for students, educators and citizen scientists to access the world of radio astronomy. The survey will produce high-quality data products that can be used to involve the public and stimulate their curiosity in astronomy and science.

VLASS will generate 500TB of raw data, which NRAO will process into two-dimensional images of the sky that will take up 40TB, plus about 500TB of image cubes coarsely sampled in frequency space (with spectral resolution reduced by a factor ~100). However, these will only yield a small fraction of the information in the raw data. Making full image cubes (images of the sky at every frequency the VLA observes) would require 64 Petabytes (PB), compared to our current archive size of a few PB. NRAO is thus looking to leverage community efforts to make and store enhanced data products.

VLASS is designed to complement, rather than compete with, surveys planned by two SKA-precursors, the Australian SKA Pathfinder (ASKAP) and the Karoo Array Telescope (MeerKAT). By observing at a higher frequency and with higher angular resolution, the VLA will be able to study source details that are inaccessible to lower-frequency surveys, but will be able to use those surveys to obtain accurate fluxes for the few percent of large radio sources that will be partially resolved by VLASS.

Low Frequency Radio Astronomy

Low frequency radio astronomy has attained new prominence in modern astrophysics, driven predominantly by the search for the 21cm neutral hydrogen signal from the intergalactic medium (IGM) during cosmic reionization (at redshifts z ~6–8, corresponding to frequencies below 200 MHz). Discovery of this cosmological signal has comparable scientific promise to the first detection of the cosmic microwave background. But interest in low frequency radio astronomy is not one dimensional, with exciting new results emerging in areas ranging from the recent discovery of radio emission from meteors to searches for low frequency radio bursts from exoplanetary systems.

NRAO is fostering the growth of low frequency radio astronomy in the community in a number of ways. The Observatory was a founding member of the HERA project—the flagship reionization experiment of the U.S., with broad international participation. HERA is well underway, with 37 elements operating in the Karoo radio-quiet preserve in South Africa, with construction of 351 elements on schedule for completion by 2019. NRAO. Socorro hosts the data archive for HERA, making it the epicenter for HERA data storage and processing. The NRAO is also involved with HERA commissioning and science data analysis, and the project's RF design. In parallel, NRAO staff are leading the electronics design of a proposed low frequency dipole in orbit around the Moon (Dark Ages Radio Explorer, or DARE), to perform dark ages cosmology using the all-sky 21cm signal.

NRAO is working with the University of New Mexico and the Long Wavelength Array (LWA) project to design a powerful low frequency array, including the ngVLA and LWA stations across New Mexico. The on-going VLA Low Band Ionospheric and Transient Experiment (VLITE) and VLA Low Band Observatory (LOBO) programs for commensal low-frequency observing at the VLA, in collaboration with the Naval Research Laboratory, are part of this broader low frequency development.

ALMA Development Program

NRAO coordinates the ALMA development program in North America, providing a steady source of development funding to the community to keep ALMA state-of-the-art, and foster millimeter-related technological expertise in the community. On-going initiatives have focused on completing the ALMA bands, thereby providing full frequency coverage over the available sky windows from 30–950 GHz: (a) Band 1 (35–52 GHz) is under construction and will be commissioned in 2020; and (b) Band 2 (67–95GHz) passed its Preliminary Design Review in May 2017. The ALMA Solar Observing and Phasing projects are complete, with phasing capability extensions to 373 GHz, and spectral line and pulsar observations underway. Sensitive millimeter VLBI with ALMA as an element of the Event Horizon Telescope was completed in 2017 with further observations planned for 2018 and beyond.

Pending ALMA Board approval, the baseline correlator will be upgraded, giving wider high-resolution windows to characterize protostellar disk ices with added sensitivity provided by 4-bit correlation. The bandwidth will also be increased, allowing advantage to be taken of the receivers whose bandwidth exceeds current correlation capacity (Bands 6, 9, and 10). ALMA Band 2 will be the first band providing 16 GHz bandwidth in two polarizations to the correlator, which may be used with a planned Intermediate Frequency (IF) upgrade. The correlator upgrade and proposed improvements in cryogenic technology both increase observing efficiency and reduce operations costs. The cryogenic development work has long-term implications for future radio facilities, such as the ngVLA.

Algorithm Development

NRAO is at the forefront of developing the techniques required for full realization of the science capabilities of future arrays, including the ngVLA and the SKA. A particular area in which the NRAO is breaking new ground in data processing is in the area of nano-Jansky continuum deep fields. These studies are exploring the techniques needed to perform future ultra-deep, wide-field, wide-band, polarimetric imaging. NRAO is also pursuing advanced data visualization and analysis tools for complex spectral line imaging programs with ALMA and the VLA.

2.3 Longer Term Developments in Radio Astronomy

As a national observatory, NRAO has the mandate to serve as steward for the long-range future of radio astronomy, fostering the long-term growth of the U.S. astronomical community.

The North American ALMA Science Center (NAASC) supports annual ALMA development workshops for the community. The NAASC is participating in the formation of an ALMA 2030 program, targeting major telescope improvements in the 2030 timeframe. A series of community discussions are on-going to delineate the science drivers and technical requirements for propelling ALMA well into mid-century.

NRAO, with the support of AUI and the Kavli Foundation, sponsored a series of successful open community meetings to consider broader development across the radio-millimeter-submillimeter (RMS) spectrum, from meter to submillimeter wavelengths. The goal is to have a comprehensive, coherent approach for radio astronomy development going into the 2020 Decadal Survey.

ALMA 2030

The international ALMA project has drafted an outline for long-term development of ALMA, well into the next decade. These developments cover a wide range of potential major improvements, including broader bandwidth, a substantial increase in collecting area, longer baselines, and cameras to dramatically increase the field-of-view. The NRAO is supporting this effort through community meetings to discuss long-term ALMA development. Community meetings on ALMA Development held at the International Union of Radio Science General Assembly in August 2017 and in Kyoto in October 2017, focused on longer baselines.

Next Generation Very Large Array

Over the last few years, the NRAO has engaged the community in the design of a next-generation mega-radio facility, building on the legacies of ALMA and the VLA. An extensive series of open science and technology meetings have been held, organized by active science working groups and science and technical advisory committees, involving hundreds of astronomers from the broader U.S. community. The NRAO has also funded and run a design studies program, through which the community has been deeply engaged in the core design of the prospective telescope.

What has emerged is a clear definition for a next generation Very Large Array (ngVLA), with a growing, compelling, community-driven science program, and tractable, cost able designs for all major elements of the array. The ngVLA entails an interferometric array with 10 times more effective collecting area and 10 times higher spatial resolution than the VLA and ALMA, optimized for operation in the frequency range of 1.2–116 GHz. The ngVLA opens a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond resolution, as well as unprecedented broadband continuum polarimetric imaging of non-thermal processes.

The ngVLA capabilities are the only means to address and answer a broad range of scientific questions that have come to the fore in modern astronomy, including those highlighted below.

Cradle of Life: The dominant themes emerging from the discussion of star and planet formation are the necessity to image the formation of planets in the terrestrial zone of dusty protoplanetary disks, i.e. on scales of ~1 AU at the distance of the closest major star-forming regions (130 parsecs away, requiring 10 milli-arcsecond resolution), and the parallel study of prebiotic chemistry in these forming planetary systems. These are two crucial requirements for advancing our understanding of the ultimate development of life in other planetary systems. Only the ngVLA will have the resolution and brightness sensitivity to image directly the formation of Earth-like planets at wavelengths at which the terrestrial zone becomes optically thin, and the sensitivity to detect the weak lines from large organic, and potentially prebiotic, molecules in planet-forming regions. These capabilities complement plans for future optical space missions, for which the primary science drivers are direct imaging of terrestrial planets and the search for biosignatures in planetary atmospheres. The ngVLA and these optical missions form an evolutionary sequence in studies of planetary systems, from birth to maturity.

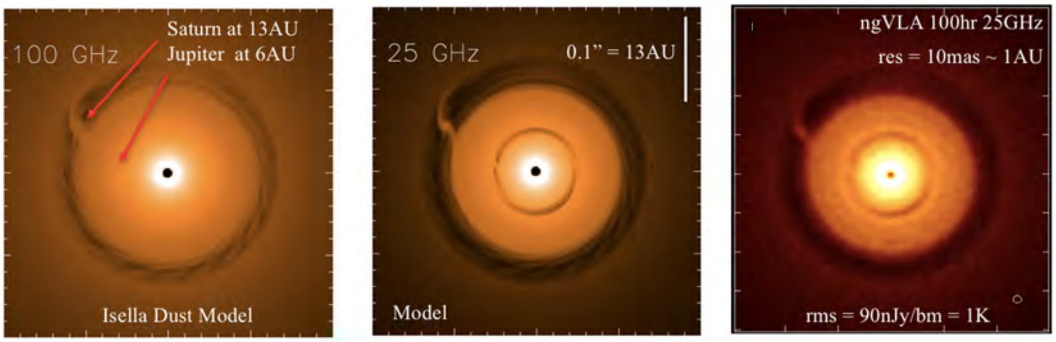

Figure 2.3.1: ngVLA imaging simulations of a 1 solar mass, 1 Myr protoplanetary disk with ~ 1 AU resolution (Isella et al. 2017).

Milky Way and Nearby Galaxies: A major challenge to studies of the physics of gas cycling and star formation in galaxies is the requirement for very wide-field, ultra-low surface brightness imaging, but retaining sufficient resolution to resolve structures on molecular cloud scales in the nearby Universe. Only the ngVLA will have the sensitivity to image the line emission from molecules other than CO in external galaxies at sub-arcsecond resolution. The spectrum between 70–115 GHz is of particular interest, containing a rich spectrum of ground-state transitions from the most important astrochemical tracers. The full frequency range of the ngVLA covers multiple continuum emission mechanisms, from synchrotron through thermal free-free to cold dust—all key and complementary tracers of star formation. Overall, the ngVLA will enable Milky Way-type studies of ISM physics and chemistry, and star formation, out to the Virgo cluster.

Galaxy Formation: While ALMA and the VLA are making progress in the study of the molecular gas in distant galaxies, it has become clear that, given current sensitivity limits, probing cosmologically significant volumes for molecular gas (the fuel driving the star formation history of the Universe) remains problematic. Likewise, these telescopes still require major time investments to image even a single source at sub-kiloparsec resolution to obtain the gas dynamics and distribution. The order of magnitude improvement in sensitivity of the ngVLA, over the critical frequency range of 20–100 GHz, will revolutionize the study of molecular gas in galaxies back to cosmic reionization. The ngVLA will perform a complete census of the dense gas history of the Universe, while imaging the gas distribution and dynamics in hundreds of distant galaxies over a broad range of galaxy types. The ngVLA, together with the study of the stars and star formation with the JWST and future 30m-class telescopes, represents a suite of powerful new tools to perform a comprehensive study of the physics of galaxy formation throughout cosmic time.

Time Domain, Physics, and Cosmology: The exciting areas of intense community interest for which the ngVLA will provide a dramatic advance in capabilities include: (a) pulsars as probes of General Relativity and gravity waves; and (b) time domain astronomy, in particular explosive transients and exospace weather. The pulsar program focuses on discovering pulsars in orbit around the SMBH at the Galactic Center—a discovery that would represent the greatest tool to test strong-field General Relativity. The time domain includes localizing FRBs, and exploiting these sources as new cosmological probes, as well as searches for electromagnetic counterparts to gravity waves. The exospace weather program relies on the unprecedented ability of the ngVLA to study broadband radio phenomena, and the impact of star-planet interactions on the development of planetary atmospheres, and potentially, the persistence of life.

The immediate goal of the ngVLA project is to present to the 2020 Decadal Survey a compelling science case, and a rationally costed and realizable design for all the major telescope elements. This effort is being driven by the community and coordinated by NRAO. The science working groups are fully engaged in quantifying and expanding the science case, efforts that will result in a ngVLA science book by the end of 2018. The ngVLA technical advisory committee along with industrial and community partners are defining the detailed array design, with a goal of developing a detailed cost model in which all major cost drivers have been quantified. The cost model will provide clear guidance for tradeoffs between cost and science performance. A project office has been established at the NRAO to coordinate these efforts.

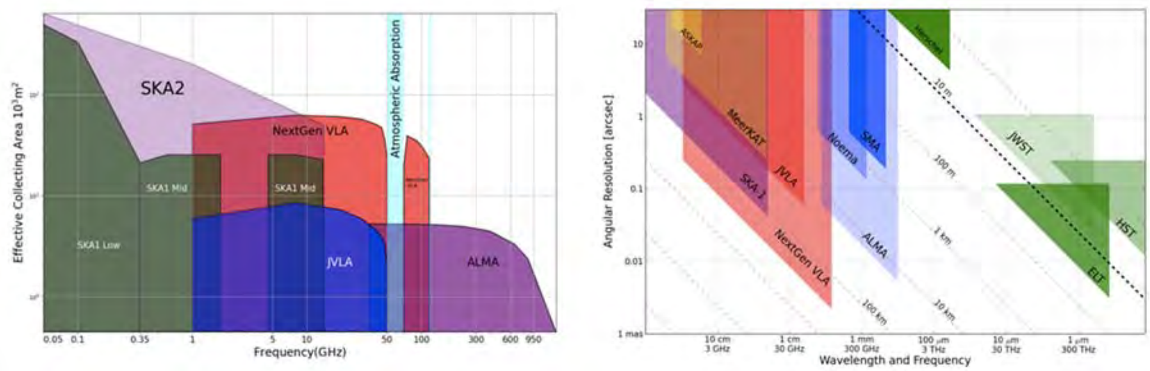

Figure 2.3.2: Parameter space for the Next Generation Very Large Array, and other present and future facilities, including collecting area and angular resolution.

Broadening the User Base

The proposal pressure and publication records indicate clearly that the VLA and ALMA appeal to a broad user base. NRAO will continue to reach out with programs designed to educate the community on the use of these facilities, and maximize ease-of-use for all scientists. A major initiative for the development of Science Ready Data Products from the VLA and ALMA has been established, thereby facilitating the use of our telescopes by an ever-growing community. NRAO hosts world-leading schools on the techniques of radio astronomy, as well as community days to inform astronomers as to the use of our facilities and improvements in their capabilities.

2.4 Summary

Over the next five years, NRAO will implement community-defined science programs that complement the multi-messenger astronomy driving discovery in modern astrophysics, while exploiting the unique capabilities inherent to radio astronomical studies of the cosmos. The NRAO Long Range Plan emphasizes the synergies between NRAO facilities and existing and imminent telescopes across the electromagnetic spectrum. Over this timescale, a number of international radio facilities will begin operation, including MeerKAT and ASKAP. These projects are all strongly survey-focused, operate in the one to few GHz regime, with resolutions of a few arcseconds, at best. The VLA and ALMA will remain the primary PI-driven science facilities with sub-arcsecond resolution, operating from 1 GHz to nearly 1 THz.

NRAO will promote the near-term growth of the U.S. astronomy community through consideration of impactful developments to NRAO facilities, and the promotion of incisive experiments, such as HERA, at low frequencies. On longer timescales, NRAO will engage the community in planning for well into the next decade, through ALMA 2030, the ngVLA, and follow-on programs to the Kavli series of meetings. In particular, the science and design for the ngVLA has matured and solidified dramatically in the last two years, and a clear project has emerged, driven by the community, with a clear path forward to proposal and construction over the next five years.

Looking out to 2030 and beyond, NRAO envisions a powerful suite of new radio astronomical facilities appropriate for the middle of the 21st century, ranging from meter to submillimeter wavelengths, with ALMA 2030 probing new depths in submillimeter astronomy, the ngVLA opening exciting new parameter space in thermal imaging at milliarcsecond resolution between 0.3 and 3cm wavelength, and the SKA offering new opportunities from decimeter to meter wavelengths. NRAO will pursue this vision, and will work to keep the U.S. at the forefront of radio astronomical research in the coming decades.

3 SCIENCE SUPPORT AND RESEARCH

Enabling astronomers to conduct forefront research by using the NRAO telescopes effectively and efficiently is central to the Observatory mission. The NRAO is supporting its users with an increasingly unified and integrated suite of services that enables them to more effectively prepare and submit observing proposals, to prepare for their observations, and to access and process their data, thereby enabling them to fulfill their scientific objectives. A critical element to ensuring optimum support of both NRAO users and NRAO instruments is the scientific staff. The NRAO has a world-leading staff of astronomers, research engineers, and computational scientists. The scientific staff also plays a key role in broadening the impact of the NRAO through student training, postdoc mentoring, and visitor interaction.

The NRAO Science Support and Research (SSR) department coordinates and manages the efforts to support scientific users of NRAO facilities, seeks to broaden the Observatory's impact through education and visitor programs for scientists, and both supports and oversees the research and scientific productivity of the scientific staff.

SSR is responsible for three major activities serving the community of science users of the NRAO: Telescope Time Allocation; Science Ready Data Products; and Scientific User Support and Student Programs. SSR also provides three Observatory-wide reference services: the NRAO Library, the Historical Archives; and Statistics and Metrics. In addition, SSR supports and oversees the research activities of the NRAO scientific staff and the Jansky Fellowship postdoctoral program.

During the period covered by this LRP, SSR will oversee a significant Observatory-wide effort to develop Science Ready Data Products (SRDP) to be delivered from both of NRAO's instruments, the VLA and ALMA. NRAO will build on the implementation of an automated calibration and imaging pipeline for ALMA, extend the approach to VLASS, and ultimately to the bulk of standard VLA observing modes, and thereby facilitate the use of NRAO telescopes by a growing scientific community that extends beyond the radio astronomy domain experts. The other significant initiative is the development of a new tool suite to support the preparation, submission, and review of VLA proposals, that is better integrated with the preparation of observing scheduling blocks, and that is better aligned with the process and tools used by ALMA.

3.1 Telescope Time Allocation

The current proposal review and Telescope Time Allocation (TTA) process for the VLA, VLBA and GBT was implemented in 2011 and is managed by SSR. ALMA proposals are managed separately by the JAO consistent with international agreements.

NRAO issues two calls for VLA observing proposals each year with deadlines on February 1 and August 1. The proposal review and telescope time allocation process employs panel-based reviews. Eight Science Review Panels (SRPs), each composed of members of the wider scientific community, conduct proposal reviews based on scientific merit. Members of the NRAO scientific staff conduct technical reviews of proposals. The Chairs of the SRPs comprise the Time Allocation Committee (TAC), which integrates the scientific rankings from the SRPs and makes recommendations for time allocation and scheduling priorities. In addition, the TAC makes recommendations for large proposals (requesting 200+ hours of telescope time).

In October 2016, the VLBA and GBT were formally split from the NRAO, and the Long Baseline Observatory (LBO) and Green Bank Observatory (GBO) were established as separate entities. As part of a transition arrangement it was agreed that NRAO would continue to run a single integrated proposal submission and ranking process on behalf of all three observatories and this began with the Call for Proposals for the 17B observing semester issued on 4 January 2017. The transition was essentially seamless for users of the three observatories, though a number of process changes were implemented by NRAO, LBO, and GBO.

The NRAO proposal evaluation and time allocation process requires a substantial suite of purpose-built software which represents a significant investment in both development and maintenance effort. The software suite includes a Proposal Submission Tool (PST), a Proposal Handling Tool (PHT), a Proposal Finder Tool (PFT), a General Observing Setup Tool (GOST), and various exposure or sensitivity calculators. The PST is used by astronomers to prepare and submit proposals, and by NRAO, LBO, and GBO staff to manage and to support the proposal review process. The PHT is used to support TAC meetings. The tool suite and associated databases supporting the NRAO North American proposal review and time allocation process have become increasingly cumbersome to maintain and develop and it is becoming correspondingly more difficult to respond to user needs.

The ALMA proposal evaluation process is led by the JAO in concert with NAASC and our international partners, using tools developed relatively recently. The degree of alignment between the ALMA process and tools and those employed by the NRAO for its North American facilities is limited.

The NRAO proposal review system has come under increasing pressure during the past few semesters due to a growing imbalance between the number of proposals allocated to the different science areas dealt with by the different SRPs; these trends reflect shifting scientific interests in the community. As a result, two or sometimes three SRPs have to deal with more proposals than intended, straining both the tools and the process, and imposing an unsustainably high workload on the members of those SRPs. Compounding the issue is the fact that there is considerable variability in the load on the individual panels from semester to semester, so a simple redefinition of the science areas addressed by the panels would not necessarily be sufficient to effect a lasting rebalancing of the load. Interim measures to manage the situation have been in place since Semester 17A and consideration is being given to making changes to the system. It is very likely that some changes will be implemented early in the time of this LRP, with the goals of balancing the workload across the SRPs, ensuring robustness to variability between semesters, preserving the value of historical metrics, and minimizing the effort required to redesign and implement software tools.

NRAO studies of the proposal review and time allocation outcomes have revealed that there are gender-related effects that favor male over female PIs in the proposal rankings for the VLA, ALMA, GBT, and VLBA. The NRAO is concerned by the evidence of gender-related bias revealed by this study, and is committed to improve the level of equity and inclusion in its review processes. The Observatory will continue to monitor and investigate the effects and the root causes of gender-related systematics, and will explore mechanisms to ensure greater equity and transparency, including providing information to review panel members and the astronomy community regarding these issues. Although it is not clear that the make-up of the Science Review Panels and the Time Assignment Committee is a direct contributor to the gender dependent outcomes, NRAO will pay particular attention to gender balance on these committees. We urge all members of the community to work with the Observatory as we strive to deliver on our commitment to the principles of equity and inclusion in all aspects of NRAO's activities, and ensure that the prime criterion for time allocation remains scientific merit.

A major initiative during the term of the LRP is to replace the NRAO TTA tool suite and databases, building on the investment in the ALMA tools and thereby achieving closer alignment between ALMA and the North American facilities for our users. Delivering a new tool suite better integrated with VLA telescope operations and more robust in terms of performance and maintainability are significant drivers for this initiative. Requirements for the tool suite were expected to be developed in FY2017 but progress has been slowed by competition for limited programming resources from the development of a new Archive Access Tool (released Q3 FY2017), and uncertainty regarding the appropriate scope of the new TTA tool suite arising from the divestment of the VLBA and GBT from NRAO. Requirements for the new tool suite will be determined in FY2018 and the project is expected to be completed in FY2020.

3.2 Science Ready Data Products

Science Ready Data Products (SRDP) is a new initiative that will build on the implementation of an automated calibration and imaging pipeline for ALMA, extend the approach to the VLA Sky Survey (VLASS) and ultimately to the bulk of standard VLA observing modes, and thereby facilitate the use of NRAO telescopes by a growing scientific community that extends beyond the radio astronomy domain experts. SRDP is a key strategic initiative in NRAO's Strategic Plan and was formally initiated as a project in FY2017 with the appointment of a dedicated Project Director.

The aim of the SRDP project is to deliver data sets that are ready to use for scientific study by a wide range of astronomers, including those not expert in interferometry, thereby broadening the user base and increasing the scientific impact of NRAO's telescopes. Ultimately the initiative may involve the incorporation of scientific optimization and value-added data products delivered by expert PI teams and reincorporated into the Observatory archive for use by the broader astronomy community.

The period of this LRP begins with several SRDP precursor projects at various stages of development and operations. Over the next five years the SRDP project will unify these efforts and normalize operations across the Observatory.

Currently the ALMA calibration and imaging pipeline is the most advanced of the precursor projects, and our best model for routine operations. The ALMA pipeline is used to calibrate over 80% of standard mode projects in Cycle 4 and the imaging pipeline provides reference images without manual intervention in approximately two thirds of projects. The ALMA project has prioritized maximizing the number of projects which can be processed by the pipeline, and delivering standard data products to provide a homogeneous archive. The SRDP project will focus on the complementary objectives of delivering tailored data products (i.e. specialized to meet the PIs scientific objectives) and optimizing the quality of the delivered products. By the midpoint of the planning period, NRAO will provide North American ALMA users with tailored image products through the Archive Access Tool (AAT), these products will be produced on demand and quality assured.

The VLA has two SRDP precursor projects, the VLA Calibration Pipeline and the VLASS. During FY2018, the VLASS project will use the slightly modified VLA Calibration pipeline to perform science quality calibration of the survey data. This is the first time that science level QA will be uniformly applied to the results of the calibration pipeline. Following the first year of VLASS operations which start Q1 FY2018, the SRDP project will perform an equivalent level of QA on all VLA pipeline executions. Based on the experience from ALMA, one to two years of operation are expected before the VLA calibration pipeline consistently delivers science-quality calibration in a high fraction of the observing projects.

The VLASS imaging pipeline is the next step towards delivery of pipeline produced images for the VLA. Significant differences exist between the VLASS imaging case and a standard PI project. Once reliably calibrated data is available for a significant fraction of VLA projects, the SRDP project will begin to offer on demand imaging capabilities to the user community. Based on the same technologies as the ALMA data products, users will be able to request tailored products to meet their scientific needs.

Both for the VLA and ALMA, value-added data products generated by the PI using Observatory tools, will be stored into the NRAO Archive and made available. Through this process, the NRAO archive will be populated with quality assured, reproducible, science quality images. Late in the period covered by this plan SRDP will work with the DMS department to develop persistent Digital Object Identifiers (DOIs) cataloging the products as well as a full suite of information uniquely identifying the origin of the data and the processing steps.

In the last two years of the planning period, the SRDP project will use the records of the on-demand imaging performed both for the VLA and for ALMA to evaluate the efficacy and priorities of automated (as opposed to on demand) generation of science products. At the same time the project will begin on-demand production of value added products such as line lists, source catalogs, and moment maps. These products require high quality images as initial starting points and thus must necessarily be sequenced after generation of high quality images is a routine part of operations.

In the final year of this period, the SRDP project will begin to plan the transition from the project phase, to operations. In the operations phase, enhancements to the SRDP capabilities will be a standard Observatory activity, with responsibility for the various roles distributed across the relevant departments.

3.3 Scientific User Support and Student Programs

Scientific User Support (SUS) is responsible for providing the scientific community with the support necessary to execute successful scientific programs with the VLA. SSR also manages a range of undergraduate and graduate student programs.

Scientific User Support

The initiative to deliver Science Ready Data Products will drive an increasing alignment between NRAO's user support groups for NA ALMA and the VLA. Over the period covered by this LRP, the result will be some evolution of the organizational structure in these areas, but the significant changes will be to the software, tools, and workflows used to provide data and data products to NRAO's scientific users.

Throughout this LRP period, SUS will devote a considerable fraction of its effort to the delivery of VLASS, a major Observatory initiative that will use around 10% of VLA observing time to conduct a three-epoch survey of the entire sky over seven years starting in FY2018. In many ways the delivery of VLASS results serves as an early stage of the implementation of SRDP, building on the experience of the automated ALMA data processing pipeline and the VLA calibration pipeline.

The SUS group (like the NAASC) will increasingly use the products of the SRDP project to provide the scientific support necessary for users to access, reduce, calibrate, and analyze their data as well as to help the community generate new and innovative ideas for science by fostering cross-disciplinary and cross-field ideas and techniques. In doing so, SUS will provide support to an increasingly broad user base extending beyond the traditional radio astronomy community.

The SUS group provides education and outreach services to astronomers who use NRAO facilities, including face-to-face visitor support and data reduction visits, Helpdesk support, Knowledgebase articles, Science Forums, NRAO Community Day events, science meetings and conferences, science web content and the NRAO User Portal interface, user documentation, workshops and tutorials, online training, and educational material. SUS coordinates with the NAASC (which handles such activities for North American ALMA users) to ensure that NRAO users as a whole benefit from these services.

SUS also supports certain user data and scientific software services, including assistance with manual data reduction, pipeline testing, and requirements definition for a number of projects; e.g. the AAT/ASA user interface, the integrated science portal, and the integrated helpdesk. SUS staff are responsible for or contribute to a range of other data services for the VLA—notably, scheduling block validation, pipeline data processing, pipeline heuristics development, and the associated quality assurance.

Student Programs

Fostering a strong scientific community of researchers and helping to train the next generation of astronomers, engineers and computer scientists remain important parts of the NRAO mission. The NRAO supports a broad range of student opportunities including undergraduate, graduate, and post-graduate programs; instrument and visitor programs to enhance University—NRAO collaborations; as well as workshops, schools, and conferences.

Undergraduate students: The long-running (since 1959) NRAO summer student program continues to be very successful. This 12-week program allows approximately 25 students to work under the supervision of NRAO staff members at sites in New Mexico and Virginia (and West Virginia, through the GBO), to carry out original research in astronomy, computing and engineering. Most of these students are funded through the NSF Research Experience for Undergraduates (REU) program. Outstanding students that are otherwise ineligible for support by the REU program, graduating seniors, foreign students, and early-career graduate students, are supported by NRAO operating funds or by external grants to NRAO staff members. A proposal for further NSF funding for the REU program will be developed and submitted in FY2018 and if successful will support NRAO's undergraduate student programs through much of the period covered by this LRP.

The NRAO also supports a co-op program that enables undergraduate engineering students to gain practical, career-based experience as part of their formal academic education. Students from participating institutions work at NRAO sites for two semesters. Under the supervision of NRAO technical staff, co-op students are engaged in R&D on the technological frontier.

A modest amount of funds is available for undergraduate internships, where promising undergraduate students participate in scientific or engineering activities, supervised by NRAO staff, over a period of weeks to a semester.

SSR coordinates very closely with student programs organized by NRAO's Office of Diversity and Inclusion (ODI), including the National Astronomy Consortium (NAC), Louis Stokes Alliance for Minority Participation (LSAMP), Physics Inspiring the Next Generation (PING), and Socorro Electronics Division's Laboratory Experience for Undergraduates (SEDLE). Participation in SSR and ODI student programs is closely intertwined, and SSR supports the selection of NAC students through the web based forms and data base used for all summer student applications.

Graduate students: The NRAO is committed to training the next generation of scientists in radio astronomical science, techniques, and technology. Several NRAO programs exist for this purpose. Graduating seniors and first- and second-year graduate students are able to participate in the NRAO summer student program described above. This gives students experience in radio astronomy research early in their graduate careers, allowing them to incorporate these skills into their thesis research. The

NRAO also awards Reber Predoctoral Fellowships to students who have completed institutional requirements for doctoral candidacy so that only their thesis research remains for them to complete their PhDs. Such fellows take up residence at one of the NRAO sites, typically for two years, while they complete their research and thesis under the supervision of an NRAO staff member.

The NRAO also supports many of the 100+ PhD students making use of NRAO telescopes each year. Travel reimbursement, low-cost accommodation, and computing facilities are provided on-site to assist these students. Support is provided for stays lasting several weeks to several months by students to collaborate with NRAO staff scientists as part of their PhD research. These student internships help forge valuable long-term links between the NRAO and the university community.

Student Observing Support: Financial support is available on a competitive basis for students at U.S. universities observing with ALMA or the VLA through the Student Observing Support (SOS) program. SOS funding is designed to provide a stipend and cover miscellaneous expenses such as computers and travel to conferences to a maximum of $35,000 per award. This program is supported through NAASC and SSR funds.

3.4 Reference Services

SSR provides three Observatory-wide reference services:

- The *NRAO Library* provides access to journals and reference materials, tracks a range of metrics related to the publication and citation of scientific results based on NRAO telescopes and by NRAO staff, and manages financial support to meet page charges associated with such publications, and publishes and maintains access to NRAO memos, reports, and conference papers.
- The *Historical Archives* group collects, curates, and makes accessible materials relevant to NRAO activities and other radio astronomy research and development when appropriate.
- *Statistics and Metrics* aggregates data related to the scientific delivery and use of the Observatory for internal use and to report various metrics to the NSF, AUI, and external review committees.

The *NRAO Library* has been proactive in migrating to online, distributed access to research and reference materials for NRAO staff and the wider community. This has resulted in a significant increase in usage, and ensures the availability and retention of these documents that are used by NRAO and the wider scientific community.

The NRAO Library is responsible for the publication, posting, and maintenance of the 68 different NRAO Memo and Report series, both refereed and non-refereed. This ensures the availability and retention of these documents that are used by NRAO and the wider scientific community.

The Library staff support NRAO internal and external reporting functions by collecting a variety of data and metrics in coordination with Statistics and Metrics services. This effort includes ongoing development of ALMA and VLA user and publications metrics in addition to the standard metrics collated monthly, quarterly, or annually.

The existing NRAOPapers software used by the NRAO Library to track NRAO-related publications and a variety of associated statistics is obsolete and has become challenging to maintain. Over the period of this LRP, the Library will continue efforts to transition to a new bibliography metrics database, BiblioMetrix, to interface with the Astrophysical Data System (ADS).

The NRAO Library provides services not only to NRAO, but also to scientists from other organizations, to other libraries around the world, and other government and science organizations.

The *Historical Archives* are supported by NRAO and AUI. The Archives actively seeks out, collects, organizes, preserves, and provides access to institutional records, personal papers, multimedia materials, and oral histories of enduring value that document NRAO development, institutional history, instrument construction, and ongoing activities, including NRAO's participation in multi-institutional collaborations. As the national resource for radio astronomy, the Archives also includes materials on the history and development of U.S. radio astronomy. The Historical Archives has been successful in securing external funds in partial support for its activities, and will continue an ongoing long-term project of processing NRAO and AUI records as well as extensive materials on radio astronomy history. In the period of this LRP, the Archives will continue to make key materials from all collections available digitally via the Archives web pages and other web resources. The Archives continues to collaborate with EPO in developing an indexing and access system for historical images, and hopes to continue successful mentoring of history of science interns. The Archives also hosts and supports the IAU-URSI Historical Radio Astronomy Working Group web site.

Prior to FY2017, *Statistics and Metrics* focused primarily on key data illustrating the demand for and delivery of the NRAO's astronomical observing capabilities. These data were aggregated from proposal submissions, telescope operations, science data archives, student programs, and the Library, and were collated for the VLA and ALMA (the NAASC) as well as for the GBT and VLBA. During the recompetition of NRAO funding in 2015/16, the development of an NRAO Performance Evaluation and Management Plan including the compilation of statistics and metrics across the full range of Observatory activities was requested by NSF. In response, NRAO has appointed an additional resource within the Director's Office and in early FY2017 a preliminary set of Observatory-wide metrics was identified. During the term of this LRP, the set of metrics and associated processes will continue to evolve. New metrics providing insight into the delivery and use of science ready data products, project and program management, and EPO activities are now being tracked. The data are used for a variety of purposes: as a management tool within the Observatory to track performance; as a data-driven means of informing AUI and NSF of key trends—including both successes and possible pressure points; and to inform external committees (e.g., the AUI Visiting Committee and the NSF Annual Program Review Committee), NRAO users, funding-related stakeholders, and members of the public.

3.5 Scientific Staff and Jansky Fellows

SSR has primary responsibility for the research environment at the NRAO, and for oversight of the scientific productivity of staff with a research component to their role. SSR oversees the research aspects of all astronomers, computer scientists, and research engineers and is involved in recruitment and other HR issues involving scientific staff.

A productive and scientifically active staff is a prerequisite for the successful operation of a cutting-edge national observatory. The scientific staff is key to telescope testing, operations, user support, and long-range development and planning, as well as promoting productive scientific exploitation of the Observatory's capabilities. NRAO has a world-class staff of approximately 80 astronomers, computer scientists, and research engineers, recognized internationally for their excellence in telescope design and support, as well as their technical and scientific knowledge and leadership.

SSR will continue to refine the oversight of the research environment and scientific performance of the NRAO staff, seeking to improve the alignment of the policies and processes specific to the scientific staff.

A significant priority over the period of this LRP will be the rejuvenation of the scientific staff as a whole which has a top-heavy age distribution as a result of the integrated effects of past recruitments. This represents both an opportunity—including the chance to bring in new skills to match the evolving direction of the Observatory; and a challenge—as staff with a wealth of experience and corporate knowledge leave the organization. Attention to the research directions and priorities in computer science, technology and astronomy relevant to SRDP and the ngVLA will be particularly important over this period.

SSR oversees the Jansky Fellows postdoctoral program—NRAO's long-standing prize research fellowships. This highly competitive program attracts some of the best young scientists to postdoctoral appointments at an NRAO site, or at external institutions in the U.S. (non-resident Fellows). NRAO also hosts postdoctoral fellows funded by other institutions, such as Hubble, Einstein, and NSF Fellows.

Steps to increase the alignment of the Jansky Postdoctoral Fellowship Program with the mission of the NRAO and the unique opportunities it provides will begin to take effect at the start of this LRP period, and will then evolve more slowly. Increases to the salaries and research funds made available to Fellows will be implemented, and a more strategic approach to the number of initial offers issued will be adopted. NRAO will also seek to increase the number of Jansky Fellows over the period of this LRP.

4 OBSERVATORY TELESCOPE OPERATIONS

4.1 Atacama Large Millimeter/submillimeter Array

ALMA is an interferometer consisting of 66 array elements and located at 5000 meters' altitude in the high Atacama Desert of northern Chile. ALMA was formally inaugurated in March 2013 and construction of the science instrument was completed in 2014. ALMA is now in its fifth observing cycle. Early science observations began in 2011 with Cycle 0, during which observing time was shared with construction and commissioning. This phase concluded with Cycle 2 and a transition toward Steady State Operations began, as defined by achieving the performance levels for observing hours offered, number of array elements available, data processing equilibrium, and availability of pipeline reductions targeted for stable and efficient operations. Steady State Operations will be achieved in Cycle 5 (FY2018). Full Operations will be achieved when the full suite of observing capabilities are available, including the 12-meter array, the ACA, Bands 1, 3, 4, 5, 6, 7, 8, 9, and 10, solar observing, longest baselines up to Band 7, long baselines at the highest frequency bands, total power in continuum, polarization of spectral lines, and a few additional capabilities. The target for Full Operations is no later than Cycle 7 (FY2020), with some of the listed capabilities available earlier. Operation of the ALMA Observatory in Chile is the responsibility of the JAO.

North American ALMA (NA ALMA) is the NRAO department that provides NA operational support for ALMA, and has two primary missions: to support the NA astronomy community in its use of ALMA, and to provide NA's scientific and technical partnership support to the international ALMA Observatory.

NA ALMA ensures that the NA scientific community has the tools, information, support, and access to make optimal scientific use of ALMA. NA ALMA also works to foster, expand, and diversify the community so that ALMA capabilities and opportunities result in the best and most expeditious science, and are available to the widest number of users.

NA ALMA also provides scientific, technical, and business support to ALMA operations in Chile. This support is carried out in concert with the JAO staff and the other ALMA regional partners. NA ALMA provides extensive support for hardware and software built by the NA ALMA construction project. In addition, it supports a long-term development program for ALMA technical enhancement. As part of the offsite budget, NA ALMA funds a business office in Chile that provides administrative support for the JAO.

NA ALMA consists of four divisions:

1) the North American ALMA Science Center (NAASC),
2) the Offsite Technical Maintenance and Support groups (software and hardware), which includes NA ALMA Construction Warranty Support,
3) the NA ALMA Development Program, and
4) the NRAO-Chile Office.

The NA ALMA Development plan is described in Section 5.2.

Strategic Objectives

NA ALMA's strategic objectives during FY2019–2023 are as follows.

Imaging Pipeline and Expedited Data Delivery: Bring the Imaging Pipeline to full maturity and expedite data delivery to NA ALMA PIs. The Imaging Pipeline advanced rapidly in Cycle 4 and its capabilities will be further expanded to include more observing modes and the ability to successfully reduce larger fractions of data. In conjunction with the JAO and international colleagues, the team will continue to streamline data processing procedures with a goal of delivering data within 30 days of the completion of observations.

Science Ready Data Products (SRDP): The objectives of SRDP, to provide science ready data to PIs, is closely aligned with long-standing NAASC goals of facilitating all steps of data processing. Consequently, the NAASC is matrixing significant staff to the SRDP initiative and will support the initiative through the LRP period. (SRDP is described in more detail in Section 3.2.)

Expedite NA ALMA Community Science Publication: Improve tools (e.g., data visualizers, data mining tools, etc.) and training to expedite science throughput and the publication of results. These initiatives will be helpful to both experienced and novice users and will help to broaden the NA ALMA user base (and complement the SRDP initiatives).

Refine NA ALMA Construction Deliverables: Based on the experience of early operations, ensure that NA ALMA hardware and software deliverables are meeting all practical and reasonable design requirements, and that an adequate stock of spares are available.

Streamline Offsite Hardware Technical Support: Work with the JAO and ALMA Integrated Coordination Teams (IXTs) to set up the software (database) infrastructure to enable predictive, condition-based maintenance for receiver and other instrumentation hardware. In addition, work with the JAO and IXTs to identify responsibilities and processes for obsolescence mitigation and associated cost sharing.

Facilitate JAO Operations: Strengthen training, services, and communication between the NRAO-Office of Chilean Affairs (OCA) and the JAO to help improve JAO's efficiency of operations, safety, and employee morale.

Facilitate ALMA 2030 Strategic Development: Through calls, outreach, and workshops, promote and facilitate next-generation ALMA development through ALMA Development Studies and Projects. Facilitate the ALMA Development Working Group and community white papers for Astro2020 identifying ALMA 2030 upgrades.

North American ALMA Science Center Operations

The NAASC is the scientific support arm of NA ALMA Ops, and is the North American scientific community's interface to the ALMA Observatory for expert advice and assistance in the use of ALMA, including proposal preparation and submission, data reduction and reprocessing, ALMA-specific documentation, and on-line tools and resources. Embedded within the NAASC is the North American ALMA Regional Center (NA ARC), which provides the core services specified by the ALMA Observatory for scientific support in the regions and contributed support for Chile operations. The NAASC also coordinates with the science operations of the other ALMA partners in Europe and East Asia.

SRDP and NAASC Team Structure in FY2018: The team structure introduced in FY2016 was retained through FY2017. Every NAASC team had a successful year with improvements in data delivery, the delivery and deployment of the ALMA imaging pipeline, the start of the ALMA Ambassadors program, more efficient reporting of antenna or array issues to the JAO, and the extension of capabilities and observing time for ALMA Cycle 4 observations.

In FY2018, the NAASC will matrix staff to SRDP which will deliver data sets ready for scientific study by a wide range of astronomers. The NAASC Software Support and Testing Team, which has for the past few years focused on ALMA data reduction pipeline testing and heuristic development, will be functionally matrixed to SRDP. The ALMA data reduction pipeline is now maturing in its basic functionality for calibration and imaging and the Software Support Team can help facilitate the SRDP goal of delivering more advanced scientific products to investigators.

In addition to the Software Support Team, the CASA Scientific Testing Lead, which has been a NAASC-led function, will be matrixed to SSR, which should promote a balance between ALMA and VLA test requirements for CASA. This transition will happen over the course of FY2018 but core deliverables to the JAO and ALMA project will be prioritized and continue to be delivered to the ALMA project from the NA ARC.

As such, the long-term objectives of the former Software Support and Testing Team of the NAASC will be integrated into the long range plan of SRDP and SSR. The objectives of the remaining NAASC teams over the FY2019–2023 LRP period are described below.

Telescope Interface and Diagnostics Team

The NAASC Telescope Interface and Diagnostics Team will provide the JAO with operational support and technical expertise from the NA partner. Specific responsibilities of this team include coordination of Astronomer on Duty (AoD) shifts, Level 2 Quality Assurance (QA2) reassessments, providing technical and diagnostic liaison to the JAO, Phase 2 Group (P2G) scheduling block preparation and support, and Extension and Optimization of Capabilities (EOC) support.

Key objectives of the Telescope Interface and Diagnostics Team for FY2019-2023 are as follows:

Diagnostics: The team lead will be a critical participant in the JAO technical and diagnostics-related meetings and telecons, such as the JAO Science and Engineering Coordination and the Control System and Correlator Group weekly meetings and software readiness review meetings. The team will report on issues found from the NA ARC to the JAO technical and engineering staff and vice versa. This includes repeated problems uncovered during QA2 that do not result in QA2 failures but nonetheless occur often and impact efficiency and the data quality unless flagged, as well as QA2 failures (which include, but are not limited to, data taken with less than optimal resolution for imaging, too low elevation, and other issues). The team will also investigate and track technical issues that lead to QA3, a number of significant examples of which have been identified at the NAASC and whose fixes are coordinated between the NAASC and the JAO. Team members will maintain close interaction with NAASC data reduction team and the JAO to ensure all problems are reported and tracked as efficiently as possible. Goal: to expand effort for diagnostic and trouble-shooting support for problems occurring during array operations and faster turnaround on problem-reporting, to improve efficiency and data quality.

Support of Telescope Operations in Chile: Coordinate with the JAO and other ARCs on scheduling of AoD shifts in Chile and provision of AoDs in support of telescope operations in Chile. Goal: within NA, ensure a pool of trained AoDs is maintained.

Phase 2 Group: Provide the technical expertise required to critically review all Phase 2 materials submitted by NA PIs and modify any scheduling blocks (SBs) that require expert technical input, and ensure that all SBs are ready to run on the telescope. In addition, provide any necessary changes to SBs during a given Cycle following a change request or other edits requested by the PI or as needed for scheduling. In preparation for an upcoming Cycle, participate in software testing of the ALMA Observing

Tool (OT) and relevant End-to-End tests, as well as related software such as the Project Tracker. Coordinate with the JAO and the other ARCs on developing P2G best practices. Goal: as well as leading the Phase 2 process in NA, provide P2G training to additional staff as the Phase 2 process evolves.

ALMA Proposal Review Process: Provide technical expertise in support of the ALMA proposal review process, the Proposal Handling Tool (PHT) technical assessment as needed, and technical secretary functions. In addition, the NAASC will provide support from the Phase 1 Manager Cognizant Lead to the ALMA Proposal Review and Time Allocation Committee meeting.

Extension and Optimization of Capabilities: The team will interface with the ALMA North American Science Advisory Committee (ANASAC) and JAO and, with the ALMA Science Advisory Committee (ASAC) when needed, on setting the priorities of ongoing EOC work needed to complete these activities in future Cycles. The team also provides domain-expert support for carrying out these activities. Team members will attend and play an active role in the annual Observing Modes (ObsMode) and Computing Planning Meeting (CPM) meetings and contribute to the preparation of the OT requirements document for proposed features for upcoming Cycles.

ALMA Software Support and Testing Team

The Software Support and Testing Team will provide NA support for ALMA operational and in-development software. Responsibilities of this team will include tools and algorithm development, CASA support and testing, software liaison to the JAO for Control and Correlator, pre-release software testing, and development of software requirements and process improvements. Starting in FY2018, this team will be integrated into the SRDP Project Office and the SSR Department (See Section 3.2).

Science Data Services and Archive Team

The Science Data Services and Archive Team is responsible for delivering QA2 reference images to the PI and to the ALMA archive, and for assisting the PI with data reduction. Specific responsibilities include archive improvements and testing, quality assurance testing (QA2), project tracking tools for staff and the PI, support for QA3 requests, PI data reduction, and imaging including pipeline processing.

Key objectives of the Science Data Services and Archive Team for FY2019-2023 are as follows:

Data to PI's in 30 Days from QA0: During much of Cycles 3 and 4, QA2 took so long that many re-observation opportunities were missed because the array had changed configuration by the time the assessment had taken place. Delays also affect the timeliness of publication of results and submission of follow-up proposals in subsequent observing cycles. We will work with the ALMA data management group to reduce the average delay from a successful observation through to QA2 and delivery of the data from 70 days in Cycle 3 and the first half of Cycle 4, to 30 days for standard mode data and 45 days for data taken in non-standard modes. The efforts of the Data Processing Tiger Team in FY2017 put the plans in place to hit this milestone in FY2018. As part of this initiative, a new processing workflow will be put into place at the start of Cycle 5. This workflow is primarily designed for the long-term goal of performing all pipeline processing at the JAO as specified in the ALMA Operations Plan, but includes the ability for the ARCs to contribute to pipeline processing activities.

Maintain a Current Instance of the Pipeline at the NAASC: This will be used to supplement the data reduction efforts of the JAO should that prove necessary. Staffing of the data analyst pool will be maintained at a level sufficient to support the NA data reduction effort. This initiative addresses the key strategic goal to facilitate NA community science publications.

LUSTRE Access and Management for External Users: The team has overall responsibility for ensuring that users can interact effectively with their data. Over the course of this LRP, the current situation where reference images only are provided by the standard data reduction, will evolve to one where SRDPs are provided to users for most datasets. However, as the SRDP initiative is unlikely to satisfy all use cases, the team will support users who wish to reprocess their data themselves as follows:

- The team will continue to provide calibrated measurement sets to PIs as a NAASC added value service, and will also generate them on demand. In future this on demand service will be automated via the pipeline processing interface (discussed below).
- The team will provide temporary accounts on the NAASC cluster for users, both visitors and remote, for interactive data reduction. In practice this may be limited by capacity, though so far the team has been able to support all requests.
- The pipeline processing interface (PPI) will be able to run the pipeline to create both new images and calibrated measurement sets. This will be the preferred means of support for users who wish to remake the pipeline products with small changes to the imaging or calibration, and/or use the latest version of the pipeline.

The team will also undertake the following work that will complement that of the SRDP Project Office.

- The team will support the development and deployment of the NRAO archive access tool and pipeline processing interface. This initiative will be transferred to the SRDP Project office in FY2018 (See Section 3.2).
- The team will continue to support the ALMA QUality Assurance (AQUA) tool, the Project Tracker (PT) and the scheduling subsystems with the aim of improving the process from data taking through QA2. In particular, the team will work towards full integration of the Observatory project lifecycle, rendering the current workarounds obsolete. The team will also support SRDP-led efforts to integrate the Object Oriented Data Technology (OODT) processing workflows into the overall ALMA data processing workflow.
- The team will lead support for integration of the enhanced metadata and products from the NA-led ALMA Data Mining Toolkit (ADMIT) development program into the ALMA archive, with the ultimate aim of producing an archive with rich metadata, suitable for data mining applications.

Science Community Interface Team

The Science Community Interface Team will serve as the bridge between ALMA and the NA user community. This team will be responsible for organizing community outreach, diversity, and broadening participation activities, including Community Day / NRAO Live! Events, science web and ALMA Science Portal improvements, Helpdesk / Forums management and oversight, Contact Scientist support and oversight, end-user documentation, face-to-face visitor support, coordination with the NRAO Office of Diversity and Inclusion, and coordination with the Education and Public Outreach Office.

Key objectives of the Science Community Interface Team for FY2019–2023 are as follows:

ALMA Ambassadors Program for Proposal Preparation Support: The NAASC will expand upon the existing, successful ALMA proposal preparation workshops (called Community Days and NRAO Live! Events) and continue the ALMA Ambassadors program which funds up to ten postdoctoral researchers to visit the NAASC and receive training to run the workshops at their home institutions. Participating postdocs will receive a monetary grant and will be encouraged to present their research while visiting the NAASC. NAASC staff will also host three to four Community Days per year.

User Support and Guidance During Observations: The NAASC will provide all PIs a Contact Scientist whose responsibilities include: reviewing PI scheduling blocks, aiding in determining appropriate telescope configurations for each project, tracking a project throughout the observing cycle, assisting with data reduction and analysis for visiting PI teams, and supporting remote requests for pipeline re-processing.

Training and Tools for Expediting Publication: The NAASC will continue to provide the tools to assist PIs to bring ALMA results to publication including: one-on-one support of up to two members of an ALMA project team to reduce and analyze the data during a visit to the NAASC, and the hosting of two data reduction workshops per year for up to 12 participants each.

Tools for Current and Prospective ALMA Users: In support of the broader ALMA user community, the NAASC will maintain management of the Helpdesk with guaranteed responses within 48 hours, and support continued development of Knowledgebase articles in response to frequent user questions. All user documentation will be updated and clearly organized in the ALMA science portal, which will become a more dynamic source of news, telescope updates, and ALMA science results.

Scientific Meetings and Workshops: The NAASC will continue to host or sponsor scientific meetings and workshops. Specifically, the NAASC will continue to be a major corporate sponsor of the yearly International Symposium on Molecular Spectroscopy, sponsoring new initiatives and outreach opportunities including the LGBTQIA reception.

NRAO-Chile Office

NRAO Chile provides direct support to the JAO as the NA partner for Chilean business operations. The office works in concert with AUI-Chile, the legal entity for NA ALMA support in Chile, to provide accounting, contract and procurement, travel services, support for NA international and local staff, HR and payroll services, union relations and liaison with Chilean authorities. Together, NRAO-Chile and AUI-Chile comprise the Office of Chilean Affairs (OCA).

Key objectives of the OCA for FY2019–2023 are as follows:

- Continue to work on relationship with JAO on HR/payroll, CAP, safety/environment and other areas. The OCA has established better communications and a stronger presence on site than in the past, but there is still room for improvement through more frequent and effective face-to-face interactions (e.g. trainings on CAP best practices and travel procedures).

- Implement the provisions of the FY2018 collective contract while addressing the challenges posed by the new Chilean labor law (e.g. no automatic extension of benefits).

- Measure performance with agreed indicators. During FY2017, high-level OCA/ALMA metrics were identified for NRAO´s reporting to NSF. In FY2019 and beyond, OCA will measure its performance with specific indicators that align each area and individual PEP goals with overall office objectives. To the extent that it is possible and relevant, the aim will be to compare OCA performance with market standards/benchmarks. However, given the unique nature of OCA and ALMA, an important indicator will be related to JAO perception of service level.

- Make progress on diversity and inclusion/broader impact initiatives such as the NINE program and Sister Cities. In FY2017, research was conducted on STEM capabilities and underrepresented minorities in Chile. A major finding was that women and poorer sections of the population are far less likely to pursue STEM careers than other groups. In FY2019 and beyond OCA plans to focus outreach efforts on these groups (e.g. raising visibility of gender issues in STEM).

- Reassess the possibility of moving OCA to the JAO office in Santiago. If this option is not feasible due to space or other restrictions, evaluate cost effective alternatives in the vicinity.

- Develop and maintain an OCA risk register taking into account safety, environmental, labor, financial and any other relevant matters. Assess risk impact and probability, and implement mitigation strategies.

4.2 Very Large Array

The VLA continues to be highly productive, offering sensitive and high resolution capabilities throughout the 300 MHz to 50 GHz frequency range. Scientific studies focusing all the way from the mapping of coronal mass ejections from the Sun, and extending out through the Universe to detections of the molecular gas in high redshift galaxies, are enabled by the VLA. During FY2019–2023 there will be several new capabilities coming online that will open new fields of study, such as the ability to respond very quickly to an external fast-transient trigger, as well as the ability to detect very fast transients and generate those triggers for other observatories. In addition, the seven-year long VLASS—a multi-epoch, all-sky, 2–4 GHz survey with the highest spatial resolution ever obtained for an all-sky radio survey—will be underway, with the potential of vastly increasing access to radio data products outside the traditional radio astronomy community.

Scientific Capabilities

The VLA system performance is summarized in Tables 4.2.1 and 4.2.2. The VLA currently offers the observing modes and capabilities shown in Table 4.2.3 through its General Observing (GO) program. These GO capabilities are well-tested and are supported at all phases by mature software. The capabilities support a wide range of scientific studies, from observing the Sun and planets, to star formation regions, to stars themselves, to galaxies. Continuum, spectroscopic, and polarimetric observations are all supported within the GO program.

Table 4.2.1: System performance of the VLA receiver bands

Band name	Wavelength	Frequency range (GHz)	SEFD[(a)] (Jy)
4	4m	0.058–0.084	(b)
P	90cm	0.23–0.47	2800
L	20cm	1.0–2.0	420
S	13cm	2.0–4.0	370
C	6cm	4.0–8.0	310
X	3cm	8.0–12.0	250
Ku	2cm	12.0–18.0	350
K	1.3cm	18.0–26.5	560
Ka	1cm	26.5–40.0	710
Q	0.7cm	40.0–50.0	1300

Notes: (a) SEFD is the System Equivalent Flux Density (Jy), defined as the flux density of a radio source that doubles the system temperature; (b) The full 4-Band system is yet to be fully commissioned; its SEFD will be measured during that exercise.

Table 4.2.2: VLA Performance Summary

Parameter	Description/Capability
Antennas (diameter, m)	27 (25)
Array Configurations (maximum baseline, km)	A (36.4), B (11.1), C (3.4), D (1.0)
Frequency Band Designations	4, P, L, S, C, X, Ku, K, Ka, Q
Angular Resolution at 74 MHz in arcsec (configuration)	24 (A), 80 (B), 260 (C), 850 (D)
Angular Resolution at 45 GHz in arcsec (configuration)	0.043 (A), 0.14 (B), 0.47 (C), 1.5 (D)
Maximum Bandwidth in GHz	2 (8-bit samplers), 8 (3-bit samplers)
Maximum number of frequency channels	4194304
Frequency resolution range	2 MHz to 0.12 Hz
Continuum sensitivity in one hour in microJy/bm (band)	7.4 (L), 9.6 (Q)
Spectral line sensitivity in one hour over 1 km/s in mJy/bm (band)	2.9 (L), 1.9 (Q)

Notes: See Table 4.2.1 for more information.
Assumes uniform weighting using a full 12-hour synthesis observation of a source which passes near the zenith.

Table 4.2.3: VLA General Observing Capabilities

Capability	Description
8-bit samplers	• Standard default setups for: o 2 GHz bandwidth continuum observations at S/C/X/Ku/K/Ka/Q-bands o 1 GHz bandwidth continuum observations at L-band o 256 MHz bandwidth continuum observations at P-band • Flexible setups for spectroscopy, using two independently tunable 1 GHz basebands, each of which can be split into up to 16 flexibly tunable subbands • Single, dual, and full polarization products
3-bit samplers	• Standard default setups for: o 8 GHz bandwidth continuum observations at K/Ka/Q-bands o 6 GHz bandwidth continuum observations at Ku-band o 4 GHz bandwidth continuum observations at C/X-bands • Flexible setups for spectroscopy, using four independently tunable 2 GHz basebands, each of which can be split into up to 16 flexibly tunable sub-bands • Single, dual, and full polarization products
Mixed 3- and 8-bit samplers	• Allows more flexibility for simultaneous continuum and high-resolution spectral line observing
Subarrays	• Up to three independent subarrays using standard 8-bit continuum setups
Phased array for VLBI	• All antennas phased to simulate a single antenna with larger collecting area ("Y27")

In addition, the VLA offers Shared Risk Observing (SRO) capabilities, which are not as well-tested as the GO capabilities, but can be set up within the software system. One example of a current SRO capability is On-The-Fly Mosaicing (OTFM), where antennas are slewed quickly across large parts of the sky while taking data. Finally, the VLA also offers Resident Shared Risk Observing (RSRO) capabilities, which allows users full access to many other modes of observing, but the observations cannot be currently set up within the standard software system. Such capabilities include observations of pulsars, fast transients, the Sun, and those involving frequency averaging. During the FY2019–2023 period, NRAO plans developments in the following SRO and RSRO capabilities, with the ultimate goal of making them available through the GO program.

OTFM: OTFM observations have been well-tested at a low level within the VLA observing software system, mostly in preparation for VLASS. It is possible, but difficult, to set up these observations in the Observation Preparation Tool (OPT), and this has only been tested extensively for the particular setup used for VLASS; because of this OTFM observations are considered an SRO capability. There are some issues in the higher-level software (the OPT and the AAT) that will be addressed in FY2019, involving control of the antennas and storage of data in the archive. In addition, enhancements to the ability of users to set up OTFM regions on the sky will be made in the OPT, such as being able to easily define these regions and being able to visualize regions on other all-sky radio maps (e.g. NVSS). OTFM observing will move to GO in the 2018B observing semester.

Pulsars: There are currently two modes for observing pulsars possible on the VLA: the de-dispersion mode, which uses software implemented outside the VLA correlator (Wideband Interferometric Digital Architecture, or WIDAR); and the phase-binning mode, which uses WIDAR itself. Both of these modes are supported in the low-level VLA software, but it is not possible currently to set either of them up in the OPT, nor is proper archiving of the data for the de-dispersion mode enabled. Because of this, they are both considered RSRO capabilities. Requirements written for the necessary software have been acknowledged by the software group that will implement it. Over the FY2019–2023 timeframe, both of those items will be addressed: de-dispersion pulsar observations should change from RSRO to SRO in FY2019; and phase-binning observations should change from RSRO to SRO in FY2020.

Fast Transients: It is possible to observe over a relatively narrow bandwidth (256 MHz) with all of the VLA antennas, recording visibilities every 5ms. However, the setup of these observations in the OPT is not currently supported, which makes this an RSRO capability. This item will be addressed, and such observations should transition from RSRO to SRO in FY2019. In addition, the group anticipates that the ability to record wider bandwidths at shorter timescales will be developed (FY2020). Finally, the Realfast commensal transient detection hardware and software will be implemented on the VLA (FY2017–19), which will allow fast (and other) transient detections (See Section 5.3).

Observing the Sun: It is currently possible to observe the Sun with the VLA, but scripts must be hand-crafted, as they are not supported in the OPT. In addition, new solar hardware has been commissioned which allows observations of the Sun at X- and Ku-bands. This item will be addressed, and such observations should transition from RSRO to SRO and thence to GO in FY2019.

Frequency Averaging: It is currently possible to observe with wider channels than are normally used in continuum observations, allowing data rates and volumes to be reduced considerably, but it is an RSRO capability. Software requirements have been written for implementation of this capability, and it will be transitioned from RSRO to SRO in FY2019.

Operations

Activities related to the operations of the VLA will be carried out by the responsible groups within New Mexico Operations in a manner similar to previous years. The most significant change in standard operations during the FY2019–2023 period will be the completion of the switch to remote operations of the VLA during evening and night shifts.

Mitigation of Radio Frequency Interference: Radio-Frequency Interference (RFI) is a particular problem for the VLA, with interference generated both internally and externally. NRAO strives to minimize the internally generated interference by shielding its electronics. Externally generated interference, mostly originating from satellite communications, satellite radio, cell phones, aircraft radar, military bases, weather balloons, and other transitory sources, limit the available ranges of frequency space in which the VLA can operate for astronomy. Algorithms and other tools for identification and excision of such signals from astronomical data have been and continue to be developed for the VLA and CASA.

RFI is detected at the VLA by spectrum analyzer monitors that are separate from the array, and by annual RFI-specific observations and analysis. The spectrum analyzers are not connected to all antennas in the array. The annual RFI sweep is sensitive, but is costly in analyst time and provides data only on those signals present within a very short time window. With the addition of some software infrastructure it should be possible to perform a daily RFI analysis as a commensal observation during and between science operations. Data can be extracted from the radio-frequency signal path using engineering taps in the Data Transmission System (DTS), and while its sensitivity will be low, acquisition is cheap and intermittent and short-term signals can be spotted and tracked. The Electronics Division will investigate and develop a database to allow tracking of RFI. It will also automate the analysis to identify strong RFI before it impacts a significant number of observations and to allow for the analysis of the RFI properties for further investigation. This work is scheduled for completion in FY2018.

Maintenance and Infrastructure Improvements

The VLA maintenance plan is based on more than 35 years of VLA operations and maintenance experience. The expected lifetime of the array after the upgrades of the EVLA project is 20+ years, and the current age of its predominant components (the antennas are now more than 35 years old) means that effective preventive maintenance is vital for protecting this investment. The AUI Proposal for the Management and Operation of the NRAO included a staged "3+7" VLA infrastructure maintenance and development plan, starting with a dedicated three-year period to renew the VLA's physical infrastructure. Thus, the bulk of the following items occur early in this FY2019–2023 LRP, with the remainder staged as needed throughout the rest of the AUI award period.

Antennas: Traditionally, NRAO has conducted periodic inspection and overhaul cycles in which an antenna is cycled out of the array every six to seven weeks. Thus, every 3.5 years each of the 28 antennas will be thoroughly overhauled as part of a continuously repeating cycle. Each antenna overhaul includes structural inspections; mechanical, electrical, and electronic systems upgrades; touch-up structural painting; and the repair and replacement of parts as needed.

The need to upgrade the VLA Antenna Control Units (ACU) became apparent five years ago and the design for new ACUs was completed. Since that time and as funding has allowed, NM Ops has retrofitted six antennas with the new systems. The infrastructure improvement plan in the new cooperative agreement provides funding to upgrade the balance of the ACU systems at a rate of three per year. This work, along with the refurbishment of antenna subreflectors and focus/rotation mounts, will be performed as part of the antenna overhaul process. In these cases, the time required to overhaul an antenna increases by approximately one month. We anticipate that all 28 VLA antennas will be upgraded in this fashion within seven to eight years.

VLA antenna azimuth bearings tend to wear out over time. These will be replaced at a rate of one bearing per year. The Engineering Services Division has bearings in stock to perform this task through FY2018, with the new funding for additional bearings commencing in FY2019.

To maintain structural integrity, the antennas require insulation patching, rust repair, and overall painting. This effort will begin in FY2019 and will require additional term-limited staff for approximately five years. These staff will work in the colder months to install automatic grease distributors on the antennas. This work is also funded under the new cooperative agreement.

Track: The VLA railroad tracks must be inspected continuously to ensure safe travel by the maintenance vehicles (used daily by technicians to service antennas) and the transporters that carry the antennas during reconfiguration periods (about 60 individual moves per year). Supporting track maintenance requires specialized railroad repair vehicles and equipment, as well as ballast, rails, and track sections. The deterioration of the old rail ties used to construct the VLA rail system became critical in the last decade, and as a result a plan was developed to increase the rate of replacement to approximately 5000 ties per year, along with an increase of pad intersection replacements from three to five per year. This plan was developed with the assistance of a railroad maintenance consultant (2013 Holland Track Survey) and is being followed on average, with priority areas receiving first attention. Funding provided through AUI's new cooperative agreement supports this pace of tie replacement through FY2026. VLA maintenance specialists currently assess the overall condition of the track as fair; it does not pose a safety hazard to antennas or equipment. In order to assess the future health of the track and the relative success of this program, an ultrasonic track survey has been planned for FY2020.

Correlator: The VLA's WIDAR correlator will require routine yearly maintenance of its heating, ventilating, and air conditioning (HVAC) equipment, fire suppression, and dedicated UPS systems. The level of maintenance and repair for the WIDAR correlator boards, racks, fans, power supplies, and other parts will be carefully assessed and quantified.

Heavy Equipment: The equipment required at the site for heavy jobs, such as specific equipment for track repairs, dump trucks, forklifts, cranes, and the like, has been historically obtained through General Services Administration (GSA) surplus. This equipment is now very old and is increasingly difficult to maintain and repair. Furthermore, when it is possible to do so, obtaining replacement equipment from government surplus is becoming more expensive. There have been no funds in the Observatory's budget specifically to replace heavy equipment. Through the new cooperative agreement, funds now exist in FY2019 to purchase a new rail crane. Funding for additional heavy equipment, depending on the specific need, is available in FY2018, FY2019, and FY2020, and in outlying years up through FY2026.

Machine Shop: The VLA machine shop uses several high-end mills and lathes to fabricate feeds, vacuum dewars, transporter axles, and many other antenna system and support components. These machines, which average well over 20 years of continuous use, are approaching their end of life. The new cooperative agreement provided funds to purchase a new Computer Numerical Control (CNC) mill in FY2017. Another CNC mill will be purchased in FY2020.

Electrical Infrastructure: The VLA site electrical infrastructure, which includes the hatch power distribution gear, the back-up generators and their associated switchgear, the site power transformers, and the various power distribution panels, has been in constant use for over 40 years. The major components of this infrastructure were originally obtained second-hand. Parts of the hatch gear are no longer useful in the way in which they were designed, and the performance of the generator switchgear has become increasingly inconsistent. The unit also poses a potential safety risk. Funding to cover the replacement of the hatch, generators, and generator switchgear will be available in FY2018. Additional funding for replacement of some of the older array arm switches becomes available in FY2019.

The VLA site's well pump controller will also be upgraded. In FY2019, the aging controller unit will be replaced with one that will gradually increase the water pressure to the potable water and fire suppression systems, rather than providing water at full force. This feature will help to maintain the structural integrity of the site water pipes. Additionally, the power which feeds the pump controller and well will be re-routed to a dedicated line or generator, assuring that water for fire suppression is available during any time when power is consciously removed from the site at large (such as during a fire).

Buildings: The Control Building roof leaks during times of rain and snow. The roof will be replaced in FY2020. The tube exchanger for the Control Building cooling tower will also be replaced in FY2020. Spare compressors for the site HVAC systems will be purchased the same year. To improve energy efficiency at the site, additional insulation and new doors will be purchased and installed in FY2019.

Test Equipment: The testing of newly constructed or repaired Front End receivers creates a scheduling bottleneck when installing them on the antennas. A Front End SOIDA test rack and additional instrumentation will be purchased to decrease the overall receiver delivery time. The first of two test racks was purchased and assembled in FY2017. The remaining test rack will be purchased and assembled in FY2020.

Road and Parking Lot Repair: The roads and parking lots around the site buildings will be repaired or repaved. Full funding for this task becomes available after FY2022.

Summary of VLA Infrastructure Improvement Plan: Staging of the infrastructure improvements described above is slightly different from that in AUI's successful proposal for the new NRAO Cooperative Agreement. The staging of the improvements in New Mexico had to be revised to accommodate increases in infrastructure costs, to support ngVLA earlier in the term of the new Cooperative Agreement, to facilitate urgent repairs, and to gain operational efficiencies. The scope of work and budget for the infrastructure and development program has not changed—only the timing for performing each activity has been revised. The current version of the infrastructure improvement plan, as described above, is summarized in Table 4.2.4. The overall program will continue to be monitored and possibly revised depending upon future operational priorities and unforeseen equipment failures.

Table 4.2.4. Current Version of Major Equipment and Large-scale Repair Items for NM Operations. Budget amounts are in $K.

VLA Equipment	FY16	FY17	FY18	FY19	FY20	FY21	FY17-26
Two track high rail vehicles	0	128	0	0	0	0	128
CNC lathe	0	0	0	0	0	0	0
Cooling tower tube exchanger	0	0	0	0	55	0	55
Front End SOIDA rack (2)	0	101	0	0	105	0	206
Heavy vehicle replacement	0	189	25	162	114	0	1,034
New switches - E,W, N arms	0	0	0	50	0	0	50
Repair VLA CB roof	0	0	0	0	101	0	101
Replace two CNC knee mills	0	99	0	0	99	0	197
Replace generator switchgear & hatch gear	0	0	1,000	0	0	0	1,000
Replace rail crane	0	0	0	103	0	0	103
Replace azimuth bearings	0	0	0	62	124	66	610
Replace VLA cafeteria roof	0	87	0	0	0	0	87
Replace standby generators	0	0	1,375	0	0	0	1,400
Replace National boom truck	0	270	0	0	0	0	270
Spare HVAC compressors	0	0	0	0	80	0	80
Tie inserter	0	85	0	0	0	0	85
Passenger bus repair facility	0	0	0	0	0	0	149
Road & parking lot maintenance and paving	0	0	0	0	0	0	442
Subtotal VLA Equipment	**0**	**959**	**2,400**	**377**	**677**	**66**	**5,996**
Large Scale Repair and Maintenance		-	-	-	-	-	-
Replace ACU & FRM motors	183	46	30	90	90	118	1,067
Antenna automatic grease distributors	0	0	0	14	42	14	70
Replace ties and intersections	0	542	0	601	722	524	4,527
Refurb AAB overhead crane	0	70	0	0	0	0	70
Antenna rust removal, paint and insulation	0	0	0	140	88	58	387
Well pump power controller	0	0	0	110	0	0	110
Improve site building insulation	0	0	0	73	0	0	73
Replace exterior doors and windows	0	0	0	150	0	0	150
Ultrasonic track inspection	0	0	0	0	50	0	50
Subtotal Repair and Maintenance	**184**	**658**	**30**	**1,178**	**992**	**714**	**6,505**
Carryover	0	470	-470	0	0	0	0
ngVLA Development	-184	752	0	0	-568	0	0
Grand Total	**0**	**2,838**	**1,960**	**1,555**	**1,102**	**780**	**12,501**

Technical Upgrades and Enhancements

Several technical upgrades and enhancements will be undertaken during the period of this LRP in order to improve capabilities, complete existing upgrade programs, or to improve ease of operation and/or maintenance. Technical upgrades are chosen based upon considerations of safety, operational efficiency, ease of maintenance, impact on data quality and delivery of science, cost, and impact on overall NRAO strategic goals. A description of the activities planned for FY2019–2023 is given below.

Solar-Capable Receiver Installation: The solar receiver upgrades to the VLA's L, S, C, X, and Ku-band receivers will proceed in parallel and will be completed in FY2020.

4-Band Dipole Installation: During FY2017, a costed plan was developed for completing the outfitting of the VLA antennas with 4-Band dipoles. The installation of the dipoles will be completed by FY2019.

Dry-air Systems: The radome material used at the VLA was investigated for efficacy in FY2017. It was determined that the material used is effective and is not subject to premature aging. Instead, leaks were found to be mostly due to failures in the mechanical seal between the material and the feed horn, in addition to damage from hail storms. With the further development of the dry-air system, VLA staff will be able to identify these types of leaks and correct them as needed.

High Level Diagnostic Tools: The sheer volume of monitor points on the VLA—a consequence of both the number of antennas and their extensive instrumentation—often makes it difficult to evaluate the health of a system, or to spot the not-infrequent, subtle failures that do not cause alerts to be triggered. A higher-level analysis of available data will allow more rapid and accurate fault diagnosis, while also reducing data flagging and the time burden on operators, engineers, and scientists. To enable this high-level analysis, the Electronics Division will develop trend analyses to include: rule-based evaluators, fault-tree analyses, and summary dashboards. This effort began in FY2017 and will continue through FY2020.

5 OBSERVATORY DEVELOPMENT PROGRAMS

5.1 Central Development Laboratory

The Central Development Laboratory (CDL) has long been regarded as a national technology resource by the U.S. astronomy community. As the Observatory's main instrumentation Research and Development (R&D) facility, the CDL's core mission is to: (1) develop critical capabilities for upgrading NRAO's current facilities, and to facilitate the capabilities of the Observatory's next-generation facilities; (2) help the community realize mid-scale projects, as recommended by the NSF-sponsored Decadal Surveys; and (3) provide critical maintenance support to NRAO's existing instruments.

As the U.S. radio astronomy community and NRAO increasingly turn their attention to planning the next major radio instrument beyond ALMA—currently typified by the ngVLA concept—and its relationship to the 2020 Decadal Survey, it is increasingly important that CDL's long-range R&D efforts encompass programs that support the scientific and engineering requirements of the emerging instrumental concept. At the same time, the maintenance and enhancement of the capabilities of the ALMA and VLA interferometers must remain firmly within the scope of the Laboratory's activities, and several such R&D projects directed at these critical activities are described in this plan.

CDL Strategic Directions

Staffing: CDL plans to hire additional staff in general accord with the staffing plan presented in AUI's Observatory management proposal to NSF. This plan consists of two major components:

- Stopping the erosion of the CDL engineering staff by backfilling positions left vacant by retirements and other departures. (The specific qualifications of replacement personnel shall be determined by Laboratory and Observatory senior management according to evolving CDL needs.)
- Strategically hiring additional laboratory staff to reinforce critically important capabilities (and thereby preclude single-point personnel failures) and to enable development of promising new technologies.

The staffing increase described in the AUI proposal is based on hiring a Research Engineer, Engineer and Technician in each of five disciplines, for a total of 15 new staff members, over a period of five years FY2017–22. As of Q4 FY2017, three positions have been filled. Budget constraints may postpone some, or all, planned hires in FY2018. Laboratory needs assessment and hiring decisions will continue to be made on a case-by-case basis throughout the term covered by this plan.

New Technical Areas: New technical areas for future CDL study are being considered during FY2018; these programs may begin in FY2018 and continue into this LRP timeframe. Naturally, new research areas identified for investment will influence the hiring plans discussed above.

Possible new focal areas include:

- Increased emphasis on the use of cryogenic Monolithic Microwave Integrated Circuits (MMICs), possibly through new institutional partnerships;
- Exploring techniques for expanded field of view including enabling technologies for Phased Array Feeds (PAF) and Focal Plane Arrays (FPA).
- Exploration of the application of superconducting Traveling-wave Kinetic Inductance Parametric (TKIP) amplifiers as extremely low-noise, broadband RF front ends and IF amplifiers;

- Expanded efforts in Digital Signal Processing to study:
    - high-speed A/Ds, including developing and testing the latest devices;
    - wideband beamformers for PAFs;
    - correlators and array beamformers that use the latest Field-Programmable Gate Array (FPGA) technology and signal processing techniques;

- Development of real time image processing accelerators using FPGAs and, potentially, Application Specific Integrated Circuits (ASICs). Ultimately, this could lead to the development of demonstrators for the VLA and ALMA;
- Research and development on higher efficiency and more reliable cryo-cooler technology (in coordination with the Socorro Electrics Engineering Division), with the goal of significantly reducing operating costs and increasing operational robustness for large interferometric arrays such as VLA/ngVLA; and
- Establishing an NRAO-managed repository for intellectual property of all kinds of applications and platforms, such as those for FPGAs, Graphics Processing Units (GPUs), and other multi-core devices using a variety of languages.

Ongoing Technical Efforts

Integrated Receiver Development: CDL continues to be a world-renowned resource for high-performance integrated receiver technology—not only for NRAO telescopes, but also for those of our sister institutions abroad with whom NRAO regularly shares MMIC chip designs, advanced packaging techniques, and completed sub-assemblies. It is the role of the Integrated Receiver Development (IRD) Group to continue the advance of these technologies by pushing the state of the art in receiver architecture and fabrication, with a focus on high-performance, low-cost, mass-production, and alignment with current trends in industry.

The alignment with industrial standards is a cornerstone of the IRD program, and it positions the CDL to take the greatest possible advantage of the massive investments made in the commercial sector, while simultaneously enabling us to return our own innovative developments to industry by means of licensing agreements. The IRD program has already produced a number of commercially viable concepts, for which several patents have been awarded both in the U.S. and internationally, and at least one of which (the reflectionless filter) is now being mass-marketed by a well-known U.S.-based commercial vendor. This product line and its sales have been growing since it was launched, and has the potential to become a significant source of income for the Observatory in the coming years. We look forward to continuing to help our industry partner expand its product offerings with the latest conceptual advancements and fabrication techniques.

IRD will also continue to support and nurture NRAO-heritage telescopes such as the GBT, VLA, VLBA, and ALMA by providing construction and repair services on the multi-chip modules used in those facilities, as well as instrument upgrades as funding allows. The IRD group is uniquely qualified to carry out the specialized design and micro-fabrication tasks for such instruments, and takes seriously its responsibility to keep that institutional knowledge current via cross-training within the group, as well as with our collaborators in the newly formed GBO and LBO.

In the next five years, IRD will build upon its past successful developments to enable even greater capabilities, such as wider front-end bandwidth at higher operating frequencies, faster bit-rates, greater power efficiency, and enhanced receiver stability in robust, modular designs. These are the key characteristics needed in order to build truly mass-producible, field-replaceable receiver units on the next generation of cm-wave radio astronomy facilities.

Low-noise Cryogenic Amplifier Development: For over 30 years, CDL has provided NRAO and the astronomical community with the world's lowest-noise amplifiers operating in the frequency range from 0.1–115 GHz. These low-noise amplifiers have been key to the high sensitivity and the resulting scientific success of the VLA, GBT, VLBA, and ALMA, and have also been used by nearly every other astronomical instrument requiring cm-wave low-noise amplifiers built in the past 30 years, including the Wilkinson Microwave Anisotropy Probe (WMAP), Combined Array for Research in Millimeter-wave Astronomy (CARMA), Degree Angular Scale Interferometer (DASI), Cosmic Background Imager, Planck, and many others.

Discrete Heterojunction Field Effect Transistors (HFETs) have been the workhorse for much of this cryogenic receiver effort, and their use in first-stage front-end Low Noise Amplifiers (LNAs). This trend is not expected to continue, as a Swedish commercial company, Low Noise Factory AB, is now able to provide the state-of-the-art noise performance up to frequencies of about 115 GHz. CDL experience in building state-of-the-art amplifiers using discrete transistors and chip-and-wire technology will continue to be useful in the future for specific applications where a commercial source cannot deliver a state-of-the-art performance. Retaining this competency is considered necessary for servicing a large number of amplifiers already in the field, including but not limited to those on NRAO, GBO, and LBO telescopes. A limited set of Indium Phosphide (InP) transistors fabricated by the Jet Propulsion Laboratory (JPL) on their Cryo 3 wafers fabricated under the NASA Cryogenic HEMT Optimization Program (CHOP) should provide a sufficient number of devices for this limited effort.

FY2017 saw the continuation of CDL production of 150 first-stage amplifiers for ALMA (NAOJ) Band 1 cold cartridge assemblies. CDL is under contract for this effort which is expected to continue through FY2019.

Additional work falling within the horizon of this Long Range Plan includes projects currently under consideration involving Ka-band amplifiers for LBO under United States Naval Observatory (USNO) funding, as well as possible CDL involvement in the development of cryogenic amplifiers for the Russian space based VLBI mission Millimetron.

In collaboration with both academic and industry partners, CDL will continue pursuing the development of low-noise MMIC amplifiers being fabricated using a number of different processes. These are likely to include the emerging 35nm InP (HFET) process technology being developed jointly by JPL and Caltech at Northrop Grumman Corporation, and the 100nm InP HFETs being produced by Low Noise Factory AB at Chalmers University, Göteborg, Sweden.

Millimeter and Sub-Millimeter Receivers: The current generation of millimeter and sub-millimeter Superconductor-Insulator-Superconductor (SIS) receivers used on ALMA resulted from a long period of CDL development in collaboration with the University of Virginia Microfabrication Laboratory (UVML). This included the introduction of niobium-based superconducting circuits for radio astronomy, development of wideband SIS mixer integrated circuits, and the use of sideband-separating SIS mixers which were pioneered at the CDL. ALMA and other millimeter telescopes in North America, such as Arizona Radio Observatory (ARO), Large Millimeter Telescope (LMT), and Sub Millimeter Array (SMA), require access to a U.S. superconducting device foundry for instrument upgrades and new or second-generation suites of instrumentation. With the suspension of SIS mixer fabrication at the Jet Propulsion Laboratory, UVML is the only remaining U.S. facility capable of producing superconducting devices suitable for operation at millimeter/submillimeter wavelengths. A strategy for preserving access to this facility is essential to the execution of the millimeter and sub-millimeter development initiatives described in this Section.

As part of its core mission, the CDL will continue to support and supply SIS mixers to ALMA and as Work For Others (WFO) performed outside of the Cooperative Agreement to other millimeter/sub-millimeter observatories, including those participating in the VLBI Event Horizon Telescope (EHT) program. Also, as part of its core development program, the CDL will continue to work with UVML to develop second generation SIS mixers for ALMA Bands 6 and 10. For Band 6, this program will work toward developing mixers with wider RF bandwidths by using Nb/Al-AlN/Nb SIS junctions. Ultimately, these will be used in a balanced sideband-separating configuration to reduce the contribution of residual local oscillator (LO) sideband noise to the receiver noise temperature. For Band 10, our goal is to develop highly reproducible junctions for sideband-separating receivers that utilize Nb/Al-AlN/Nb SIS junctions with high critical current density. This will potentially improve ALMA observing speed at Band 10 by as much as a factor of four. For both our Band 6 and Band 10 programs, balanced IF amplifiers will be used to minimize interaction between mixer and amplifier without the additional loss of a wideband IF isolator.

The newly emerging superconducting TKIP amplifier technology has the potential to improve the sensitivity of cm- and mm-wavelength receivers by a factor of two or more. The recent demonstration of TKIPs at 4 Kelvin indicates that they will be suitable for use on ALMA, either as RF amplifiers or as IF amplifiers following existing SIS mixers. A wideband IF TKIP design could replace the current ALMA IF amplifiers in all the SIS receivers—a one-size fits all solution—resulting in a substantial increase in sensitivity and with sufficient bandwidth to take full advantage of the proposed next-generation ALMA correlator. To date, most TKIP development has been focused on the quantum computing industry. CDL is planning to collaborate with the superconducting circuits foundries at UVML and JPL, which have the capability to fabricate TKIPs, to apply this new technology to radio astronomy.

Digital Signal Processing: The field of Digital Signal Processing (DSP) has benefited from a massive commercial investment and continues to grow substantially in popularity and importance. Essentially, all new instrument development for radio astronomy requires advanced DSP and, in many cases, DSP development is a dominant part of any such initiative. NRAO has a long tradition of providing complex DSP instrumentation for its telescopes. Recent examples include the 64-antenna correlator for ALMA, the VLBA Digital Backend, the SNAP CASPER data acquisition board, and the integrated circuit boards that enable the phasing capability of the ALMA Correlator.

Over the next five years, NRAO will continue to design and produce advanced DSP systems. Specifics depend largely on project funding. In the short term, an upgrade to the ALMA Correlator will be produced—a design study for which has already been completed and a proposal for construction of the upgraded correlator was submitted in response to the ALMA Cycle 5 Call for Development Projects. In the longer term, innovative designs for correlators for ALMA and the ngVLA will be explored. In general, NRAO will continue to leverage developments by industry, including, but not limited to, FPGAs, ASICs, data routers and data transmission systems, for use in astronomical signal processing.

NRAO will also continue to collaborate with other institutions on DSP-related projects. A recent example is a collaboration with the Massachusetts Institute of Technology (MIT) Haystack Observatory to produce a VLBI backend for the ALMA telescope. This collaboration leveraged existing expertise in both institutions to produce a system allowing ALMA to take part in the Event Horizon Telescope radio array, an attempt to image the immediate vicinity of the Milky Way's central black hole. During the next few years, NRAO hopes to collaborate with Bordeaux Observatory (Floirac, France) in upgrading the ALMA correlator to process a larger bandwidth, subject to project approval and funding by ALMA.

More research-oriented projects in this time span include wide-bandwidth beamformers for Phased Array Feeds, and high-speed digital links that will enable large numbers of data channels to be efficiently transmitted from the telescope focus to central processing stations. As necessary, CDL staff will collaborate with Observatory astronomers to develop new FPGA and GPU algorithms for science-specific applications, such as pulsar search strategies, more accurate pulsar timing; DSP techniques for detecting signal anomalies, such as those from radio frequency interference or fast radio bursts. As these projects develop, they will spawn new ideas for signal processing in the LRP time frame. This work has broad application across nearly all fields of astrophysics.

Electromagnetic Components and Optics: Feed horns, polarizers, and quasi-optical elements lie in the primary path of the signals from a radio telescope antenna on their way to the low-noise receiver. These components must therefore have good matching properties, low insertion loss, and broad bandwidth. These performance characteristics are unique to radio astronomy and such components are generally not commercially available.

CDL has designed and built such electromagnetic components for the EVLA, GBT, and VLBA receivers, and also for some ALMA bands. CDL-developed components have been incorporated into other non-NRAO telescopes, such as the Shanghai 65-m telescope and the Effelsberg 100-m telescope. Where necessary, novel manufacturing techniques have been developed and employed to overcome challenges posed in the fabrication of our component designs. For example, low frequency, secondary focus corrugated feed horns for the VLA have been built out of aluminum sheet metal in order to meet weight limits. At V and W-bands (and at higher frequencies), the corrugations in feed horns or polarizers are so small that they cannot be directly machined, necessitating the use of electroforming on machined mandrels. The CDL has also been able to deliver optics designs meeting specifications when alternative options had already been ruled out. A critical ingredient in all of these efforts is CDL's ability to carry out sophisticated electromagnetic analyses of optical designs, such as main beam response, near and far sidelobes, as well as overall resulting receiver efficiencies and antenna temperatures.

In addition to developing optical designs for proposed upgrades to ALMA and VLA receivers as well as for expected new receiver designs under external WFO contracts—such as for GBT and LBO, CDL will be involved in optimizing telescope optics design for ngVLA during the time frame of this plan. Various designs, including dual-offset antenna approaches, will be analyzed, not only because of the advantage offered by an unblocked aperture, but also because more real estate at the antenna focal plane will be available to accommodate receivers. The current ngVLA receiver plan calls for frequency coverage from 1.2–120 GHz, which is expected to require four or more receivers with conventional feeds and polarizers. Effort emphasizing the development of very broad-band optical components to reduce the number of receivers per antenna will also be studied.

Field of View Expansion: One of the major limitations of ALMA is its relatively small field of view (~1 arcmin at Band 3 and inversely proportional to frequency), determined by the diameter of the antennas and their primary beam. There is considerable scientific interest in increasing the field of view to enable faster wide-field mapping of extended objects. Survey and imaging science will benefit from this. The primary way to attain potentially large gains in mapping speed is to develop multi-pixel array receivers for interferometry. Such receivers are likely to occupy a significant fraction of the (already tightly packed) available focal plane space, and are likely feasible for only one band at a time and with only modest pixel counts without major redesign of the antenna optics. Nonetheless, it makes a lot of sense to investigate the tradeoffs in replacing a high-demand band (e.g., Band 6 or 7) single-element receiver with a multi-pixel receiver. The technical and scientific tradeoffs involved in developing and using multi-pixel receivers in ALMA are complex and require investigation to evaluate feasibility. Upgrading even one band to a multi-pixel receiver requires a number of improvements in elements downstream (IF transport, correlator, archive), and possibly upstream (LO distribution). Some of these improvements may be parallel with improvements required by larger bandwidths. In particular, for many science projects that require mapping of one spectral line, it may be practical to share bandwidth among pixels (large-scale mapping of continuum sources would not be practical with such a scheme). CDL is investigating two approaches to expansion of ALMA's field of view:

- **Phased Array Feed Development**: Over the past several years, the construction and characterization of PAF receivers was an area of intense activity at the CDL. Those activities culminated in FY2017 with the demonstration of a cryogenic L-band phased array feed receiver (incorporating Integrated Receiver technology) with world-leading sensitivity (using the metric of synthesized aperture efficiency normalized to system temperature). Further development is on hold pending identification of uses cases for such a receiver on NRAO telescopes. Effort will also be made to try to identify interested outside partners who could benefit from this technology and might wish to have PAF receivers built for their specific application.

- **Focal Plane Arrays**: In radio astronomy, a Focal Plane Array (FPA) is an array of two-dimensional CCD (Charge-Coupled Devices) at the focus of a radio telescope. FPAs operate by detecting photons at particular wavelengths and then generating an electrical charge, voltage, or resistance in relation to the number of photons detected at each pixel. This charge, voltage, or resistance is then measured, digitized, and used to construct an image of the object, or phenomenon that emitted the photons. The CDL has proposed a two-year-long, collaborative Strategic Study with the University of Virginia. The Study will exploit recent UVA development of high-power-capability millimeter-wave photodiodes. The goal is to develop photodetector technology to enable LO distribution in multipixel SIS arrays. A baseline assumption for this work is that the Local Oscillator for an SIS multibeam array is a necessary design goal, and provision of the LO (quasi-optically or by means of waveguide distribution) is problematic for ALMA because of existing space constraints.

Local Oscillator for ngVLA: During the time frame of this plan, the ALMA LO Group expects to support the ngVLA by studying and characterizing remote LO generation and stabilization. CDL developed several LO and timing technologies for ALMA. For synthesis arrays such as ngVLA, these techniques can be extended over longer distances by including new technologies that will improve performance and reduce costs.

Research Community Collaborations: An effective instrument R&D program includes collaborations with the research community to address forefront science objectives that greatly motivate and guide the development of instruments that push the boundaries of conventional approaches. Lessons learned from direct involvement in such activities help improve our engineering, at all levels, while the pursuit of new techniques provide a stream of challenging problems that engage our next generation of instrumentalists in search of solutions.

Precision cosmology of the early universe is a prime thrust area for instrument R&D, and the challenge of detecting and characterizing highly redshifted, 21cm radiation produced during the Cosmic Dawn epoch of the Universe forms the scientific backdrop for our current set of collaborations. Notable planned effort areas include the following:

- **Hydrogen Epoch of Reionization Array**: HERA is a scientific road map investigation aimed at exploring the large-scale structure in the baryonic universe via the 21cm line of hydrogen. Funding was acquired as a sub-award from the Moore Foundation (via MIT) to help cover the cost of a University of Virginia graduate student and postdoc participation in instrument R&D activities at

CDL. The goals of the three-year work package (June 2017-May 2020) are as follows: (1) assist MIT researchers to develop designs for a 60–120 MHz narrow band feed and a 60–200 MHz wideband feed for the existing HERA dishes to extend the frequency range to that required for Epoch of X-ray studies and (2) make improvements (portability, extended frequency coverage, and complex sampling) to the antenna beam mapping system that currently makes use of downlink signals from the Orbcomm satellite constellation. This work will be performed in collaboration with the University of California, Berkeley.

- **The Network for Exploration and Space Science**: NESS will implement cross-disciplinary partnerships to advance scientific discovery and human exploration at target destinations in the solar system. NESS includes research in "astrophysics and heliophysics that is uniquely enabled by human and robotic exploration of Target Bodies." The foundations for the next generation Cosmic Twilight Polarimeter (CTP) will be supported by this grant to assist the concept development for a similar instrument on the Moon. Funding was obtained as a sub-award from the NASA SSERVI Program for graduate student support at the University of Virginia over five years (July 2017- June 2022). This work will be performed in collaboration with the University of Colorado Boulder.

- **Dark Ages Radio Explorer**: DARE will observe, for the first time, the formation of primordial stars, black holes, and galaxies by measuring their spectral effects on the redshifted 21cm hydrogen line. These were the very first objects to illuminate the Universe ending the Dark Ages (pre-stellar) and beginning the Cosmic Dawn (first stars) at redshifts of z=35–11. The UV and X-ray radiation emitted by these first objects ionized and heated the intergalactic medium and imprinted characteristic features in the 21cm spectrum. For this epoch, the 21cm (1.4 GHz) signal is redshifted into the 40–120 MHz radio band. A combination of terrestrial radio interference, the Earth's ionosphere, and solar radio emissions make it difficult to measure the redshifted 21cm spectral features with the required fidelity from the Earth. For DARE, the Moon will be used as a shield from this interference via observations on the lunar farside. By operating over a two-year mission lifetime in a "frozen" low (50×125 km), lunar equatorial orbit, DARE will take advantage of the quietest RF environment in the inner solar system to measure the 21cm spectrum. DARE will accomplish a priority NASA and Astrophysics Decadal science goal of exploring the origin and evolution of the first stars and galaxies. When funded, planned NRAO contributions include short-term ("Phase A" ~1.5 years) activities to develop proof-of-concepts for the long-term development initiatives, as well as eventually building the flight-ready front-end electronics, calibration and measurement methodologies (long term, about five years). Funding notification for Phase A is expected in January 2018. This work will be performed in collaboration with the University of Colorado Boulder, NASA Ames Research Center, and Ball Aerospace Corporation.

- **Earth Based Calibration of Lunar Orbiting Antennas for Ultra-Precision Radiometry**: A proposal has been submitted to NASA Science Mission Directorate, Astrophysics Research and Analysis program (APRA funding notification is due to be received in August 2017) to study the feasibility of measuring the beam pattern of a radiometer antenna in-orbit about the Moon to a dynamic range of over 40 dB. High-accuracy beam measurements are required to correct wide field-of-view measurements of the radio sky as is anticipated for DARE. A primary component of this technique is the round-trip measurement of the signal power that has reflected off the lunar regolith and returns to the Earth. This measurement is required to correct for ionospheric effects. A proof-of-concept system will be developed and evaluated on the GBO 140-Foot telescope in Green Bank. The study will include measurements and statistical analysis of time-dependent ionospheric loss and pointing corrections, Faraday rotation, Doppler modulation, and diurnal libration-based fluctuations of the lunar scattering cross section. Results of this work will be used to characterize the errors in this technique and, where necessary, explore possible solutions. This work will be performed in collaboration with the University of Colorado Boulder.

- **Tone-Based Rapid Calibration Technique for Ultra-Precision Radiometers**: A proposal has been submitted to NASA SAT (funding notification is due to be received in August 2017) to develop a non-switching, fast, precise calibration technique for space-borne radiometers requiring high dynamic range measurements where conventional on/off source calibration is impossible or where dynamical modulation techniques may be required to separate sky signals. One example is DARE. The new approach involves injecting amplitude-modulated, narrow-band continuous wave signals into the receiver to simultaneously measure the receiver's gain and the antenna's reflection coefficient to an overall accuracy of less than 10 ppm with a 10 second cadence. This work will extend the successful proof-of-concept, currently at TRL-3, to a level approaching TRL-6.

5.2 ALMA Development

The ALMA Trilateral Agreement obliges each Partner to contribute, on average, the equivalent of $5M per year toward the ongoing enhancement/upgrade of the ALMA Observatory. These contributions are evaluated and cost-balanced every five years. The next evaluation period will conclude in CY2021.

The goals of the North American ALMA Development Program align with those set forth by the ALMA Science Advisory Committee (ASAC). In broad terms, these goals are:

- improve the ALMA archive,
- enlarge bandwidths,
- increase receiver sensitivity,
- elongate antenna baselines, and
- increase wide-field mapping speed.

Upgrades typically progress through three successive phases of development, and correspond to an increasing level of technology readiness. The principal phases are:

- Conceptual study (including scientific justification, specification, and outline costing),
- Prototype/pre-production, and
- Production and implementation.

In FY2018, the North American ALMA Development Program will have funded the longest duration studies and projects in its history. The Development Cycle 5 (FY2017) Call for Study Proposals was unusual and the program solicited proposals for a new category of *Strategic Studies*. The size of the individual awards was enlarged to $0.4M for strategic studies, and the period of performance prolonged to two years (compared to the $0.2M award and one-year duration of a conventional study) which carries the period of performance for strategic studies through FY2019.

While projects (prototype/pre-production and production initiatives) are typically funded every two years, the exceptional complexity and scope of the Cycle 5 Correlator Upgrade project will extend the period of performance through FY2022.

Calls, proposal evaluation, and the award of Studies and Projects are governed by different processes. The details of these processes are set forth in the *Principles of ALMA Development* (ALMA Project Document Number AEDM 2015-091-0.)

Development Projects

A Development Project is typically a large-scale (greater than $1.5M), multi-year initiative involving a relatively mature technology, which may lead to full implementation in the ALMA Observatory. The North American ALMA Development Program budget allocates approximately ten percent (10%) of the Project award pool to meet subsequent implementation costs.

Planned Projects: The Development Cycle 5 Call for Project Proposals notices of Award will be made on or about 01 December 2018. The following projects are expected to be in progress from FY2019 through FY2022.

- A significant upgrade to the ALMA correlator, providing additional high resolution capability and the potential for broader bandwidth processing, particularly attractive for the three ALMA Bands which present more bandwidth to the current correlator than can be processed (Bands 6, 9 and 10),

- Upgrades to the ALMA Phasing Project to include Band 7 and spectral-line VLBI to provide enhanced functionality for phased ALMA.

Future Projects: The next anticipated Development Call for Project Proposals will be for Cycle 9 (FY2021).

Development Studies

Ongoing Studies: The following strategic studies will be in their second year of work during FY2019.

- Wideband Low-Noise Balanced IF Amplifiers for ALMA Band 6, with Future Application to ALMA Bands 3-10; PI Kerr/NRAO.

- Quantum-Limited Very-Wideband 4-Kelvin RF and IF Amplifiers for ALMA; PI Noroozian/NRAO.

Future Studies: It is anticipated that Development will conduct annual Calls for General Study Proposals for Cycles 7 through 11 (FY2019 through FY2023, respectively) to be budgeted at $0.5M each call.

University of Virginia Microfabrication Laboratory

The UVML serves as the University of Virginia's center for research across a broad front of activity in devices, circuits, microsystems, materials, and processing methods. The laboratory resides in the University of Virginia's School of Engineering and Applied Science. These activities share a 3,500 square foot clean room facility for microfabrication and materials research as well as a variety of other facilities for nanotechnology, microwave and optical analysis, and device design and testing. The research facilities are maintained and operated by the research staff of the UVML, which includes graduate and undergraduate students, a full-time facilities manager, and a full-time equipment manager.

The UVML has unique, strategic capabilities in the design and fabrication of SIS heterodyne mixers, and is currently planning to fabricate TKIP amplifiers which are expected to provide the next major improvement in mm-wave receiver sensitivity. The Laboratory continues to work closely with NRAO in the design and development of millimeter and submillimeter SIS mixers for radio astronomy applications. The NA ALMA Development Program will provide approximately $0.45M per annum from FY2019 through FY2023 to support ongoing research initiatives pertinent to radio astronomy, and to sustain associated, critical infrastructure.

5.3 VLA Development

VLA Sky Survey: VLASS is a three-epoch, full polarization, S-band (2–4 GHz) continuum survey of the entire sky visible to the VLA (declinations above –40deg). With a spatial resolution of 2.5 arcseconds it will be the highest resolution all-sky radio survey ever undertaken. It will be observed in the B and BnA-configurations of six configuration cycles (seven years), at the level of ~920 hours per cycle, with half the sky covered per cycle. VLASS will begin full operations in September 2017. During the timeframe of this LRP, VLASS will be observing and delivering a range of Basic Data Products (BDPs) comprising calibrated visibility data, and Stokes IQU images and cubes. Table 5.3.1 shows the schedule for the observations and delivery of BDPs from FY2019–2023, where VLASS*x.y* denotes deliverables for epoch *x*, sky cycle *y*.

Table 5.3.1: VLA Sky Survey deliverables, FY2019–FY2023

Date	Deliverable
FY19 Q1	Deliver VLASS1.1 Single Epoch image cubes
FY19 Q3	Complete observing for VLASS1.2
FY19 Q4	Deliver VLASS1.2 Quick Look images
FY20 Q1	Deliver VLASS1.2 Single Epoch Stokes I continuum
FY20 Q3	Deliver VLASS1.2 Single Epoch image cubes
FY21 Q1	Complete observing for VLASS2.1
	Deliver VLASS2.1 Quick Look images
	Deliver VLASS2.1 Single Epoch Stokes I continuum
FY21 Q2	Deliver VLASS2.1 Single Epoch image cubes
FY21 Q3	Deliver VLASS2.1 Cumulative Stokes I continuum
FY22 Q1	Deliver VLASS2.1 Cumulative cubes and tapered images
	Review delivery of data products to date; decide on execution of 3rd epoch
FY22 Q2	Complete observing for VLASS2.2
	Deliver VLASS2.2 Quick Look images
FY22 Q3	Deliver VLASS2.2 Single Epoch Stokes I continuum
	Deliver VLASS2.2 Single Epoch image cubes
FY23 Q1	Deliver VLASS2.2 Cumulative Stokes I continuum
FY23 Q2	Deliver VLASS2.2 Cumulative cubes and tapered images
FY23 Q3	Complete observing for VLASS3.1
FY23 Q4	Deliver VLASS3.1 Quick Look images
	Deliver VLASS3.1 Single Epoch Stokes I continuum

Next Generation VLA – ngVLA

NRAO, in concert with its North American user community, is considering a future large area radio array optimized to perform imaging of thermal emission down to milliarcsecond scales. The ngVLA will have ten times the sensitivity of the current VLA, operate from 1.2–116 GHz, have 10 times longer baselines (300 km), and include a dense core on kilometer scales for high surface brightness imaging. The current VLA site in the southwest U.S. is the proposed location for the ngVLA. Work is already underway to develop a broad, compelling science case for the ngVLA that appeals to the whole astronomical community and a rationally costed, realizable design for submission to the Astro2020 Decadal Survey.

In FY2018–19, ngVLA activities will focus on continuing to engage the astronomy community in developing and refining the science case, further development of the technical concept, and establishing a credible and defensible cost estimate for the array. Community engagement activities in FY2018 will include a special session on the VLA and ngVLA at the AAS winter meeting, in addition to a large meeting on ngVLA science and technology in the summer. The Science Advisory Council and Science Working Groups will build upon the science use cases they have already developed by refining and concatenating them into an ngVLA Science Book to be completed in early FY2019. Given the scale of the ngVLA and the broad interest in it, strategic partnerships with domestic and international institutions, as well as industry, will need to be formed in order to advance the project. The high level technical requirements developed for the ngVLA in FY2017 will be further refined into a reference design for the array, culminating in a series of internal reviews in FY2018. The cost of the antennas is the major factor influencing the total cost of the ngVLA, and a conceptual design of the antenna and a subsequent estimate of its production costs are needed. This will be accomplished in FY2018 via a Request for Proposal (RfP) for a conceptual design and costing of the antennas based upon antenna performance specifications that were developed in FY2017. In anticipation of a favorable review at the Decadal Survey and a subsequent start into the Large Facilities Major Research Equipment and Facilities Construction (MREFC) process, a plan for the detailed design and development phase will be developed in FY2018. An ngVLA proposal, including a science case, technical concept, management plan, estimates of construction and operations cost, and a construction schedule, will be submitted to the Decadal Survey in mid-FY2019. Activities post-FY2019 are largely dependent upon the outcome of the Decadal Survey and the project's success in the subsequent MREFC proposal process. If the project is viewed favorably, a series of MREFC reviews would need to be successfully completed, likely on the timescale of FY2020–24, before construction could commence in FY2025 or thereafter.

Realfast Commensal Fast Transient System

The ability to observe fast transients (notably FRBs) with the VLA is currently limited to relatively narrow bandwidths (256 MHz), and relatively long timescales (5ms). In addition, the current implementation using the standard Correlator Back End (CBE) software delivers 1 TB of data per hour of observing, consuming considerable disk space both for the archive and for data processing. To address these shortcomings, an NSF Advanced Technologies and Instrumentation (ATI) proposal (PI Casey Law, UC Berkeley) was recently approved to implement a hardware and software system on the VLA, called Realfast. This system will include hardware to support fast transfer of data from the correlator and to enable fast analysis of this data; low-level software to collect and deliver visibilities over wider bandwidths and shorter timescales than is currently possible (implemented within the CBE software); and all the software necessary to do the analysis to look for FRBs. In addition, the system will provide a data spigot that is flexible enough for other investigators to plug in their own back end hardware and software to do different types of transient detection. These capabilities are being developed over a three-year cycle that began in FY2017. Deliverables falling under the timeframe of this LRP are: purchase, install, and develop code for GPUs and support transient searches at 256 MHz bandwidth and 3ms timescales in the VLA's D, C, and B configurations (FY2018); develop a periodicity search pipeline and alert system and support transient searches at 512 MHz bandwidth and 1ms timescales in all VLA configurations (FY2019).

Square Kilometer Array Engagement

NRAO is continuing a technical and scientific dialog with the international Square Kilometre Array project, seeking opportunities for collaborations and improved understand. A small joint project between NRAO and the SKA to work on parallelization of the CASA scientific data format began in 2017.

6 EDUCATION AND PUBLIC OUTREACH

In the next five years, EPO will continue to build and conduct unique programs that incorporate NRAO knowledge and discoveries to strengthen education and public awareness of radio astronomy science, engineering, and technology. To promote and support these activities, 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. With the plethora of astronomy education efforts already in existence, efforts will be uniquely informed by NRAO's mission statement and Observatory-wide initiatives like ngVLA and VLASS, by discoveries made possible by the Observatory and by engineering innovations at CDL. Equity, inclusion, and diversity will be central themes in the development, implementation, dissemination, and evaluation of all EPO efforts.

6.1 STEM Education

The EPO programs in FY2019–2023 will be strongly integrated with the Observatory's science, engineering, technology, professional staff, and user communities. NRAO EPO programs will focus on diversifying the future STEM workforce by building a K-12 pipeline that can feed the substantial efforts of ODI and HR.

The Observatory envisions an EPO portfolio that includes K-12 STEM education, authentic research experiences, visitor and education center experiences, a vibrant and evolving online presence, rich media engagement, and a suite of cross-cutting efforts that tie together major EPO efforts. Increased U.S. visibility in Chile will be an important component of this EPO program. Collaborations with other major U.S. astronomy facilities will allow NRAO to achieve significantly greater education impact.

NRAO will promote STEAM education initiatives throughout FY2019–2023 that are guided by national learning standards and federal priorities. The EPO team will ensure these efforts leverage resources and expertise through partnerships that significantly broaden reach and impact.

Focus areas for K through college STEM education will include: (a) Astronomy 101 that incorporates radio astronomy; (b) multi-wavelength astronomy and the invisible Universe; (c) engineering practices and challenges in radio astronomy; (d) big data and computing science in radio astronomy; (e) Interferometry and array synthesis, and (f) authentic research projects in radio astronomy.

EPO efforts will employ evidence-based best practices in STEM teaching and learning, and will increase the reach and impact of programs.

AUI has transferred to NRAO the sponsorship of the Sister Cities program of middle-school student and teacher exchanges between the community around the VLA, and the community near ALMA in Chile. Both world-class astronomy facilities are in proximity to indigenous populations. As NRAO builds trust in the communities, through consistent outreach, this can grow beyond a cultural exchange to a program that draws on the alumni as mentors and leads to additional science and radio astronomy activities beyond the exchange months.

STEM education resources and findings will be published in peer-reviewed journals, conference presentations, and professional development workshops for educators. Collaborations will be promoted between NRAO EPO and the STEM coordinators in state education offices, who disseminate materials to thousands of teachers each year.

Some NRAO staff are interested in participating in STEM outreach, but are uncertain how to do so. A robust EPO resource library and training program will be crafted to enable staff and users to access appropriate presentations, lesson plans, activities, student project ideas, and other STEM education resources. The EPO resource library will include a FAQ and a list of "Expert Wanted" opportunities, such as science fair mentors, that employees can browse. Continuing in FY2019, NRAO will offer annual STEM communications training for interested employees and students. This training is modeled after the NSF-funded Portal to the Public and will be led by EPO staff.

6.2 Authentic Research Experiences

In the coming decade, the long-standing tradition of high-quality NRAO research experiences for students and educators will be evaluated and structured according to available resources.

Research Experience for Teachers (RET): NRAO envisions a new RET program focused on NRAO astronomy and engineering by FY2022. A cohort model and team approach could be implemented, rather than the traditional pairing of a single teacher with a single scientist. NRAO will also strive to secure additional RET positions via new external grants and corporate sponsors. The goal is to support 12 educators (K-12) each year, four each at NRAO Headquarters, the VLA, and ALMA in Chile.

Research Experiences for High School/Middle School Students: Building on the research experiences developed for Radio Astronomy Path to University Physics (RAP-NM) and Sister Cities participants, expansion opportunities will be explored. NRAO has a rich tradition offering research and field experiences for high school and middle school students, and will do so in FY2019–2023 at the VLA, ALMA, and NRAO Headquarters.

EPO Internships: NRAO will annually employ up to six undergraduate or graduate student interns to learn key EPO skills, including news and media engagement, web development, science visualization, and formal and informal STEM curriculum development.

Citizen Science (CS): Building on the success of programs such as the Pulsar Search Collaboratory, NRAO will launch new CS efforts that broadly engage the public and the informal and formal learning communities. A team of astronomy educators, amateur radio astronomers, NRAO astronomers, engineers, and software developers has already developed a portfolio of next-generation CS ideas, the most promising of which will be launched in FY2019.

6.3 Visitor and Education Center Experiences

With interest in space-themed tourism growing in New Mexico, and a national spotlight on the importance of STEM learning, opportunities for a new VLA Visitor and Education Center will be pursued following a model of a National Park interpretive center.

VLA Visitor and Education Center: Recent studies have indicated the potential to increase attendance at the VLA Visitors Center to ~30,000 visitors annually. In FY2019–2023, NRAO will continue to operate the existing VLA Visitor and Education Center and will actively pursue external funding opportunities to expand its capabilities and educational offerings.

NRAO Traveling Exhibit: Beginning in FY2019, NRAO will explore interest in an NRAO traveling exhibit set and seek external funding to design, develop, and market one each for the U.S. and Chile to significantly expand the Observatory's reach. This exhibit will focus on ALMA and VLA science and engineering, and be aggressively marketed to science and nature museums that serve a broad audience base. Beginning in FY2020–21, external funding will be sought to design, develop, and deploy smaller exhibits suitable for libraries and smaller science centers and museums, permitting NRAO to reach more under-represented groups and financially disadvantaged communities.

6.4 Evolving Online Presence

The advent of Internet-based communities and citizen sharing of online content has expanded options for EPO design and dissemination. The Observatory's online presence will continue to expand and extend its reach throughout FY2019–2023, including:

- Public website – https://public.nrao.edu
- Facebook – https://www.facebook.com/TheNRAO
- Twitter – https://twitter.com/TheNRAO
- YouTube – https://www.youtube.com/user/NRAOEPO
- Vimeo – http://vimeo.com/nrao/videos
- Instagram – https://www.instagram.com/theinvisibleuniverse

The EPO creative team interprets STEM topics into accurate learning experiences for users of all ages and demographics. NRAO's online communities engage daily with the Observatory, and the EPO content reaches tens of thousands of people every week. Educators engage in dialogue with the public, connecting a diverse audience with NRAO technical staff, and responding to public requests for deeper STEM content and resources.

6.5 Media Engagement

The NRAO Public Information Office will continue to share the excitement of ALMA and VLA scientific discovery and the CDL's engineering innovations by interacting with telescope users, astronomers, engineers, and technicians to evaluate the newsworthiness of scientific discoveries and technology advances, then identify and tell the most compelling stories through a multifaceted series of news products. These products include news releases, announcements, feature stories, image releases, and stand-alone video products. Each incorporates evocative visualizations, be they data images, illustrations, videos, or animations produced either in-house by the NRAO creative team or by outstanding scientific visualization experts. The NRAO public information office will continue to use advanced newswire distribution systems, strong linkages with the national and international news media, and close collaborations with other outreach offices, including the NSF's Office of Legislative and Public Affairs.

Journalists, television news crews, and documentary filmmakers visit NRAO facilities throughout the year. EPO will continue to cultivate and manage such opportunities across the Observatory.

The Hispanic population is the fastest growing U.S. sector, and more than 37 million people speak Spanish at home. Internationally, NRAO has a vested interest in Chile, home to ALMA. NRAO's ALMA news releases are already translated into Spanish through either the ALMA Education and Public Outreach Office or through the AUI/NRAO outreach office in Santiago. NRAO EPO will continue to foster positive relationships with Chilean communities, striving to develop a strong STEM-literate citizenry and workforce within Chile.

6.6 Evaluation

NRAO EPO products and programs will use a rigorous system of formative, summative, and embedded evaluation in determining and reporting EPO effectiveness.

AUI has established an external EPO Advisory Council, representative of EPO stakeholder groups, including members with expertise in STEM education research. The Advisory Council will conduct bi-annual face-to-face reviews of the NRAO EPO programs in FY2018, 2020, and 2022, and will make recommendations via a formal written report. Abbreviated reviews will take place in alternate years (FY2019, 2021). Advisory Council reports will be shared with the EPO team, the NRAO Director, and AUI. The EPO team will meet annually for a multi-day, face-to-face workshop to review recommendations made by the Advisory Council, share evaluation metrics and resources, and plan future EPO activities.

Validated EPO metrics developed by NSF and others—such as those available in the Online Evaluation Resource Library and in publications such as the Framework for Evaluating Informal Science Education Projects—will be used by EPO personnel to measure and report program impacts. EPO staff will work with partners and external evaluators to develop additional tools as needed. EPO personnel engaged in STEM education and outreach activities will publish in peer-reviewed journals and present their work at appropriate conferences, participating in research on learning across formal and informal education. By leveraging and contributing to this research, more can be done to engage learners of all ages in meaningful ways. Recent national STEM education initiatives, like the National Science and Technology Council's Committee on STEM Education *Federal STEM Education: Five-Year Strategic Plan*, provide a framework to guide modification of existing programs and new development.

7 OBSERVATORY-WIDE SERVICES

The Observatory-wide services include headquarters, as well as dispersed activities housed at each NRAO site, that support the overall Observatory including: Data Management and Software (DMS, Section 7.1), Program Management (PMD, Section 7.2), Administration (ADMIN, Section 7.3), Human Resources (HR, Section 7.4), the Office of Diversity and Inclusion (Section 7.5), Computing and Information Services (CIS, Section 7.6), and the Director's Office (DO, Section 7.7).

7.1 Data Management and Software Department

During the timeframe of the Long Range Plan, the NRAO Data Management and Software department will play a key role in the evolution of NRAO from an Observatory producing raw data to one for which SRDP—normally images of sufficient quality for scientific analysis—are the primary science operations data product. To facilitate this, and more generally improve the ease of use of the Observatory, DMS will improve NRAO user interfaces, most notably the NRAO Archive, PST, and OPT, and visualization in CASA. Given that the basic infrastructure of CASA is now about 25 years old and this vital platform for data processing is required for the foreseeable future, DMS will undertake a program of CASA refurbishment. DMS will also create the software, including specialized pipelines, required to support the VLA Sky Survey (Section 4.2).

In view of the ever-increasing data-processing load both at the NRAO and at the home institutes of users, NRAO will provide integrated systems for External Data Processing on both commercial cloud services and NSF-funded High Performance Computing (HPC) facilities. DMS will put into production observing systems for High Time Resolution Processing and for Agile Triggered Observing, the former for observations of transient objects, and the latter for follow-on observations triggered by events from LSST and other observatories. To position NRAO for both the mid-term and long-term futures, DMS will augment efforts in Algorithm and Platform R&D.

The motivations for these initiatives are:

- Increase the uptake of NRAO data and data products by all members of the astronomical community;
- Increase the scientific productivity and capability of current and planned instruments to carry out cutting-edge research into the key science questions of this decade and beyond;
- Increase the efficiency and utility of instruments and user services in order to meet the growing needs of the community within the operating budget. Position NRAO to be an integrated member of the international Observatory system in the era of LSST and SKA precursors, and to prepare for the next generation of facilities (ngVLA, SKA).

Science Ready Data Products

The NRAO will continue the move from delivering raw observational (UV plane) data to PIs, to providing science-quality images for PIs. This has two principal advantages:

- It makes ALMA and the VLA accessible to non-radio astronomers (both as PIs and as re-users of public archive data).
- Even for radio-astronomers fully conversant in data calibration, flagging, and imaging, it should make them more efficient users of telescope time (from observation to publication), effectively shifting effort from time consuming data reduction activities to scientific analyses.

Almost all DMS software systems will have to be updated to accommodate SRDP. The SRDP initiative details are consolidated in Section 3.2.

Improve User Interfaces

DMS will replace the current NRAO AAT with an easy to use, modern, user interface that can search for, and return data from, ALMA and the VLA. (At present, ALMA data is in a separate Archive without a common interface). Although first versions of the new AAT were released for comment in late FY17, it will continue to be significantly evolved during the period covered by this plan, in response to SRDP and user feedback. DMS will also investigate fully linking the archived data sets with the published literature, e.g., through the dataset identifiers now in use in the Astrophysics Data System. Through such links scientists can easily find the data underpinning research papers and, while searching the archive, find the research papers in which the observations are presented and analyzed.

During the LRP timeframe, DMS will completely revamp the PST and OPT for the VLA, improving their performance and ease of use. Parameters will be added to align the automatic SRDP data processing with the science goals of each project. DMS will look for opportunities to increase the commonality with the equivalent ALMA tools (which are the responsibility of the European Executive).

CASA Refurbishment

CASA is NRAO's flagship post-processing package for the VLA and ALMA. CASA is also the base for development of the processing for SRDP. An active forward-looking development path for CASA is critical for leveraging the investments of NRAO and the community moving to the next decade. While CASA is primarily developed for ALMA and the VLA, it also supports a diverse set of observatories both through the direct use of the CASA package and also through the widespread adoption of the underlying *casacore* libraries.

Scientists pushing the frontiers of radio interferometric imaging algorithms around the world also use the *casacore* libraries. The existence of this common infrastructure provides a conduit for the rapid exchange and collaboration on implementations and algorithmic developments.

The underlying technology of CASA (including much of *casacore*) dates from the early 1990s. Many architectural decisions should be revisited to ensure that CASA can continue to meet the processing and algorithm needs of ALMA and the VLA, and to provide a platform for ngVLA development. For example, the CASA libraries are not thread-safe, a significant impediment to performance improvements in an SMP and multi-core co-processor world. Similarly, the I/O system is layered on top of a homebrew "Table I/O" package, which requires that performance tuning be done by team members rather than by re-using work of vendors or open source communities. Also, many of the original architects of CASA are at retirement age, or are no longer engaged in technical work.

DMS will start an initiative to re-architect *casacore*, taking into account current best practices and building in scalability sufficient for ngVLA. While maintaining high-levels of abstraction of radio astronomy concepts, it will be built with performance and portability as primary objectives, both to enable ALMA and VLA data rate increases and to enable it to be a platform for ngVLA development.

When the new infrastructure is in hand, the team will gradually port applications to the new framework. DMS will also have to provide some conversion tools as the on-disk data formats are likely to be completely different.

Given the widespread adoption and interest in the current *casacore*, the team will explore the creation of a consortium to develop its replacement. Of particular interest may be common development with the SKA. An initial collaboration to test the waters was initiated in late FY2017.

External Data Processing

This initiative will provide the ability for users to access and process data and data products from distributed centers (e.g. through XSEDE) and the Cloud, currently Amazon's Web Services (AWS). This will be critical to provide large amounts of data and processing capabilities without NRAO itself becoming a supercomputing center. Evolving into a supercomputing facility in its own right is outside NRAO's mandate and funding. To accommodate the high-speed networking, distributed access, many-Petabyte class storage, and parallel processing capabilities implied by large collaborative surveys, high data rate proposals and new computationally complex imaging algorithms, the NRAO must transition to a model which incorporates resources on external facilities.

To facilitate migration to external computing resources, NRAO will work closely with national facilities through the NSF supported Extreme Science and Engineering Discovery Environment project (XSEDE). The XSEDE project, through a partnership of 17 institutions, provides integrated tools, digital services and collaborative support to efficiently utilize 16 supported supercomputing facilities, as well as commercial cloud providers, currently Amazon AWS.

Initially NRAO will work with cloud providers and XSEDE to ensure efficient execution of CASA pipelines on those platforms. NRAO intends to establish itself as an XSEDE Science Gateway (*https://www.xsede.org/gateways-overview*). A Science Gateway will allow NRAO to request aggregate XSEDE allocations on behalf of the user base and is a prerequisite to providing a common interface and portal to XSEDE-enabled service provider resources. Suitably scaled allocations will be requested for:

- Computational resources to accommodate high throughput, time sensitive observations, and computationally intensive imaging cases.
- Storage resources to support long term, large scale collaborative observations (e.g. surveys), and large volume transient candidate snapshots.
- Visualization resources for large cube analysis at specialized immersive visualization facilities.
- Development support resources for assistance in improving CASA performance, development of advanced parallel imaging algorithms, and development of distributed visualization and analysis tools.

High Time Resolution Processing

This initiative covers the hardware, software, networking, computing infrastructure, and algorithms needed to commensally search for transients in the VLA data stream.

Adding commensal transient detection capabilities to observations will drive the data rates dramatically higher. At 5ms time resolution, visibilities would be produced at a rate of about 33 PB per 1000 hours of observing (this is about 50% of the capacity of the VLA correlator). Producing and saving images in high spatial resolution observations would result in a much higher data rate (200 PB per 1000 hours of observing). This greatly exceeds NRAO's computing capacity (for example, at the moment NRAO has about 2 PB of disk storage split between archive and short-term (staging for processing) resources.

The VLA's transient detection system will build upon the recently accepted Realfast transient system, funded under the NSF ATI program. The system will consist of a special purpose fast-transient VLA backend which processes the visibility stream at high time resolution (<=5ms). It will operate in a triggered fashion, i.e. it will continuously process the data from a large buffer, and write data sets for further processing when the trigger is activated. The long-term visibility and image storage requirements will not appreciably affect the average data rate stored into the archive given the current understanding of the frequency of these phenomena. The VLA fast transient system will be developed in close collaboration with external groups, who will take the lead in the initial implementation. This should be a mutually productive collaboration.

The situation for fast transients and ALMA is less clear. The fastest read-out rate for interferometric data from the ALMA correlator is 16ms, so it may be a less attractive platform for millisecond scale transient detections, even before discussions about the likely observing frequencies of scientific interest. Should it turn out that ALMA is well positioned for such observations, NRAO staff would play the key role in the software implementation of this capability as DMS is responsible for the monitor and control of the baseline correlator and the overall observing system.

Agile Triggered Observing

Agile triggered observing refers to the ability of NRAO's telescopes to respond to triggered alerts with the minimum possible latency and start collecting data from the position of a transient source. This is critical for the instruments to respond to transient alerts from other telescopes, particularly in the era of Advanced LIGO and LSST.

The technical challenges are relatively straightforward: NRAO will connect to a publish/subscribe event notification system—probably VOEvents, as that is the system proposed for use by the LSST—and when a given event passes established filtering criteria, the currently executing Scheduling Block (SB) would be stopped (either gracefully or immediately, depending upon Observatory policies), and a special SB will be filled in with parameters from the event and executed upon the telescope. The principal software systems affected would be the control subsystem, the scheduling subsystem (which are a responsibility of the NRAO for ALMA), and perhaps the Phase 1 and 2 observing preparation tools.

In additional to the technical developments, a considerable amount of policy work will be needed.

Algorithm and Platform R&D

Imaging and image deconvolution steps constitute the dominant computing and data I/O bottlenecks in an end-to-end processing of data from modern interferometric telescopes. Standard algorithms ignore many effects and are insufficient for full-sensitivity wide-field wide-band imaging with current telescopes such as the VLA and ALMA. NRAO has developed advanced imaging algorithms that account for all the wide-field and wide-band effects that affect the imaging performance of NRAO telescopes. However, these algorithms are inherently more expensive and increase computing load by 10–100 fold. The imaging performance of future telescopes like the ngVLA will be even more severely limited when these effects are ignored. Moreover, there are algorithm areas which have been underserved in recent years, such as automated RFI detection and excision. In addition to developing improved algorithms, the team will investigate novel computing platforms that may be needed for them to execute effectively. DMS will increase the effort available in these areas in the plan period.

7.2 Program Management

The Program Management Department (PMD) supports each of the NRAO departments in the implementation and continuous improvement of Program Management, Project Management (PM), and

Systems Engineering (SE) practices. Support provided by PMD includes the processes, tools, and techniques described in the PMD Standard Operating Procedures (SOP), by being responsible for their PM/SE implementation; often performing as the project manager or systems engineer, in both internal and external work-for-others projects. Furthermore, PMD supports each of these departments and site operations and their management, assisting them in accomplishing reporting responsibilities, Observatory-wide Risk Management, and other activities as requested. The PMD support activities are divided into the following areas of responsibility: Program Management Operations, Proposal Development, Project Management, and Systems Engineering processes.

Program Management Office Operations

For FY2019–2023, the Program Management Department focus will be on managed processes and optimization of Project Management (PM) and Systems Engineering (SE) frameworks. An internal PMD assessment of process maturity will be completed every year. PMD staff will continue to coach and mentor project directors as needed to ensure that projects are initiated and led with appropriately integrated PM/SE frameworks. The SOPs are available Observatory-wide and for LBO. PMD will continue to mature and revise the SOP's to meet the needs of the Observatory and will continue to provide support, training, mentoring, and leadership to continually improve the Observatory's ability to execute projects.

PMD staff now routinely use PMD Standard Operating Procedures (SOPs) and templates for projects. A growing library of projects completed with the SOPs has helped to establish best practices. PMD will continue providing Observatory-wide training on project management and systems engineering methods. This training may include high-quality video and web learning opportunities, on-site consultant delivered courses, informal learning sessions, and other training opportunities as requested by the site Assistant Directors. The SOPs will mature through continuous improvement processes, as they are intended to be living documents.

Flow down from strategic plans to long-range plans to POP milestones will influence the prioritization of projects and the development of project roadmaps. Resource allocations across the organization will be managed from a program to project perspective. As NRAO undertakes large-scale initiatives such as the ngVLA, as well as ongoing R&D efforts in CASA development and SRDP, the maturity of PM/SE processes will guide the innovative development of efforts toward cost effective and value-driven results. Standardization of specifications, design reviews, testing, acceptance reviews, interface controls, risk management, verification management, quality, performance, and testing management will become normalized, with adaption of processes using accepted tailoring protocols. The achievement of managed process maturity enables process optimization and continuous improvement efforts to become part of the organizational culture. PMD will facilitate process improvement efforts through focus on value streams across the organization. This focus on value stream delivery in particular supports the work of CDL in advancing the state-of-the-art in receiver architecture and fabrication, with a focus on high-performance, low-cost, mass-production, and alignment with current trends in industry.

With a sustained PMD influence over several years, disciplines will mature and be routinely practiced deeper into the project lifecycle. Project closure is a vital stage as it provides feedback required for continuous improvement. Disciplined closure includes reporting on project deliverables, project metrics, lessons learned, retrospective comments, and captures other useful comments from project participants. The distributed PMD staff members will continue to provide support to sites to include planning, executing, monitoring and controlling of projects, change management, and risk management activities. PMD support will include leadership, coordination, and assistance in achieving appropriate reporting of Quarterly Status Updates, End of the Year Report, and the Observatory-Wide Risk Register and will use every opportunity to advance the implementation of PM/SE practices through normal interaction with stakeholders. In addition, PMD will continue to provide program management of the ALMA Development activities. These activities are done in close collaboration with the Assistant Director: NA ALMA and the NRAO Contracts and Procurement office.

The Long Baseline Observatory (LBO) PMD Office supports the LBO operations and leadership. PMD will continue to support LBO in all aspects of project management, and support LBO leadership in maintaining a LBO document repository; maintaining an LBO-wide Risk Register and Risk Management Plan; and providing LBO Leadership with assistance in long range planning. The LBO PMD office will continue to provide support in proposal development work including Construction/Production Projects, Research and Development Projects, and others in which PMD involvement is requested. PMD support will include leadership, coordination, and assistance in achieving compliance with, and where warranted adaptation of, NRAO Standard Operating Procedures.

The long-term goal of PMD is to enhance its decision support capabilities and to optimize the use of project metrics to establish the normal variance for project scope, budgets, and schedules, and provide the lessons learned. As more projects close with Standard Operating Procedures (SOP) applied, this knowledge base will grow and be used for statistical assessment of project performance. As the knowledge base and experience with the SOPs grow, PMD will be able to tighten project variance and improve project performance. PM reporting and metrics on overall project and research and development efforts at NRAO and LBO will be vitally important input to the various organizations contractually funding these observatories. Analytics derived from systems used by PMD are used to ensure that prior to new work being undertaken, impacts to NRAO existing work are well understood and that any new work is aligned with NRAO's strategic goals and objectives. PMD uses these tools to complete the various executive level reports that are required and will continue to drive these systems to improve performance in order to obtain better quality results.

Project Management/Systems Engineering Activities

From FY2019–2023, projects supported include ngVLA, SRDP, and the construction of the sport facility at the ALMA OSF. The PMD office will provide project management and systems engineering support to the Project Director for the ngVLA design and development project. PMD will also continue to provide project management and systems engineering support for SRDP to deliver capabilities through multiple cycles of requirements decomposition and validation, managed under a rolling wave planning strategy. The Project Manager will work closely with the SRDP Project Director to align the planning horizons with availability of resources and scheduled releases from DMS. The construction of the sports facility at the ALMA OSF is expected to be completed and turned over to the JAO in Q1 of FY2019.

7.3 Administration

Administration encompasses the following NRAO groups: Observatory Business Services (OBS), Budget (BUD), Contracts and Procurement (CAP), Environmental Safety and Security (ES&S), Computer and Information Services (CIS, See Section 7.6), Management Information Systems (MIS), and the Technology Transfer Office (TTO).

Observatory Business Services

The OBS division provides facilities planning and general business administration for Charlottesville operations and Observatory-wide requirements. OBS will continue to support these functions in FY2019–2023. The NSF Large Facilities Group may conduct a full or partial Business Systems Review in the first or second year of the plan. An audit of ALMA Construction is anticipated to begin in FY2018 and will have impact on OBS in FY2019.

General Business and Administration: The business and administration duties include: approval of the Observatory Commitment Authority list (prepared by CAP), preparation and approval of Blanket Travel lists (managed by AUI Fiscal); procurement and management of non-medical insurance; invoice processing and, for Charlottesville, cash receipts of non-NSF monies (grants and other funding sources); petty cash; credit card processing; employee relocation; and general clerical support.

Charlottesville Facilities: The Charlottesville facilities activities include managing all operational aspects of the facilities, lease management and property owner relations, office assignments, and assuring the safety, security, and usability of the Headquarters (HQ) site at Edgemont Road and the CDL on Boxwood Estate Road.

With the growth of the NAASC and Data Management Services, and the cessation of ALMA construction, space utilization between the two facilities will be adjusted and rebalanced over the duration of this plan.

The lease with Ivy Road Properties, LLC, for the CDL on Boxwood Estate Road was extended in 2016 to expire on September 30, 2023; the lease with the University of Virginia for the Edgemont Road building expires October 31, 2023.

It has been a long-term vision to combine the HQ and CDL into one location. A study will be initiated in in FY2020 as to whether NRAO will continue with the HQ and CDL at their present locations or elsewhere. Neither lease has an extension clause. Over the course of this plan, this vision will be considered and a process established to evaluate locations to combine these operations and begin the design process for a possible new facility.

Sustainability: NRAO is committed to sustainability efforts to benefit its workplace, the environment, and the communities in which it operates. Each facility and location provides unique challenges—suburban industrial, academic campus, and desert. NRAO aims to ensure minimization of its carbon footprint through viable approaches that combine social, ecological, and economic benefits. At present, the approach to sustainability varies at each site. Basic efforts are in place at all locations for the recycling of paper, cardboard, plastic, and batteries. The location in New Mexico has a sustainability committee.

Efforts at all locations are coordinated through the Observatory's Associate Director of Administration. Initiatives to research during the FY2018–2022 planning cycle include diminishing energy use in NRAO buildings for motors, compressors, lights, computing, and HVAC, and research regarding the use of solar power at the VLA (considered and rejected as not cost effective in 2013, but may be reconsidered as the technology improves and if there are no RFI issues). In 2014, the NSF engaged Noblis to conduct an energy assessment at the GBO and VLA. That report included recommendations for upgrades and improvements; no new funds were provided by NSF to carry out the recommendations. Some improvements have been completed and others will continue to be accomplished with the use of programmatic funds. Examples include replacing motors with newer energy efficient models, compressor upgrades, replacing refrigeration systems and some new windows. The VLA site infrastructure budget includes funding for insulating windows and doors during FY2019. RFI issues must be considered for any electrical improvements.

Budget

The Budget Division manages, conducts, and develops the Observatory-wide budgeting activities for NRAO, which includes North American ALMA Operations and coordination with budgeting activities of the OCA and the JAO in Chile, as well as other AUI radio astronomy programs. The division monitors cash flow, budget conformance, and develops recommendations for adjustments; defines, manages and monitors ICC recovery, including the annual submissions to NSF; coordinates detailed financial analysis and research, and any special research and other projects as required; monitors budget status and ledger reports; and assists project managers and various budgeting entities in submitting accurate and viable budget proposals. Consistency of sound Observatory practices and procedures is ensured while adopting best practices applicable to Federally Funded Research and Development Centers (FFRDC). Budget managers are located at each site.

The risk insurance brokers and risk insurance program are the responsibility of this division with input from the ES&S Manager.

During this plan, the division will build a ngVLA financial model, an effort that requires the creation of a full-time cost estimator position. Additionally, the transition of ALMA to full operations requires participation of the Assistant Director of NA ALMA and the Senior Budget Manager with the Associate Director of Administration in the review of ALMA operating budgets through the ALMA Heads of Administration Advisory Group. Effective CY2017, ALMA Budgets are prepared and managed in Chilean Pesos rather than US Dollars.

As a result of the FY2017 ICC study conducted with GBO, the ICC structure will have five pools. The new structure will promote the equitable distribution of costs across GBO, LBO, and the NRAO domestic and international locations. The division will continue to monitor and adjust the ICC structure to accommodate the evolving mix of services and bases.

Contracts and Procurement

CAP seeks to procure products and services for NRAO in an efficient manner, utilizing competition to obtain the best product at the lowest price consistent with the specifications, performance, and delivery schedule. The goal is for the result of all procurements to provide the best overall value to NRAO. The division has a procurement manual in place incorporating 2 CFR Part 200 regulations to promote a common understanding of procurement objectives and to insure uniform interpretation of Cooperative Agreement requirements, NRAO policies, and other government laws and regulations. These policies provide a basis for establishing management control, and they set standard procedures for procurement personnel in placing orders and in developing contracts. The division has procurement staff at each of the sites.

The division also manages the Import/Export compliance program for the Observatory, assuring policies and procedures are in place and providing training and support to Observatory employees. Related to this, CAP performs denied party screenings on all entities with whom AUI/NRAO does business (including vendors, customers, and visitors) for all AUI/NRAO facilities.

The division also establishes and tracks awards from outside funding sources that supplement the main Cooperative Agreement funding and objectives.

Environment, Safety and Security

The mission of the NRAO ES&S Office is to support NRAO's long-term commitment to the safety and security responsibilities of NRAO employees, visitors, contractors, and casual visitors. The mission of ES&S includes support of NRAO's commitment to environmental protection of the Observatory facilities. Site Safety Officers are located in Socorro. The ES&S department provides safety officer support at each

NRAO Facility, including the Central Development Lab and Edgemont Road locations in Charlottesville. In addition, as a permanent member of the ALMA Safety Advisory Group, the ES&S manager provides executive counsel for safety of ALMA Operations in Chile.

In FY2017 a security model was developed for each NRAO location, recognizing the diversity of the locations and the unique circumstances and assets of each.

The ES&S division will also provide planning support regarding planning, permitting, environment, safety, and security for the ngVLA over the duration of this LRP.

Management Information Systems

The MIS Division provides Observatory-wide business systems support including general ledger, electronic timekeeping, payroll, human resources, accounts payable, business computers (Windows-based and SQL), and supportive computer hardware. MIS is also responsible for providing financial reporting via business systems, user support, and enhancements along with upgrades for business computer systems. MIS utilizes the Oracle J.D. Edwards (JDE) EnterpriseOne 9.0 product as the NRAO Enterprise Resource Planning (ERP) business software (upgrade to 9.2 scheduled for FY2018).

During FY2019–2023, new releases will be applied to JDE and MIS will investigate whether to implement unexploited capabilities within the system. NRAO may also begin, in conjunction with AUI, the exploration of the capabilities of leading enterprise planning software systems. After evaluating those against the current JDE software, a decision can be made on pursuing a formal RfP.

Technology Transfer Office

The TTO was established in January 2013, with the hiring of a Technology Transfer Manager. The charge of the manager is to review, update, and improve technology transfer policies, procedures, and forms, and to patent and promote the technologies, software, and trade processes of NRAO for potential sale, licensing, or spinoff. During the course of this LRP, efforts to educate employees on the opportunities for invention disclosures that may lead to commercialization success will continue. The NSF I-corps Lite training will be offered as appropriate to assist employees in determining whether markets exist for their patents. Forming technology development partnerships with industry may provide additional revenue and research capabilities to NRAO.

7.4 Human Resources

Human Resources (HR) serves as a strategic partner across the NRAO and is committed to providing the highest caliber of advice, guidance, and collaboration in delivering human resources services. HR will continue its leadership role in supporting NRAO's vision by promoting the concept that employees are the most valuable resource and will be treated as such. The HR department continues to act as a catalyst to enable all staff to contribute at optimum levels toward the success of the Observatory.

HR's mission is to provide a sense of approachability, professionalism, and transparency through internal consulting, problem resolution, and the delivery of efficient, customer-responsive human resource services. HR strives to:

- Recruit and retain dedicated and highly qualified employees;
- Develop and recognize individual and group performance;

- Maintain competitive compensation and benefit programs; and
- Provide employee relations support that balances the needs of staff and management.

NRAO has benefited from decades of effort by unique and highly skilled staff. Moving forward, a focus on knowledge capture and staff renewal is necessary to position the Observatory to achieve new initiatives. The HR department provides professional service and administrative expertise in response to the changing needs of the organization, to optimize the contribution of employees to the organizational mission, and to support their well-being. HR activities and staff are headquartered in Charlottesville in support of NRAO and ALMA with additional HR staff support and offices in Green Bank and Socorro.

Human Resources' areas of responsibility include workforce management, policy development and administration, training and development, compensation, benefits administration, employment (including recruitment and hiring, diversity), employee relations, Human Resource Information System (HRIS), regulatory compliance, HR oversight of NRAO International Staff in Chile, and support of HR staff in the JAO and OCA. HR works closely with AUI Benefits to strategically align employee benefits offerings to the organizational mission.

Workforce Management

In alignment with the Observatory's mission of training the next generation of scientists and engineers, it is a strategic priority to focus on workforce management in a holistic manner. The loss of key personnel and the loss of key skills is a global concern across the Observatory. It will no longer be sufficient and/or adequate to think of staffing from a replacement mentality. Hiring Managers will need to have a paradigm shift regarding how to attract, retain, and scout for new talent. Recruitment strategies to attract generation Z and Millennials will need to include new and varied technologies. HR already provides video technology options for pre-screening interviewing purposes, and research continues into the evolution of recruitment technologies. The creation of digital workplaces is trending favorably. Collaborative, interactive tools and platforms to assist with geographically dispersed teams will be even more necessary in the future. Research indicates that alternate and flexible work schedule options are important to the population from which NRAO draws staff. HR is committed to exploring the efficacy of alternate and flexible work schedule with attention to operational and fairness issues across the sites. Additionally, HR will continue to partner with Hiring Managers to discuss non-traditional hiring options (contingency workers, fixed term contracts, part-time positions, role sharing, etc.). The Observatory's new initiatives will require new talent with some different skills and a new staffing distribution. Succession planning is an important component of the Workforce Management Plan (WMP) and is being incorporated into the updated staffing model. The other critical component of the WMP includes training and skills development. HR will continue to create opportunities to ensure that staff have access to training and development opportunities.

More than ever, today's teams and workforces span not just talent and tasks but generations and geographies. Workforce management includes the effective staffing, forecasting, scheduling, and real-time adjustments required for NRAO to be as efficient as possible. The objective of workforce management is to get the right number of people and the right workers, in the right place at the right time, doing the right tasks.

With the correct technology, processes, and procedures, NRAO can effectively manage the workforce for optimal performance and lowered labor costs. Workforce management is both an art and a science. It can be learned and improved upon to get continuously great results, but it requires the full support of the Observatory.

There is no doubt that the typical workforce is changing drastically. For the past few years, the nine-to-five, permanent workforce has slowly been replaced with contingent workers and more flexible employee schedules. Many employees would like the option of working from home, coming in early or leaving later, largely setting their own work hours to better suit their lifestyles. An organization with the ability to offer flexible working schedules increases its opportunities to attract good talent.

As the workforce continues to change, it is increasingly important to think creatively in regards to staffing and scheduling. An important prerequisite is in understanding that effective workforce management goes far beyond the mechanics of putting staffing plans and schedules together. A strategic partnership between HR and managers across the Observatory is essential to the establishment, monitoring, and constant evaluation of an effective plan.

Alternative Work Arrangements

An alternative work arrangement refers to any arrangement that differs from the organization's standard work schedule and location. The key to successful alternative work arrangements is the flexibility to tailor the arrangement to the particular needs of the individual and the employer. HR seeks to provide employees with a means to achieve a balance between professional and personal responsibilities. Benefits to the Observatory are: increased employee motivation and productivity; increased employee commitment; ability to attract high performing individuals; and reduced absenteeism and staff turnover. The potential benefits to the employee are: reduction in stress due to conflicting personal and professional priorities, and increased job satisfaction, energy, and creativity. In considering which of the many types of alternative work arrangements to offer employees, the Observatory should consider the arrangement's practicality, fairness, and flexibility within the environment of the organization. Typical alternative work arrangements include flexible work schedules, compressed work week, and job sharing. The Observatory has telecommuting and remote work policies in place that can be leveraged to attract and retain employees who work in positions that are suitable for flexible work arrangements. A constant review of job descriptions prior to posting vacancies can facilitate conversations with hiring managers about including alternate work arrangements in job postings with the intent of casting a wider net to attract geographically dispersed candidates.

Succession Planning

A succession plan, simply put, is a component of good HR planning and management. Succession planning acknowledges that staff will not be with an organization indefinitely and it provides a plan and process for addressing the changes that will occur when they leave. Most succession planning focuses on the most senior manager—the executive director—however, all key positions should be included in the plan. Key positions can be defined as those positions that are crucial for the operations of the organization and, because of skill, seniority and/or experience, will be hard to replace. While succession planning is not an issue that many organizations address in any systematic way, the Observatory has committed to the implementation of an Observatory-wide succession plan that is formally encompassed in the Workforce Management Plan.

There are many reasons why organizations need to think about succession planning. The most important reason for NRAO is that the Observatory relies on staff to carry out its mission, provide services, and meet the organization's goals, and planning should address what would happen to those services or the ability to fulfill the mission if a key staff member left. Another reason to focus on succession planning is the changing realities of the workplace. The impending retirement of the baby boomers is expected to have a major impact on workforce capacity. Emerging realities about the workforce include:

- New strategic, Observatory-wide initiatives require new talent/skills;
- Vacancies in senior or key positions are occurring in numerous departments simultaneously and demographics indicate there are statistically fewer people available to fill them;
- Baby boomer retirements are on the rise just at the time when the economy is growing and increasing the demand for senior management expertise;
- There is no emerging group of potential employees on the horizon as in past generations (i.e. baby boomers, women entering the workforce, large waves of immigration);
- Many organizations eliminated middle manager positions during restructuring in the 1980s and 90s and no longer have this group as a source to fill senior level vacancies; and
- Younger managers interested in moving up do not have the skills and experience required because they have not been adequately mentored.

Staff Renewal/Transition Plan

Staff revitalization within constrained budgets is a challenge across the Observatory. HR will partner with the Director's Office, Science Support and Research, and other major stakeholders across the Observatory to research viable options to allow for staff transition, a succession pipeline, knowledge capture, new hires and new skill development to ensure sustainability and revitalization necessary for new initiatives and skills.

Training/Development/Learning

In regard to the Observatory's goal of training the next generation of scientists and engineers, it is critical to adopt a learning culture that is embraced at all levels across NRAO. The pressure to improve learning and development opportunities in the work place is critical in attracting and retaining world-class talent. Advances in technology, shifts in demographics, and the need to continuously upgrade work skills, drive the need for the Observatory to put training and development as a priority. Learning is an essential tool for engaging employees, attracting and retaining excellent staff, and developing long-term leadership. Millennials and early career staff are accustomed to a self-directed learning environment and expect learning opportunities to be part of their working lives and careers.

The development and implementation of the Professional Development Central Pool in FY2017 provided funding and opportunities for staff to complete individual programs addressing specific skills needed to advance in their careers. Many staff members applied for funding to attend basic management classes or soft skills training. This, together with the Succession Planning 101 training conducted for managers in FY2017, has helped identify the need for an Observatory Leadership Cohort to develop the next generation of leaders.

Developing the next generation of leaders within the Observatory is paramount to its future. The generational switch in the next 5–10 years will leave the organization with a leadership void as today's leaders exit the workplace and Generation X and Millennials are needed to step into these roles.

The HR team will develop an Observatory Leadership Cohort during FY2018 that will address the leadership void, inspire emerging leaders, and help retain talent within the organization. This Cohort will be introduced to Observatory staff during the third quarter with the opportunity for nominations and self-nominations. The participant selection process, course curriculum and schedule development will be finalized and communicated during the third quarter. The Cohort will begin the first quarter of FY2019.

Some initial development ideas include a selection of 10–15 candidates from across the suite of AUI's North American Observatories that will participate in a year-long Leadership Cohort. The Cohort will be exposed to external classes (funded by the Professional Development Central Pool), participate in monthly talks or professional exchanges across the Observatory, and culminate with a Leadership School where the Cohort will meet at one of the sites for a week. The Cohort conference could include such components as (1) providing members with a 360 review, (2) DISC analysis, (3) individual development plans, and (4) management trainings already in use within the Observatory.

In addition to the Professional Development Central Pool efforts and the development of the Observatory Leadership Cohort, Human Resources and the Office of Diversity and Inclusion have successfully partnered with a vendor to provide a range of online training to all staff. The online training modules are available for all staff and managers to select those that are relevant to their specific roles and responsibilities. Online trainings are efficient and allow a great deal of flexibility in accommodating work schedules. The online tool has helped to deliver and establish such important policy support training such as Unlawful Harassment Prevention training for all staff and Unconscious Bias training for all search committee members.

The internally developed Compensation 101 and Performance Management training were offered to all staff in CY2018. Succession Management and Ethics training was also developed and provided to the Observatory's management group. These fundamental trainings have allowed the organization to grow the next generation of staff and continue to improve hiring practices, workplace behavior, and professional talent. This overall training and development philosophy will guide the program over the next 5–10 years. Developing talent within will be an excellent retention tool, recruiting tool, and an example to other NSF agencies.

Recruitment/Talent Acquisition

The recruitment function is the first point of contact with the Observatory that prospective employees experience. NRAO is committed to attracting and maintaining a diverse workforce. To meet the challenges of the 21st century, NRAO must continuously strive for a workforce that reflects the community and must continue to promote a work environment that places a high value on individual respect, dignity, and professional growth. The Observatory's ability to attract, retain, and develop a quality, diverse workforce is key to success. HR has made improvement in the number of veteran hires and will continue the outreach to this important demographic, and the Observatory continues to exceed the federally mandated goals for veteran hires. HR will continue to partner with the Assistant Director of Diversity and Inclusion to continue monitoring the goal of achieving parity with the nation's demographics for people of color and women. HR will continue its practice of requiring mandatory unconscious bias training for all search committee members. HR will also continue to evaluate applicant pools to ensure that diverse applicants are included. As stated in the Workforce Management Plan, the challenge ahead is to develop a strategy to effectively optimize the current skills while looking towards the future for new, different skills that will be required for new business opportunities. Strategies and tactics utilized in the recruitment and hiring of qualified candidates are key in contributing not only NRAO's commitment to diversity but to achieving the overall mission of the Observatory. HR will continue to monitor and evaluate applicant pools and demographic data to ensure continued outreach to underrepresented populations. Establishment and communication of metrics regarding recruitment and hiring will be an important part of continued assessment and monitoring of recruitment efforts to improve the demographics of the current workforce.

HR will enhance metrics and provide analysis and data related to those metrics and generate and report metrics related to diversity resources, return on investment, hires, and pipeline data.

HR will continue to elevate NRAO's current mission of ensuring a transparent, fair, and equitable recruitment process. HR collaborates closely with ODI, EPO, and community groups to solidify a pipeline of diverse and underrepresented pools of qualified applicants. To strengthen the talent pipelines, HR will continue to enhance, maintain, and disseminate resources and training for hiring managers and stakeholders across the Observatory to enable the development of relationships within these networks.

HR Analytics

HR or "people" analytics reflect the use of people-related data to improve and inform management, business and HR decisions across the Observatory. HR will utilize analytics as outlined below:

- Prioritize and target applicants who are most qualified for a specific position;
- Evaluate and monitor Time to Fill for vacancies;
- Evaluate and monitor employee turnover;
- Identify the factors that lead to greater employee satisfaction and productivity;
- Discover the underlying reasons for employee attrition and identify high-value employees at risk of leaving; and
- Establish and monitor effective training and career development initiatives.

Total Rewards Strategy

The Total Rewards strategy combines various elements, including: compensation, benefits, work-life effectiveness, performance management, recognition, talent development and career opportunities. This model serves as the framework for defining strategic long range plans to attract, motivate, engage, and retain employees in service of the NRAO mission. Employee demographics continue to change within the organization as the next generation of talent, the Millennials, continue to join the workforce.

Millennials, defined as those aged 18–34 in 2015, now apparently number 75.4 million, surpassing the 74.9 million Baby Boomers (ages 51–69), with Generation Xers (ages 35–50) projected to pass the Boomers in population by 2028 according to an April 26, 2016 article written by Pew Research Center. This shifting demographic requires a strategic and planned approach to redefining tactics in the coming years with regard to the Total Rewards Strategy (TRS).

HR will continue to identify and benchmark peer and competing organizations to assess compensation and benefits strategies and programs. Regulatory changes continue to drive change of plan designs in both the compensation and benefits disciplines. HR expects these changes will continue over the next five years in order to keep pace with global and generational landscape shifts.

- **Compensation**: HR's compensation methodology and processes are designed to attract, motivate, and retain top talent within and across all NRAO locations. Key components include performing ongoing pay analysis and competitive benchmarking, promoting career paths (job families), and maintaining sound job descriptions. HR will continue to provide transparency regarding methodology and processes of designing and determining classifications and pay, proactively implement all regulatory changes, and work to anticipate and adapt to the changing needs of staff and organizational priorities.
- **Benefits**: It will be critical to continue to assess, interpret, plan, and be prepared to respond to legislative changes that may impact health care reform. The increasing cost of health care year over year continues to place pressure on the organization for creative approaches in plan delivery to its employees. HR will be proactive in articulating a benefits strategy to address not only health care reform and the increasing cost of health care, but also the changing demographic of the

workplace. HR will also take a more integrated and cost effective approach to leave management by putting processes and policies in place to more efficiently manage leave.

- **Work Life Effectiveness**: HR will continue to take steps to actively support efforts to help employees achieve success by creating a work environment that leads to authentic engagement. Key to this strategy is continued deployment of the Employee Climate and Engagement Surveys every three years and the subsequent actions taken towards changes or enhancements. Implementation and support of the Employee Engagement policy supports the goal of work life effectiveness and performance management. In addition to climate surveys, inviting a cross-section of staff to participate in focus groups and other surveys ensure that a wide spectrum of topics and/or issues related to engagement are addressed in a timely manner.
- **Performance Management and Recognition**: NRAO aims to maintain a working culture where employees connect with their work and are motivated in achieving high levels of performance. Relationships between managers and their staff, organization of daily work, and effective organization-wide employee relations practices are key to the performance management process. HR continues to support the organization in sound performance management and recognition practices adapted to the evolving demographics of the Observatory. HR will evaluate the current recognition programs to assess areas of enhancements and improvements.
- **Talent Development and Career Opportunities**: NRAO's organizational performance improves through the increased commitment and discretionary effort of its employees when managers have the necessary access to the training, coaching, and guidance they need, and a thoughtful, structured program of engagement opportunities with their staff. HR will continue to drive the succession planning process by enhancing and expanding those areas which support maintaining a pipeline of talent. Key activities will support identification of those who obtain or who have the potential to develop critical skills necessary for the future of the Observatory. Strategic planning will continue to support management development and training efforts with key deliverables identified for each year's Program Operating Plan.

NRAO International Staff

HR will continue to work in conjunction with JAO HR and the OCA to maintain the successful integration of all ALMA staff in Chile and to enhance the experience of NRAO International Staff. Additionally, HR will work closely with JAO HR to ensure that the balance of International Staff working in Chile is improved by increasing the fraction of North American staff. This will be achieved by coordinating recruitment protocols across the Executive's with a focus on review and evaluation of applicant pools prior to release of application material to search committees. Recruiting strategies and cross-collaboration amongst HR team members during the recruitment process is critical to ensuring thorough and efficient recruitment outcomes.

The unique nature of ALMA places more HR responsibilities on NRAO than any other ALMA Executive. AUI is the legal employer of all Chilean Local Staff (LSM) working for ALMA, as such, NRAO HR oversees LSM HR policies and procedures and supports the development and training of JAO HR staff in Chile. These responsibilities are in addition to HR's responsibilities over NRAO international staff working in Chile.

The collective bargaining contract between the employees of the JAO and the union expires in June 2018. The North American representative from NRAO HR on the ALMA Human Resource Advisory Group (HRAG) will participate in discussions in preparation for the collective bargaining process. Careful consideration of the newly implemented Chilean Labor Reform Laws will be incorporated into the planning. NRAO HR will continue to partner with the Office of Chilean Affairs and the JAO HR Manager to align and improve the new employee onboarding and staff exit processes. HR will expand the

International Staff (ISM) webpage and communicate this resource to the appropriate stakeholders. HR will also ensure that the ISM new hire on-boarding checklist is utilized to ensure a positive on-boarding experience for newly hired or transitioning ISMs. NRAO HR will partner with the OCA to review NRAO's International Staff Member terms and conditions of employment. The value of some of the ISM allowances have not been re-evaluated since the beginning of the ALMA project. In order to attract and retain excellent talent to accept international assignments, it is critical that the allowances being offered are reviewed for market competitiveness and comparability to partners and are effectively communicated to existing and prospective ISMs.

7.5 Office of Diversity and Inclusion

NRAO, as a national laboratory, has a responsibility to reflect the national population. NRAO attempts to meet this challenge by continually improving its efforts to build and maintain a diverse, world-class workforce. In addition to recruiting and retention strategies described in the HR section, NRAO is committed to the development and implementation of educational and training activities and programs designed to improve representation of underrepresented minority (URM) populations in STEM fields. These two broad goals—increasing the numbers of underrepresented students in STEM fields, and increasing the diversity of NRAO's workforce—are closely tied, and require planning and coordination among multiple departments within the Observatory. ODI works across departments to develop and support programs that create a climate in which all employees are respected and valued for their unique experiences and expertise. These goals also call for collaboration with Minority-Serving Institutions (MSIs), professional organizations (e.g., the AAS, NSBP, SACNAS, etc.), and other observatories, in order to ensure that URM populations are recruited into, and supported in the pursuit of, STEM studies and careers.

ODI's five-year, long range plans include a variety of related programs and activities; each intended to build upon the strengths and successes of the others. In FY2019–2023, and beyond, Diversity and Inclusion efforts across the Observatory will continue to focus on the following key areas: broader impacts, new and on-going pipeline initiatives, workforce hiring, retention, training, and workplace culture. ODI will:

- Develop opportunities to leverage and coordinate existing resources, talents, and projects across Observatory departments (e.g., EPO and SSR);
- Expand outreach programs focused on African-American, Native American, Hispanic American, and other underrepresented populations;
- Develop and offer diversity and inclusion training for all staff;
- Support HR's diversity recruitment efforts;
- Assess and enhance NRAO's workplace culture, where inclusive practices are seen as valuable;
- Manage and improve ongoing ODI programs, with the goal of responding to the needs of the community and the Observatory; and
- Work with non-NRAO partners, including Historically Black Colleges and Universities (HBCUs) and Hispanic-Serving Institutions (HSIs) to improve opportunities for women and underrepresented minority (URM) students to participate in astronomy-related research.

The Diversity Council

The Office of Diversity and Inclusion is staffed by the ODI Director, and is advised by the Assistant Directors of HR, SSR, EPO, PMD, NM Ops, CDL, OCA, and the Director of GBO.

The Diversity Council will meet quarterly, and will provide advice as needed and requested by the ODI Director, and will assist ODI by supporting and coordinating Observatory-wide efforts to improve and enhance diversity in all aspects of Observatory operations, and facilitating communications between all departments at NRAO.

Diversity and Inclusion Advocates/D&I Committee

The Diversity and Inclusion (D&I) Advocates promote the advancement of diversity and inclusion within their NRAO site, and across the Observatory. The advocates work directly with the ODI Director to support specific D&I initiatives throughout the Observatory, in addition to providing recommendations that address site specific D&I issues. The D&I Advocates act as their site's lead spokesperson for local diversity and inclusion efforts. During FY2019–2023, ODI will continue to offer training and professional development opportunities to D&I Advocates.

Diversity and Inclusion Training

During FY2019–2023, NRAO will continue to develop and roll out training opportunities designed to improve employee awareness of the importance of a diverse and inclusive workforce, and to continue to support a climate in which all employees, including those from URM populations, are appreciated and welcomed. Opportunities will include online training modules, in-person training, brown bag lunches, invited speakers, and informal, interactive discussions on topics of interest. While efforts will be made to offer in-person training at each site, ODI will also make use of NRAO's sophisticated media infrastructure to broadcast training opportunities to all sites. In FY2019 and beyond, ODI will continue to explore new technologies that will improve NRAO's ability to share diversity and inclusion-related information and training across the Observatory. Diversity and Inclusion awareness will also continue to be incorporated in supervisor and management trainings, and NRAO's onboarding program.

Achieving Parity in the NRAO Staff

A key objective for the NRAO workplace is to achieve parity with the nation's demographics for people of color and women. HR and ODI will carefully vet all NRAO position advertisements to make them as broadly appealing as possible, and work with senior management to craft and support unbiased search committees. During FY2019–2023, ODI and HR will work together to continue to create and maintain a training program that (a) emphasizes the relevance and importance of a diverse workplace, and (b) offers learners opportunities to better understand and overcome unconscious biases that affect hiring decisions.

Partnerships and Collaborations

During FY2019–2023, NRAO will continue to strengthen partnerships and collaborations with both local and national organizations in order to increase opportunities for identifying and supporting URM students in the pursuit of STEM studies and careers. On a local/regional level, ODI will work with EPO and the OCA to maintain existing programs and develop new D&I programs. These programs include opportunities for: K-12 students from indigenous communities around NRAO telescopes to learn about radio astronomy and careers in radio astronomy; undergraduate students from MSIs to participate in training experiences in Observatory support activities; and training opportunities for local teachers to incorporate astronomy into their classrooms.

ODI will continue to work with one of its Minority Serving Institutions (MSI) partners, Hampton University, a Historically Black College/University (HBCU) and NINE Hub, to develop a radio astronomy program at the university. In FY2019, NRAO will continue to provide expertise in support of this effort by facilitating presentations by NRAO instructors and participant visits to CDL and Green Bank. In future years, NRAO will continue to collaborate with Hampton University, and expand its partnerships with other HBCUs and HSIs. These partnerships will focus on recruitment of URM students into STEM fields, with a particular focus on those areas that support radio astronomy observatories. In FY2019, ODI will continue to work with Hampton University to develop a continuing teaching relationship between Hampton University, the Hampton City School District, and NRAO. This partnership is designed to bridge the pipeline gap into STEM fields between high school and college. In support of this effort, NRAO will provide a NRAO NAC/NINE Fellowship to a student who has completed the NINE training.

Local and National Programs

NRAO has a strong interest in developing educational and training relationships with the communities in which the Observatory operates. Over the five-year period covered by this Long Range Plan, ODI will collaborate with the following organizations to continue to develop and support the STEM pipeline:

African-American Teaching Fellows (AATF): The mission of the AATF is to recruit, support, develop, and retain a cadre of African-American teachers to serve the schools of Charlottesville and Albemarle County. During FY2019–2023, NRAO will continue its partnership with the AATF by supporting its annual summer institute, and will coordinate with EPO to explore opportunities for utilizing curriculum materials as part of their teaching goals to strengthen the relationship between NRAO, AATF, and the local public schools.

Louis Stokes Alliance for Minority Participation (LSAMP): The VA-NC LSAMP program is designed to provide research experiences for underrepresented minorities in STEM. Students are identified through the University of Virginia's recruitment from MSIs.

During FY2019–2023, one to two students a year will be sponsored by NRAO for an NRAO-LSAMP fellowship. The NRAO-LSAMP fellow(s) will have opportunities to conduct hands-on research, observe with the GBT or VLA, use advanced software applications, and/or participate in classroom activities.

Radio Astronomy Middle School Path to University Physics (RAMP-UP) Program (a.k.a. "AstroKids"): Hampton University, a NINE Hub, with support from NRAO, has initiated a bridge program designed to provide a pipeline between middle-school programs (like RAP-NM) and the NAC program, by providing continuous exposure to physics and astronomy research to identified students in the Hampton Roads area until 12th grade. During FY2019–2023, ODI will continue to work with Hampton University to further develop and support this program, with an eye toward designing a path for the RAMP-UP participants to segue to NRAO's NAC program outlined below. As part of the development work, and to provide a mentor for the RAMP-UP students, ODI may partially support a Hampton University student during the relevant academic year. ODI will consult with EPO for advice regarding appropriate astronomy and physics related teaching resources for high school students. RAMP-UP students will be invited to present their research at the annual NAC meeting.

National Astronomy Consortium (NAC): The NAC is a program led by NRAO in collaboration with the National Society of Black Physicists (NBSP) and a number of minority- and majority-serving universities and observatories. The goal of the NAC program is 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 program is coordinated by the ODI Director, in conjunction with the NAC Advisory Board. NRAO hosts a yearly cohort of four to six students at one or more of its sites; NAC students interact with other REU students to take advantage of shared resources, and to increase peer networking opportunities.

In each year from FY2019–2023, the NAC program will continue to increase the number of minority- and majority-serving partner institutions in the consortium, and will recruit students through visits to MSIs, the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS) conference, and the American Astronomical Society (AAS).

The NAC will also host an annual meeting in September-October, designed to maintain and increase participation from MSIs and majority white institutions and universities, and to build and sustain an enduring pipeline of underrepresented future STEM leaders.

Beginning in FY2018, ODI will develop a NAC Fellowship designed to provide leadership and community outreach experience to selected Fellow(s). The fellowship(s) will be piloted in FY2018, and if, after evaluation, demonstrates value to the student(s) and the NAC program, will be continued in FY2019–2023.

National Society of Black Physicists (NSBP) Conference: ODI has an interest in participating in the NSBP's national conferences. AUI has assisted NSBP in previous years with hosting these conferences, and if conferences are scheduled in FY2019–2023, ODI will be present to inform participants about NRAO's NAC, NINE, and other programs that focus on development of the STEM pipeline for minority students.

Radio Astronomy Path to University Physics - New Mexico (RAP-NM): The RAP-NM program is a collaboration between NRAO-EPO and New Mexico Tech. During FY2019–2023, ODI and EPO will work together to identify and select underrepresented undergraduate students to serve as mentors for the RAP-NM students.

Socorro Electronics Division's Laboratory Experience for Undergraduates (SEDLE): The SEDLE program is designed to offer promising underrepresented undergraduate students an opportunity to gain laboratory experience with NRAO's world-class Socorro Electronics Division. ODI will recruit students through SACNAS, and direct contact with two- and four-year HSIs beyond the Socorro region. Selected students (one to two per year) will be integrated into a small team of engineers and technicians for 8–10 weeks, and will be expected to complete a project and prepare a report.

Following the FY2018 recruitment, ODI will evaluate the effectiveness of the recruitment effort and perform a cost-benefit analysis to determine if the program is meeting its goal to offer summer lab experiences to women and Native American students from Hispanic-serving institutions (HSIs).

International Partnerships

National and International Non-Traditional Exchange (NINE) Program: The NINE's primary objectives are to (1) 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, (2) to form long-term mentor/mentee relationships with staff at NRAO, and (3) position the participant to successfully develop a NINE Hub, capable of providing training in the STEM field of experience.

Elements of the NINE program are as follows:

- Exchange of students and postdocs;
- Exchange of faculty/instructors and other professionals in line with the mission of broadening participation for under-represented populations;
- Workshops to foster collaboration, professional development and networking;
- Virtual classrooms and continuous distance learning environments;
- Fostering of long-term mentoring relationships; and
- Incorporation of NAC undergraduates into the NINE training program.

The NINE Program provides learning opportunities throughout all disciplines affecting the full spectrum of activities associated with designing, constructing, and operating, radio astronomy observatories (Human Resources, Education and Public Outreach, Electronics, Engineering, Technicians, Operators, Project Management, Systems Engineering, and many others.)

In FY2019–2023, the NINE program will continue to develop relationships with national and international partners, including the development of additional hub(s).

7.6 Computing and Information Services

Computing and Information Services (CIS), reporting through the Associate Director for Administration, oversees operational computing support for the Observatory. This includes planning, policy, standards (for software, hardware, and system administration), computer security, allocation of the shared central budget, web services, staff training, inter-site computing related travel, procurements, and maintenance contracts for both hardware and software. CIS also manages the telecommunications infrastructure (voice, video, data and mobile communications) for the Observatory. In addition, CIS covers the responsibility of upgrading computing infrastructure for desktops and servers, as well as printers and the central storage and associated backup needs of the staff.

In the FY2019–2023 period, unprecedented staff and infrastructure demands will be met by the close partnership with DMS for provisioning and supporting critical science support services such as Archive, High Performance Computing, next generation networks, and web based data delivery services. Partnering with national computing research centers is an essential strategic goal for CIS, given the data and compute-intensive nature of new and enhanced Observatory instruments. Activities outlined in the plan will be accomplished within the guidance budget, with additional detail given in the preceding DMS section.

The following sections outline the support profile needed to ensure optimum computing, storage, on-line services and communications solutions are provided to the AUI Observatories. A major skills evolution will be improved support for the non-science web and cloud services starting in FY2018.

Computing Standards and Policy

To provide a uniform structure to carry out the department's mission, CIS has the responsibility to develop, evolve, and enforce standards, policies, procedures and conventions designed to maximize consistency between sites, while enabling the diversity and agility needed in an active research environment. Policies address appropriate computer use, information security, major software contracts, computer hardware purchasing and the ability to outsource key services in an accountable manner. Standards include supported computer hardware configurations and application software suites. The evolution of web-based applications, Software as a Service, mobile access, and distributed/cloud computing will require constant vigilance and leadership from CIS in the coming years to inform, and be informed by, the user community.

CIS supervises the maintenance of all off-the-shelf computer hardware and software Observatory-wide and maintains alignment through the Common Computing Environment.

Common Computing Environments (CCE)

CCE is a major facilitator in minimizing and leveraging the differences between site-specific computing environments within the Observatory. Historically, such differences risked unnecessary incompatibilities, duplication of effort, and valuable time lost for staff and user interacting with divergent systems. It is important to ensure that the Observatory-wide cooperation continues to expand from network, to hardware, operating systems and on up thorough code libraries and applications, as well as software development tools. Computing environments are never static: new operating systems emerge, new versions are released, new tools and work habits become prevalent, and emerging technologies are folded into the existing operations, while others are retired. Support for non-Science Web Applications will require the evolution of skills to cover the expending portfolio of services provided through platform-agnostic web frameworks.

Networking and Telecommunications

CIS has consolidated many long-distance phone services under a single contract through the General Services Administration (GSA) Federal Telecommunication Service Networx contract, but this contract will be re-competed within the window of this LRP. In scope for this program are web meetings, audio conferencing, international and domestic toll-free service, mobile phones and calling cards to key employees. In addition to providing the lowest service rates available, this consolidation has resulted in easier account management with consequent lower overhead, which must be maintained or improved under the new contract.

During the LRP timeframe, the archive synchronization from the ALMA JAO to the multiple regional centers will be expanded. Currently observed data is replicated to the NAASC from Santiago in near real-time over a Gigabit data connection shared with National Optical Astronomical Observatory (NOAO), but with the advent of SRDP it is expected that more advanced data products will be generated at the NAASC, and these in turn will increase the network bandwidth needs back to JAO. Additionally it is expected that archive-based research will increase for both ALMA and VLA resulting in a more interactive archive usage profile. To this end the bandwidth into the major sites may need to increase beyond the current 10 Gbps.

Finally, CIS supports approximately 25 videoconference systems, providing video communication between the conference rooms and auditoria at the major sites, leveraging the intranet infrastructure. The video systems are also widely used to relay scientific and technical colloquia throughout the Observatory and beyond. Over the next few years, CIS will push this technology to the desktop and over to external hosted providers to improve and enrich the collaboration experience for staff and NRAO users alike and increasing the integration of voice, video and data through cloud-based collaboration services.

Computing Security

Adopting a solid computer security policy is a prerequisite in securing any enterprise from on-line threats. Since 1999, the NRAO has had a policy in place that provides a framework to balance the conflicting requirements of accessibility for the wider community with the continuing need for appropriate security in an increasingly hostile environment. This policy was augmented in 2009 by well-defined data sensitivity ratings and all-employee training sessions are given annually to ensure current and relevant awareness of the evolving cyber-security threat landscape is maintained.

All NRAO operational sites are networked together. It is therefore essential that security be maintained consistently and aggressively; lack of diligence at one site will otherwise compromise security at all sites. This is achieved through the security policy by a Computing Security Committee (CSC) composed of representatives chosen from each major Observatory activity, including MIS due to their responsibility for NRAO financial systems.

The CSC has specified and implemented detailed practices to minimize security exposure. Since the implementation of these practices, there have been no serious computer-security incidents impacting science observations. However, intrusion attempts, probes, viruses, malware, spyware, and similar assaults continue to come from the Internet with a sustained frequency and with increasing scope and sophistication. The growing risk from increased use of mobile and wireless equipment is widely acknowledged in the computer industry, and is also being addressed in the context of the CSC and the security policy to ensure stewardship of sensitive data and privileged access is not compromised.

7.7 Director's Office

The Director's Office provides executive management for all aspects of the Observatory, leadership for scientific research, and community relations. The Director's Office includes the Director, Chief Scientist, the Science Communications Office, and Spectrum Management.

Chief Scientist

The Observatory Chief Scientist is responsible for extensive scientific documentation and reporting, Observatory scientific representation in numerous science community venues, leading scientific prioritization within the annual budget cycle, and serving as a consultant for EPO.

Communications Office

The Science Communications Office (SciCom) within the NRAO Director's Office is responsible for key aspects of the effective communication of NRAO science, vision, accomplishments, and plans to the science community, NRAO/AUI staff, and key external stakeholders, including NRAO advisory committees and the NSF.

SciCom will continue to collaborate with scientific staff around the Observatory to communicate NRAO science results and opportunities to astronomers and the broader science community. To better serve and grow the user community, SciCom will continue to improve, edit, and publish the electronic newsletter, *NRAO eNews* and periodic electronic announcements series, *NRAO Announcements*, which currently have 9,000+ subscribers.

SciCom will collaborate with scientific staff to organize an effective Observatory exhibition and special events presence at major FY2019–2023 science meetings, including: (a) the semi-annual (winter and summer) American Astronomical Society (AAS) meetings; (b) the American Association for the Advancement of Science (AAAS) Annual Meeting; (c) the bi-annual SPIE Astronomical Telescopes and Instrumentation conference (even-numbered fiscal years); (d) the tri-annual International Astronomical Union General Assembly (FY2021); and (e) the tri-annual International Union of Radio Science General

Assembly & Scientific Symposium (FY2020 and FY2023). SciCom and CIS will jointly organize an NRAO exhibition and technical presence at the annual International Conference for High Performance Computer Networking, Storage, and Analysis, colloquially known as the SuperComputing (SC) conference.

SciCom will design and publish an NRAO Annual Report each calendar year. This Report will feature: (a) science highlights from the community and NRAO scientific staff for the year; (b) major accomplishments at NRAO operational facilities; (c) Research & Development progress for next-generation facilities; (d) community support activities; (e) Observatory metrics; and (f) public outreach and diversity highlights. This Annual Report will be available at the NRAO science website for review, reading, and download, and will be distributed to the NSF, the U.S. Congress, and interested members of the NRAO science and technical community.

Improving internal communication will continue to be a priority at NRAO. SciCom will continue to work with the Director and the senior management team to develop and implement more effective communication across the Observatory.

Spectrum Management

NRAO's spectrum management effort is the buffer between observers and the wider world of commercial radio communications. Spectrum management aims to provide interference-free radio astronomy bands and radio-quiet conditions in the vicinity of radio telescopes. This is increasingly challenging when vast numbers of mobile consumer devices—cell phones, laptops, automobiles—transmit at frequencies up to 80 GHz and constellations of thousands of satellites are being planned to provide global wireless broadband.

The intersection of these competing interests occurs nationally at the Federal Communications Commission and internationally at the International Telecommunication Union Radiocommunication Sector (ITU-R) in Geneva. Domestic matters are driven by commercial activity and political pressure, and do not occur on fixed or predictable schedules. The FCC recently completed its decade-long reorganization of the TV broadcast band, with implications for LWA and VLA observing below 100 MHz and for the GBT at 608–614 MHz. NRAO's letters to the FCC caused WorldVu and SpaceX to coordinate the operation of their very large Low Earth Orbit (LEO) satellite constellations at 10.7 GHz, and other prospective operators will follow in due time in bands up to 42.5 GHz. NRAO is also continuing to negotiate with operators seeking to be allowed to equip aircraft with in-flight 57–71 GHz WiGig entertainment services that are presently forbidden to prevent interference to astronomy and satellite remote sensing.

Representatives from observatories and their national administrations have gathered each year since the 1950s in Geneva to coordinate radio astronomy-related activities at sessions of what is now the ITU-R. Owing to the depth of interests on its staff, its broad range of operations and its long history of engagement, NRAO has been a major source of radio astronomy's input to these sessions for some while.

The NRAO spectrum manager is the Chair of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), an ICSU-chartered body jointly funded by IAU, URSI, and COSPAR, and is responsible for organizing its budget and affairs. IUCAF arranges international spectrum management meetings (next to be held in 2019 in South Africa) and meetings discussing RFI monitoring and mitigation. It is responsible for formulating a consensus radio astronomy position regarding items of concern on the agenda of the World Radio Conference (next in 2019).

Learning the rules and intervening in a wide range of environments requires a degree of attention to detail that is well-suited to the work of a large national observatory, and NRAO will represent the interests of the GBO and LBO in national and international forums. Spectrum challenges to radio astronomy observations are multiplying and becoming more complex. NRAO is deeply committed to continuing its spectrum management work and looks forward to the opportunity to make the case for the importance of radio astronomy observations in an ever-more crowded radio spectrum.

APPENDIX A: RESOURCE PROJECTIONS

Funding	FY19	FY20	FY21	FY22	FY23
NSF Guidance Budget CSA-V	33,949	34,967	36,016	37,097	38,210
NSF Guidance Budget CSA-A	44,784	46,128	47,512	48,937	50,405
Carry-Over	12,773	11,210	8,470	7,115	5,044
Canadian ALMA Contribution	1,545	1,591	1,639	1,688	1,739
External Common Cost Recovery	3,483	3,587	3,695	3,806	3,920
ALMA Development Awards	3,875	4,410	4,213	3,256	2,573
WFO	784	807	832	857	882
Other	412	424	437	450	464
Grand Total, Funding	**101,605**	**103,126**	**102,814**	**103,206**	**103,237**
Expenses	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**
1000-Telescope Operations	**35,488**	**35,426**	**36,900**	**37,852**	**38,517**
1100-Maintenance	7,521	7,747	7,979	8,219	8,465
1200-Operations	21,570	22,433	23,331	23,564	23,799
1300-Spectrum Management	124	127	131	135	139
1400-Infrastructure Mods & Upgrades	3,354	2,112	2,362	2,745	2,827
1500-Management	2,919	3,007	3,097	3,190	3,286
2000-Development Programs	**14,275**	**17,016**	**14,905**	**14,499**	**13,869**
2100-Business Development	186	192	197	203	210
2200-Technology Development	12,675	15,368	13,208	12,751	12,068
2300-R&D Support	929	957	985	1,015	1,045
2500-Management	485	500	515	530	546
3000-Science Operations	**15,908**	**16,664**	**17,664**	**18,794**	**19,902**
3100-Observatory Time Allocation	940	969	998	1,028	1,058
3200-Reference	732	754	776	800	823
3300-Broader Impacts	1,818	1,751	1,804	1,858	1,858
3400-Scientific Staff	888	915	943	971	1,000
3500-Management	2,394	2,466	2,540	2,617	2,695
3600-Scientific User Services	3,925	4,043	4,164	4,289	4,417

Continued Expenses	FY19	FY20	FY21	FY22	FY23
Continued 3000-Science Ops					
3700-Science Software	4,456	4,990	5,639	6,409	7,201
3800-Scientific Information Services	754	777	800	824	849
4000-Administrative Services	**15,790**	**16,264**	**16,752**	**17,254**	**17,772**
4100-Business Services	8,808	9,072	9,344	9,624	9,913
4200-Facilities	5,218	5,375	5,536	5,702	5,873
4300-Auxiliaries	4	4	4	5	5
4500-Management	659	679	700	721	742
4600 Compensation Reserve	1,101	1,134	1,168	1,203	1,239
4800-NRAO ICC	(0)	(0)	0	0	0
5000-Director's Office	**7,458**	**7,767**	**7,913**	**8,150**	**8,395**
5100-Program Mgmt	752	775	798	822	847
5200-Public Outreach	2	2	2	2	2
5300-Communications	486	585	515	531	547
5500-Administration	1,237	1,274	1,312	1,351	1,392
5800-AUI Fee and IDC	4,982	5,131	5,285	5,444	5,607
6000-Education & Public Outreach	**1,475**	**1,519**	**1,565**	**1,612**	**1,660**
6100-News and Media Releases	901	928	956	985	1,014
6200-STEAM Education	441	454	467	481	496
6400-Visitor Center Operations	(24)	(25)	(26)	(26)	(27)
6500-EPO Management	158	162	167	172	177
Grand Total, Expenses	**90,395**	**94,656**	**95,698**	**98,162**	**100,114**
Designated Carry Over	**11,210**	**8,470**	**7,115**	**5,044**	**3,123**

APPENDIX B: MAJOR MILESTONES

Locator	Department/Division	Initiative	2019	2020	2021	2022	2023
3.0	**Science Support and Research**						
	TTA	Integrated Proposals/Observing Scheduling Block Tool Upgrade	X	X			
	SRDP	Science Ready Data Product Capability Development	X	X	X	X	X
		Web-based Documentation and Training Material Development	X	X	X	X	X
4.0	**Observatory Telescope Operations**						
4.1	**Atacama Large Millimeter/submillimeter Array**						
		Full ALMA Operations will be achieved no later than Cycle 7		X			
4.2	**Very Large Array**						
	Operations	Antenna Infrastructure Renewal (ACU replacement, drive motor replacement)	X	X	X	X	X
		Purchase new rail crane	X				
		Replacement of E,W,N array arm switches	X				
		Site's well pump controller upgrade*	X				
		VLA antenna azimuth bearing replacement	X	X	X	X	X
		Install automatic grease distributors on Antennas	X	X	X	X	X
		Control Building roof replacement ***		X			
		Tube exchanger for the Control Building cooling tower replacement*		X			
		Spare compressors for the site HVAC systems ***		X			
		Improve site building insulation	X				
		Front End SOIDA test rack purchase****		X			
		Heavy vehicle replacement	X	X			
		Replace CNC knee mill *		X			
		Replace exterior doors and windows	X				
		Replace 5000 VLA cross ties	X	X	X	X	X

Locator	Department/Division	Initiative	2019	2020	2021	2022	2023
		Replace five VLA intersections	X	X	X	X	X
		Conduct ultrasonic track inspection		X			
		Rust removal and paint for VLA antennas	X	X	X		
	Technical Upgrades	Solar Capable Receiver Installation		X			
		4-Band Dipole Installation	X				
5.0	**Observatory Development Programs**						
5.2	**Central Development Laboratory**						
		Band 1 LNA production complete	X				
		Quantum-Limited Very-Wideband 4-Kelvin RF and IF Amplifiers - ALMA Strategic Study Report	X				
		Wideband Low-Noise Balanced IF Amplifiers - ALMA Strategic Study Report	X				
		Band 1 LO production production complete		X			
		ALMA Correlator Upgrade Project		X			
5.2	**ALMA Development**						
		Calls for Study Proposals	X	X	X	X	X
		Notices of Project Awards	X	X	X	X	X
		Call for Project Proposals	X		X		
5.3	**VLA Development**						
		Deliver VLASS1.1 single epoch image cubes	X				
		Deliver VLASS1.2 single epoch image cubes		X			
		Deliver VLASS2.1 single epoch image cubes			X		
		Deliver VLASS2.2 single epoch image cubes				X	
		Complete observing for VLASS3.1					X
		Complete ngVLA Science Book	X				
		ngVLA proposal submission to Decadal Survey	X				
		Support VLA transient searches with Realfast (512 MHz)	X				
6.0	**Education and Public Outreach**						
		STEM Education	X	X			

Locator	Department/Division	Initiative	2019	2020	2021	2022	2023
		Authentic Research Experiences		X	X		
		Visitor and Eucation Center Experiences	X	X			
		Evaluation	X	X	X	X	X
7.0	**Observatory-wide Services**						
7.1	**Data Management and Software**						
		CASA refurbishment	X	X	X	X	X
		Basic Data Package for VLASS complete					
		Provide integrated systems for External Data Processing	X	X	X	X	X
		Enhance curated observing capability	X	X	X	X	X
		Overhaul the PST and OPT for the VLA	X	X			
		High Time Resolution Facility		X	X		
		Agile Triggered Observing				X	X
7.2	**Program Management**						
		Training opportunities	X	X	X	X	X
		Process Maturity Assessment Complete	X	X	X	X	X
7.3	**Administration**						
		Next Generation VLA financial model development	X	X	X	X	X
		ALMA Budgets prepared and managed in Chilean Pesos (v. US Dollar)	X	X	X	X	
7.4	**Human Resources**						
		Workforce Management	X	X	X	X	X
		Observatory Leadership Cohort	X	X	X	X	X
		Analytics	X	X	X	X	X
7.5	**Office of Diversity and Inclusion**						
		Annual NAC conference	X	X	X	X	X
		Summer Programs (NAC and NINE)	X	X	X	X	X
7.6	**Computing and Information Services**						
		Archive synchronization from the ALMA Santiago Central Office (SCO) to the multiple regional centers	X	X	X	X	

Locator	Department/Division	Initiative	2019	2020	2021	2022	2023
7.7.1	**Science Communications Office**						
		Observatory presence at major scientific meetings and conferences	X	X	X	X	X
		Design and publish an NRAO Annual Report	X	X	X	X	X
7.7.2	**Spectrum Management**						
		Represent NRAO, GBO, and LBO at international conventions	X	X	X	X	X

* Initially scheduled for FY2017 in recomp proposal.

***Initially scheduled for FY2018 in recomp proposal.

****Initially scheduled for FY17 and FY18 in recomp proposal.

APPENDIX C: ACRONYMS

Acronym	Definition
AAAS	American Association for the Advancement of Science
AAS	American Astronomical Society
AAT	Archive Access Tool
AATF	African American Teaching Fellows
ACU	Antenna Control Units
ADS	Astrophysical Data System
ADMIN	Administration Department
ADMIT	ALMA Data Mining Toolkit
AGN	Active Galactic Nucleus, or Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
AoD	Astronomer on Duty
ANASAC	ALMA North American Science Advisory Committee
APRA	Astrophysics Research and Analysis
AQUA	ALMA QUality Assurance
ARC	ALMA Regional Center
ARO	Arizona Radio Observatory
ASKAP	Australian Square Kilometre Array Pathfinder
ASA	ALMA Science Archive
ASAC	ALMA Science Advisory Committee
ASIC	Application Specific Integrated Circuit
AST	NSF Division of Astronomical Sciences
ATI	Advanced Technologies and Instrumentation
AU	Astronomical Units
AUI	Associated Universities, Incorporated
BDP	Basic Data Product
BUD	Budget Office
CAP	NRAO Contracts and Procurement Office
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CASA	Common Astronomy Software Applications
CASPER	Center for Astronomy Signal Processing and Electronics
CBE	Correlator Back End
CCD	Charge-Coupled Device
CCE	Common Computing Environments
CDL	Central Development Laboratory
CHILES	Cosmos HI Large Extragalactic Survey
CHOP	Cryogenic HEMT Optimization Program
CIS	Computing and Information Services
cm	centimeter
CME	Coronal Mass Ejection
CNC	Computer Numerical Control
CO	Carbon Monoxide
COSPAR	Committee on Space Research
CPM	Computing Planning Meeting
CS	Citizen Science
CSA	Cooperative Support Agreement

Acronym	Definition
CSC	Computing Security Committee
CTP	Cosmic Twilight Polarimeter
CY	Calendar Year
D&I	Diversity and Inclusion
DARE	Dark Ages Radio Explorer
DASI	Degree Angular Scale Interferometer
DESI	Dark Energy Spectroscopic Instrument
DISC	Dominance, Inducement, Submission, and Compliance
DMS	Data Management and Software
DO	Director's Office
DOI	Digital Object Identifiers
DSOC	Domenici Science Operations Center
DSP	Digital Signal Processing
DTS	Data Transmission System
EHT	Event Horizon Telescope
EOC	Extension and Optimization of Capabilities
EPO	Education and Public Outreach
eRosita	extended Roentgen Survey with an Imaging Telescope Array
ERP	Enterprise Resource Planning
ES&S	Environmental Safety and Security
EUV	Extreme Ultraviolet
EVLA	Expanded Very Large Array
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
FPA	Focal Plane Array
FPGA	Field-programmable Gate Array
FRB	Fast Radio Burst
FY	Fiscal Year (October 1 through September 30)
GBO	Green Bank Observatory
GBT	Green Bank Telescope
GHz	Gigahertz
GO	General Observing
GOST	General Observing Setup Tool
GPU	Graphics Processing Unit
GRB	Gamma-ray bursts
GSA	General Services Administration
HBCU	Historically Black Colleges and Universities
HEMT	High Electron Mobility Transistor
HERA	Hydrogen Epic of Reionization Array
HFET	Heterojunction Field-Effect Transistor
HI	Neutral Hydrogen
HPC	High Performance Computing
HQ	Headquarters
HR	Human Resources
HRAG	Human Resource Advisory Group
HRIS	Human Resources Information System
HSI	Hispanic Serving Institution

Acronym	Definition
HST	Hubble Space Telescope
HVAC	Heating, Ventilating, and Air Conditioning
IAU	International Astronomical Union
ICC	Internal Common Cost
ICSU	International Council for Science
IF	Intermediate Frequency
IGM	Inter-Galactic Medium
InP	Indium Phosphide
IQU	Stokes Intensity and Linear Polarization
IRD	Integrated Receiver Development
ISM	Interstellar Medium or International Staff Member
ITU-R	International Telecommunications Union - Radiocommunications
IUCAF	International Scientific Committee on Frequency Allocations
IXT	Integrated Coordination Team
JAO	Joint ALMA Observatory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
kpc	kilo-parsec
LASCO	Large Angle and Spectrometric Coronagraph
LBO	Long Baseline Observatory
LEO	Low Earth Orbit
LGBTQIA	Lesbian, Gay, Bisexual, Transgender, Queer, Intersex, and Asexual people
LIGO	Laser Interferometer Gravitational Wave Observatory
LMT	Large Millimeter Telescope
LNA	Low Noise Amplifier
LO	Local Oscillator
LOBO	Low Band Observatory
LRP	Long Range Plan
LSAMP	Louis Stokes Alliance for Minority Participation
LSM	(Chilean) Local Staff Members
LSST	Large Synoptic Survey Telescope
LWA	Long-Wavelength Array
mas	milliarcseconds
MeerKAT	Karoo Array Telescope
MHz	Megahertz
MIS	Management Information Services
MIT	Massachussets Institute of Technology
m	meter
mm	millimeter
MMIC	Monolithic Millimeter-wave Integrated Circuit
MOU	Memorandum of Understanding
Mpc	Megaparsec
MREFC	Major Research Equipment and Facilities Construction
MSI	Minority Serving Institutions
Myr	Mega-years
mJy	micro-Jansky
NA	North American

Acronym	Definition
NA ARC	North American ALMA Regional Center
NAASC	North American ALMA Science Center
NAC	National Astronomy Consortium
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
Nb	Niobium
NESS	Network for Exploration and Space Science
ngVLA	Next Generation VLA
NICRA	Negotiated Indirect Cost Rate Agreement
NINE	National and International Non-traditional Exchange Program
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRL	Naval Research Laboratory
NSBP	National Society of Black Physicists
NSF	National Science Foundation
NVSS	NRAO VLA Sky Survey
NWNH	New Worlds, New Horizons in Astronomy and Astrophysics
OBS	Observatory Business Services
OCA	Office of Chile Affairs
ODI	Office of Diversity & Inclusion
OODT	Object Oriented Data Technology
OPT	Observation Preparation Tool
OSF	Operations Support Facility (ALMA)
OT	Observing Tool
OTFM	On-The-Fly Mosaicing
P2G	Phase 2 Group
PAF	Phased Array Feed
PanSTARRS	Panoramic Survey Telescope & Rapid Response System
PAPER	Precision Array to Probe the Epoch of Reionization
PB	Petabyte
pc	parsec
PdBI	Plateau de Bure Interferometer
PFB	Poly-phase filter banks
PFT	Proposal Finder Tool
PHT	Proposal Handling Tools
PI	Principal Investigator
PING	Physicists Inspiring the Next Generation
PM	Project Management
PMD	Program Management Department
POP	Program Operating Plan
PPI	Pipeline Processing Interface
PST	Proposal Submission Tool
PT	Project Tracker
QA	Quality Assurance
R&D	Research & Development
RAMP-UP	Radio Astronomy Middle School Path to University Physics

Acronym	Definition
RAP-NM	Radio Astronomy Path to University Physics
RET	Research Experience for Teachers
REU	Research Experiences for Undergraduates
RF	Radio Frequency
RFI	Radio-Frequency Interference
RfP	Request for Proposal
RMS	Radio, Millimeter, and Submillimeter
RSRO	Resident Shared Risk Observing
SB	Scheduling Block
SACNAS	Society for Advancement of Chicanos/Hispanics and Native Americans in Science
SE	Systems Engineering
SEDLE	Socorro Electronics Division's Laboratory Experience for Undergraduates
SEFD	System Equivalent Flux Density
SIS	Superconductor–Insulator–Superconductor
SKA	Square Kilometre Array
SMA	Sub Millimeter Array
SMBH	Supermassive Black Hole
SNAP	Smart Network ADC Processor
SOP	Standard Operating Procedures
SOS	Student Observing Support
SPIE	Society for Optics and Photonics Technology
SRDP	Science Ready Data Products
SRO	Shared Risk Observing
SRP	Science Review Panels
SSERVI	Solar System Exploration Research Virtual Institute
SSR	Science Support and Research
STEAM	STEM + Arts
STEM	Science, Technology, Engineering, and Mathematics
STEREO	Solar Terrestrial Relations Observatory
submm	submillimeter
SUS	Scientific User Support
TAC	Time Allocation Committee
TDE	Tidal Disruption Event
THz	Terahertz
TKIP	Traveling wave Kinetic Inductance Parametric
TRL	Technology Readiness Level
TRS	Total Rewards Strategy
TTA	Telescope Time Allocation
TTO	Technology Transfer Office
ULIRG	Ultra Luminous Infrared Galaxies
URM	Under-Represented Minority
URSI	International Union of Radio Science
U.S.	United States
USNO	United States Naval Observatory
UVML	University of Virginia Microfabrication Laboratory
VLA	Karl G. Jansky Very Large Array
VLASS	Very Large Array Sky Survey

Acronym	Definition
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLITE	VLA Low Band Ionospheric and Transient Experiment
WFIRST	Wide-Field Infrared Space Telescope
WFO	Work For Others
WIDAR	Wideband Interferometric Digital ARchitecture
WISE	Wide-Field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe (WMAP)
WMP	Workforce Management Plan
XSEDE	Extreme Science and Engineering Discovery Environment
z	Redshift
3D	Three-dimensional