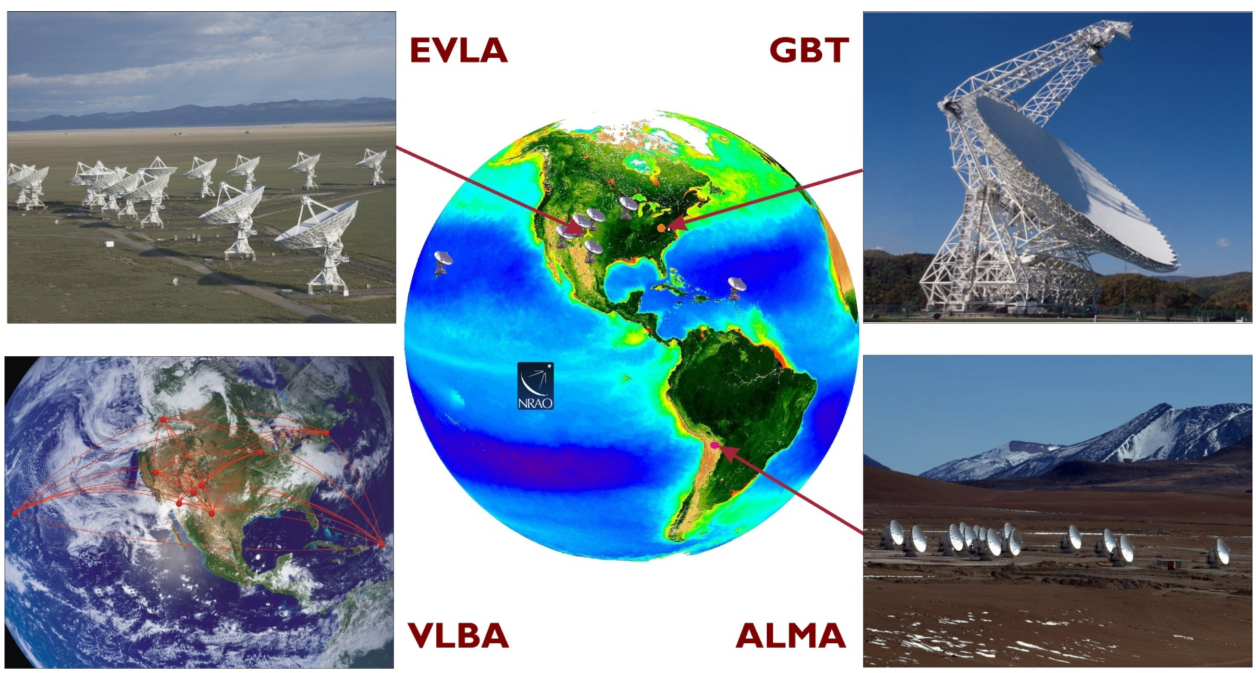
National Radio Astronomy Observatory

Five Year
Long Range Plan

FY 2013 – 2017



August 2011

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Executive Summary

During FY 2013-2017, the National Radio Astronomy Observatory (NRAO) will deliver transformational scientific capabilities and will operate a suite of four world-class telescopes that will enable the astronomy community to make new discoveries and answer outstanding fundamental astrophysical questions underlying the science objectives described in the Astro2010 Decadal Survey report, New Worlds, New Horizons in Astronomy and Astrophysics (NWNH).

The suite of telescopes includes: the international Atacama Large Millimeter/submillimeter Array (ALMA), the Expanded Very Large Array (EVLA), the Robert C. Byrd Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA). Each of these facilities is the world leader in its observing domain. Collectively, these telescopes will enable scientists to observe from sub-millimeter to meter wavelengths with an order of magnitude or more improvement over current capabilities in resolution, sensitivity, frequency coverage, or field of view. Used individually or in combination, the NRAO telescopes will provide the novel capabilities required to address many of the science themes outlined in NWNH, such as placing constraints on the nature of Dark Energy, imaging the first galaxies in the epoch of reionization and observing directly the formation of planets in proto-planetary disks.

ALMA will provide for the first time detailed images of stars and planets in formation, young galaxies being assembled throughout the cosmic history of star formation, and generally open new windows into the cold Universe via the tremendous increase in sensitivity and resolution at millimeter and submillimeter wavelengths. Now approaching completion in northern Chile, ALMA will initiate Early Science operations, on schedule, in Quarter 4 of 2011 and will achieve full science operations within another two years according to plan. The international community's strong anticipation for ALMA was demonstrated by the ~ 9:1 oversubscription for observing time in the first Early Science opportunity.

At the adjacent centimeter-wavelength range, the EVLA will have scientific capabilities comparable to those of ALMA, but exceeding those of the Very Large Array by one to four orders of magnitude, depending on the parameter. EVLA construction is on schedule, on budget, and is meeting its technical specifications and scientific objectives. Early Science programs were initiated on schedule starting in Quarter 1 of 2010 and are already enabling a wide range of science, even as construction is being completed. A special issue of the Astrophysical Journal Letters devoted to EVLA Early Science results will be published this fall, describing cutting-edge research from the Solar System to the farthest reaches of the Universe. In late 2012, the completed EVLA will transition to full science operation as the world's most capable and versatile centimeter-wave imaging array.

With comparable collecting area and sensitivity to ALMA and EVLA, the 100m GBT is the preeminent filled-aperture radio telescope operating at meter to millimeter wavelengths. Its >2-acre collecting area, unblocked aperture, and excellent surface accuracy enable precision pulsar timing to detect gravitational wave radiation, test the strong field limit of General Relativity, map the gas inflow into galaxies, detect 21 cm HI emission at $z\sim1$ via the novel Intensity Mapping approach, reveal the merging process of clusters, and probe the chemistry of the Universe. Based on an affordable plan driven by key science projects, the GBT will be augmented by new cameras that can bring an order of magnitude increase imaging speed and significantly enhance its science impact in the coming decade.

The VLBA is the premier fully dedicated VLBI array in the world. Astrometry with the VLBA has reached the precision of a few micro-arcsecond, enabling distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and moving with the Hubble flow. Its scientific capabilities will continue to improve as new receivers are installed and a major bandwidth expansion project to improve sensitivity is completed. When used in conjunction with the phased EVLA and the GBT, the resultant High Sensitivity Array greatly enhances the sensitivity for VLBI observations and broadens the range of novel scientific research. NRAO will develop a new operating model to incorporate the U.S. and international partners in VLBA for its operation and development according to five-year plans.

To maximize the usage and science impact of the NRAO facilities, NRAO aims to broaden their access to all astronomers, through uniform and enhanced user support services. These services will be provided by the North American ALMA Science Center in Charlottesville, the Array Science Center for the EVLA and VLBA in Socorro; and Green Bank Science Operations Center for the GBT, and will be closely coordinated by Observatory Science Operations.

At the same time, NRAO will also focus on developing forefront technology to continuously improve the facilities and to realize next generation facilities. Taking advantage of the outstanding technical expertise across NRAO, the Coordinated Development Lab (CDL) oversees a science-driven research and development program that will help realize key NWNH science goals, such as the detection of gravitational waves via pulsar timing (NANOGrav), the study of the epoch of reionization via the highly redshifted 21 cm HI line (PAPER/HERA) and the development of the Frequency Agile Solar Radio-telescope (FASR).

To engage the community in an ongoing discussion and planning of long-term (>10 year horizon) developments, NRAO will sponsor a series of workshop on future science and technology for the next-generation meter and centimeter-wave facilities, but in the context of multi-wavelength and time domain approach to addressing outstanding scientific questions. Taking a significant step following this general approach, NRAO has applied to become an institutional member of the Large Synoptic Survey Telescope (LSST) to ensure NRAO will be operated in a way that will facilitate the astronomy community to fully exploit the time domain in their studies of the Universe.

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 things of true significance (such as discover a pulsar or observe the radio emission from the galactic core). 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.

In order to carry out the myriads of tasks required to fulfill its primary mission of enabling forefront research under the NSF budget profile, the NRAO will continue to refine the most cost effective operating model, the 'One Observatory' approach, based on Observatory-wide planning, prioritization and coordination to utilize maximally the collective expertise and resources across the many components of NRAO.

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

1. Overview

With early science now underway on the EVLA, early science with ALMA starting this year, 2011, and with the GBT and VLBA delivering world-leading capabilities, the NRAO is fulfilling its commitment to deliver transformational facilities to the United States (U.S.) as well as the international astronomy community. The EVLA has already begun demonstrating its order-of-magnitude improvement in capability beyond the VLA with numerous new scientific results, including gas excitation studies at redshift z=6, characterization of the Spectral Energy Distributions (SEDs) of nearby Ultra Luminous Infrared Galaxies (ULIRGs), and studies of trans-Neptunian objects. The community's anticipation of ALMA is demonstrated by the 9:1 oversubscription of observing time during its first early science observing period. Impressive ALMA demonstration science is already materializing as the first dishes in the array are commissioned. With comparable collecting area and sensitivity to ALMA and EVLA, the GBT is the preeminent filled-aperture radio telescope. Recent GBT observations include unique, high resolution measurements of the Sunyaev-Zel'dovich (SZE) to probe the cluster merging process, detection of 21 cm HI emission at z~1 via the novel Intensity Mapping approach, and sub-100 ns timing accuracy of milli-second pulsars that is required for a successful detection of nano-Hertz gravitational waves. The VLBA is the most accurate astrometric facility in existence, capable of sub-10 μarcsec precision. Its exquisite astrometric capability is being used to delineate the spiral structure of the Milky Way, to determine the precise expansion of the Universe, and to search for exoplanets.

EVLA and ALMA will be the only new major, general-purpose instruments brought to the astronomical sciences in the next five years. Taken together, ALMA, EVLA, GBT with focal plane arrays, and the upgraded VLBA represent an order of magnitude or more improvement within many areas of observational capabilities, including resolution, sensitivity, and spectral capabilities, from 1 GHz to 1 THz. Such a major step, over such a wide wavelength range, has rarely, if ever, been taken in observational astronomy. These facilities will revolutionize the science being done by the U.S. and international community over the next 10 years and beyond.

1.1 Strategic Goals

The Long Range Plan (LRP) of the NRAO (over 5 years: FY 2013 – 2017) is driven by the following strategic goals. The NRAO aims to accomplish these goals in the cost-effective, 'One Observatory' approach that optimizes the collective expertise and resources across the observatory. This plan will allow NRAO to build on its record of service to the astronomical community. Built over more than five decades, NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for astronomy in the U.S., and indeed the world.

Enhance User Support to Maximize Scientific Impact

In order to ensure the astronomy community will be making optimal scientific use of the remarkable capabilities of the suite of four forefront facilities, the NRAO will focus on providing easier access to all the NRAO telescopes and enhanced support for astronomers from all sub-disciplines in a uniform and coordinated interface, under the Observatory Science Operations.

The goal is to maximize the science impact, especially along the scientific directions highlighted by the NWNH U.S. Decadal Survey report, and to be accessible to the broadest cross-section of the U.S. astronomy community.

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 recommendations of the NWNH will be carried out under Observatory Development and Programs.

NRAO will continue developments for all the operating 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 Hydrogen Epoch of Reionization Array (HERA), NANOGrav and Frequency-Agile Solar Radiotelescope (FASR), in the coming decade.

Importantly, work will be done in collaboration with research groups at universities and colleges throughout the country, which not only leverages efforts of NRAO staff in support of the university community but also provides a valuable training ground for students and young scientists to become future instrument builders.

NRAO's Outstanding Scientists and Engineers—A Key Community Resource

NRAO is more than just a collection of telescopes—it embodies a wealth of staff expertise and experience built up over more than 50 years that are unrivalled among the 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.

1.2 Introduction to the Plan

The LRP serves as NRAO's primary document for communicating the vision, mission, strategy, and initiatives that will best serve the user community and result in the best science results achievable. This 5-year plan is updated every year, to incorporate the latest scientific, technical and budgetary developments. By proactively assessing which activities should be pursued in addressing the needs of the user community in a constrained fiscal environment, NRAO develops its LRP as a guiding document against which the annual Program Operating Plan is developed.

This 5-year LRP covers the period Fiscal Year 2013- 2017. The financial basis of the projected budget and staffing levels is the established President's level budget projection. NRAO has developed this plan to represent a budget-balanced program that takes into consideration the end of ALMA Construction. NRAO has multiple sources of funding incorporated into this plan: National Science Foundation's Division of Astronomical Sciences (NSF-AST) Cooperative Support Agreement funds, NSF-AST-Scientific Program Order (SPO) funding for construction, grants, contributions from other organization, in-kind contributions, etc.) NRAO is also targeting external sources of funds to overcome some major challenges in the NSF funding allocation during this plan period, but only sources of funding that are established, or committed through a formal Memorandum of Understanding/Agreement (MOU/MOA) are included. Any additional funds obtained will be used in order of scientific priority, and could include offsets to reductions in critical staff, support services, development, or to meet various opportunities that arise.

The NRAO LRP FY 2013-2017 describes the tasks and resources that will be used to accomplish the following high-level goals:

- Completion of the ALMA Construction Project.
- Enhance User Support to maximize scientific impact.
- Research and development to evolve the NRAO facilities and to help realize mid-scale facilities recommended by NWNH.

Although this LRP is fiscally constrained, it is formulated to ensure the continued successful operation of the telescope facilities, make provisions for improving the community's optimum scientific utilization of them, and continue developments required to keep the U.S. at the forefront of radio astronomy and astrophysics. Fitting in 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 make sure the optimum and feasible Program Operations Plan is formulated.

1.3 Structure of the Long Range Plan

Operating as 'One Observatory' with many facilities to fulfill its vision and mission, NRAO is organized around four Observatory-wide functions: Science Operations, Telescope Operations, Development & Programs, and Administrative Services. The LRP is structured to describe how these functions are performed in detail in different Chapters.

Chapter 2 describes the key community-driven science goals, along the four science themes in NWNH and how the new capabilities of NRAO facilities allow the astronomy community to address the outstanding questions.

Chapter 3 describes Science Operations (OSO) whose goal is to facilitate the users in obtaining the most scientific return from the NRAO telescopes. Through OSO, NRAO provides access to all its facilities, expands access to new users, enhances user services to facilitate their scientific objectives, and aims to optimize operational efficiencies across the Observatory.

Chapter 4 describes the telescope operations (OTO). Critical to the success of NRAO is maintaining the facilities themselves in the best operating condition. By FY 2013, the NRAO will be operating a suite of forefront telescopes—ALMA, EVLA, GBT, and VLBA—observing from meter to sub-millimeter wavelengths involving eventually a total of 99 telescopes. This Chapter describes activities that will be taken to ensure their prime operational performance currently and into the future.

Chapter 5 describes the NRAO research and development activities carried out under Observatory Development & Programs (ODP): (1) continually developing critical capabilities for upgrading all the NRAO facilities and for next generation facilities; (2) helping the community to realize mid-scale projects recommended by NWNH; (3) identifying and pursuing collaborations that lead to new scientific initiative, advancements in the state-of-the art technology, as well as possible additional funding opportunities.

Chapter 6 describes the Broader Impact of NRAO. The Education and Public Outreach (EPO) efforts promote public awareness and understanding of important science results achieved by NRAO users, promote and stimulate STEM (science, technology, engineering, and math) learning and careers among students, and contribute to sustaining public support for continued U.S. participation and leadership in radio astronomy, with particular emphasis on communities where NRAO operates telescopes. NRAO endeavors to broaden and engage diverse participants in many of these activities in society as well as within the Observatory.

Finally, Chapter 7 and appendices explain the activities of NRAO administration and services, describe the resource and budget projections for all funding used by NRAO, describe above-guidance items that, although very important, could not be funded within the constrained budget available at the time of writing this document, and outline the major milestones and tasks that have been identified for this plan period.

The LRP is a living document that will be updated annually to adapt to changing events, priorities, and actual versus projected funding.

1.4 Financial and Budget Considerations

This LRP is based on the following key elements; Cooperative Service Agreements (CSAs) and other funding:

- CSA-1 Management and Operations of the National Radio Astronomy Observatory
- CSA-2 Operations and Maintenance of the Atacama Large Millimeter Array
- CSA-3 Interagency Agreements Associated with Base Operations
- Various non-Programmatic Funding (grants and projects[1])

NRAO's income and budget plan is provided in Appendices A-B. Carryover, a variable that is held no more than a few percent of the budget during this plan period, is typically used as reserve to address unexpected U.S. dollar to Chilean Peso exchange rate fluctuations, variations in assumed inflation or benefit rates, or sudden cash needs for unpredictable events such as infrastructure or other emergencies.

This LRP is written to a balanced budget based on current projections and information, but can be affected by many events, on fairly short timescales. Consequently, it will be revised yearly. NRAO works with the user community to set priorities from a diverse set of proposed projects and service models to achieve best science impact within the confines of the budget allocations. It then carefully controls performance to budgets.

At the start of this plan, the construction projects (ALMA and EVLA) will be nearing completion, and the staff roll-offs and other reductions will be in their final phases. Funding for ALMA North American Operations continues to ramp up through FY 2015, following the approved proposal. NRAO North American (non-ALMA) operations funding is essentially flat over the FY 2013-17 period, while operating costs continue to rise. Unless there is additional funding from alternate sources, starting in FY 2013, the NRAO (non-ALMA) budget incorporates enduring reductions, up to 10%, which are needed to balance the budget across all plan years. These reductions will have an impact on performance and opportunities across all areas of the Observatory and are discussed within the individual Chapters of this document. The reduction plan will be guided by the established process for setting Observatory-wide priorities to maintain optimum science impact, and to avoid irreparable damage to science infrastructure or critical staffing.

To explore alternate funding opportunities, the NRAO New Initiatives Office will pursue new scientific and technical opportunities and collaborations that are consistent with the broad Observatory mission. This effort will help reduce the magnitude and impact of NSF budget reductions and preserve the critical capabilities that NRAO provides to the community.

[1] Projects can be for services or products, such as receivers built for other organizations.

1.5 NRAO Telescope Facilities

The NRAO enables forefront research into the Universe at radio wavelengths. This is accomplished by providing the U.S. astronomical community with pinnacle-of-performance radio/millimeter/sub-millimeter telescopes, and the tools and expertise astronomers need to effectively use them.

The suite of NRAO telescopes: ALMA, EVLA, VLBA and GBT span a major portion of the electromagnetic spectrum usable for astronomical observations— five of the twenty wavelength decades from radio through gamma ray – with unsurpassed sensitivity, spatial and spectral resolution, and sky coverage. With deep collaborative ties to the community, low-overhead operational efficiencies, and telescopes anchored to terra firma, NRAO accounts in FY 2012 for just 6% of the U.S. government's proposed astrophysics expenditures (3% of the combined budgets for astrophysics, planetary science, and heliophysics).

The new capabilities provided by the suite of NRAO facilities can be summarized as follows:

- ALMA will deliver 10- to 100-fold improvements in resolution, sensitivity, and frequency coverage at millimeter and submillimeter wavelengths, enabling imaging the environments and formations processes of planets, stars, galaxies and black-holes..
- The EVLA will provide unrivalled scientific capabilities at centimeter wavelengths with similar, but complementary impact as ALMA, and will greatly facilitate the mapping of cosmic magnetic fields and the study of the transient universe.
- The GBT will combine its 100m aperture with wide-field cameras to make rapidly sensitive and high-resolution images of dust, neutral and ionized gas throughout the Cosmos. Its high point-source sensitivity with advanced processors for precision timing of pulsars makes it the premier telescope to detect gravitational waves.
- The VLBA will gain sensitivity and apply its micro-arc-second astrometric precision to map directly the spiral structure of the Milky Way galaxy, the proper motion of Local Group galaxies, and the precise expansion rate of the Local Universe.

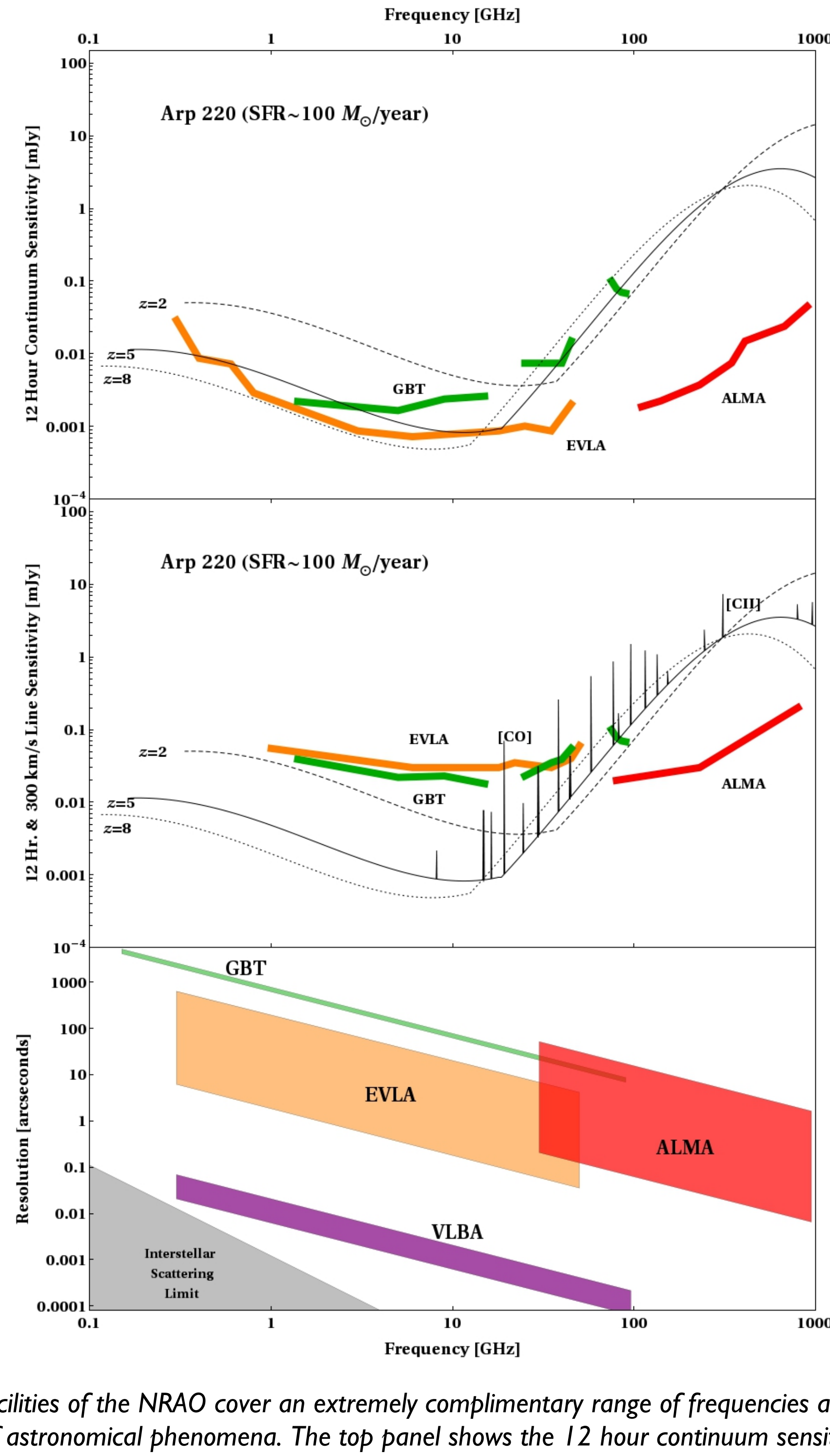

Figure 1.1 The facilities of the NRAO cover an extremely complimentary range of frequencies and are sensitive to a wide variety of astronomical phenomena. The top panel shows the 12 hour continuum sensitivity achievable with ALMA, GBT, and EVLA. The middle panel shows the 12 hour line sensitivity of the same facilities at a resolution of 300 km/s. Both panels are compared with the galaxy Arp 220 at z=2, 5, and 8 for a star formation rate of 100 solar masses per year. The bottom panel shows the resolving power and frequency coverage discernible from ALMA, GBT, EVLA, and superior resolution afforded by the VLBA. Note that gaps do exist in frequency coverage due to atmospheric opacity in the range 50 to 70 GHz due to O_2, as well as other bands for ALMA.

Atacama Large Millimeter/submillimeter Array (ALMA)

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. It will achieve order of magnitude or more improvements in sensitivity, frequency coverage, resolution, imaging, and spectral capabilities. ALMA will provide scientists with 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 will be 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). Construction of ALMA is on schedule. The first ALMA Call for Proposals for Cycle 0 Early Science was issued on 30 March 2011, and attracted proposals in such quantity as to represent a likely oversubscription ratio exceeding 9:1, comparable to the typical oversubscription rate of the Hubble Space Telescope. Early Science observations will begin in September 2011, or shortly thereafter. Full science operations will begin in early FY 2014.

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 first 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 ([O I]) and 52μm and 88μm ([O III]); these lines may be detected in several hour integration times 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 $z \sim 10$.

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 capability of distinguishing 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.

Expanded Very Large Array

The EVLA is a centimeter-wavelength telescope array of unprecedented sensitivity, frequency coverage, and imaging capability being created via a comprehensive modernization of the VLA. The EVLA multiplies VLA capabilities by one to four orders of magnitude owing to its state-of-the-art digital electronics, low-noise receivers, wideband digital correlator, fiber optic transmission system, and new on-line control systems.

Located at 2140m altitude on the Plains of San Agustin in west-central New Mexico, EVLA is an interferometric telescope array of twenty-seven 25m radio telescopes in an extended, reconfigurable array operating at frequencies from 1to 50 GHz (30 cm – 6 mm). EVLA construction is on schedule, on budget, and is meeting its technical specifications and scientific objectives. Early Science operations were initiated on schedule in March 2010 and will continue, with increasing capability, until full science operations begin in January 2013. Community access to Early Science is via two, high priority NRAO programs: the Open Shared Risk Observing (OSRO) program for the general user community; and a Resident Shared Risk Observing (RSRO) program for scientists who can be resident in Socorro. A special issue of the Astrophysical Journal Letters will be published this fall that will include 37 scientific papers that illustrate the enormous range of new science being conducted by the community at the EVLA. The EVLA Project is funded primarily by the National Science Foundation, with contributions from the National Research Council in Canada and the Consejo Nacional de Ciencia y Tecnologia in Mexico.

The primary science case of the EVLA 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 EVLA 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 EVLA 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 EVLA. 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 EVLA 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.

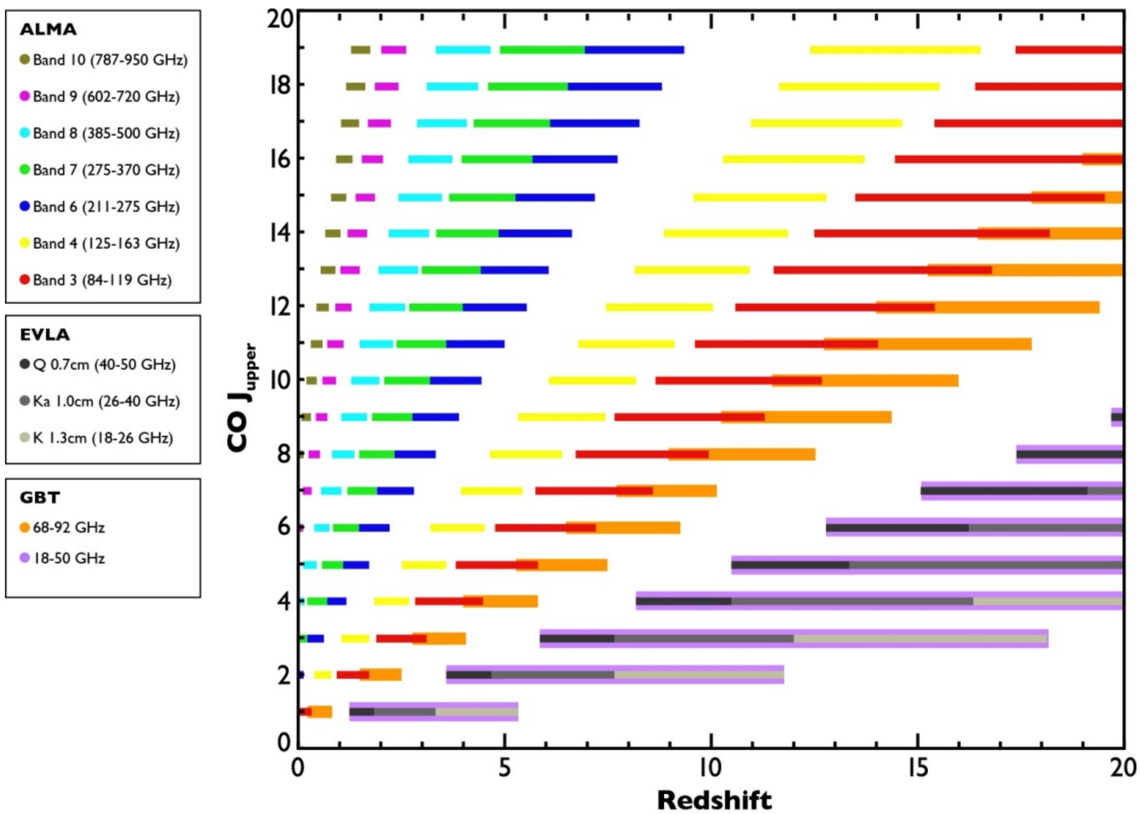

Figure 1.2 NRAO Telescope Molecular Gas Discovery Space: The carbon monoxide (CO) molecule is an excellent tracer of the distribution of molecular gas in the Universe. ALMA, EVLA, and GBT provide complementary and comprehensive coverage of the CO discovery space as a function of redshift. The horizontal lines indicate which CO transition (y-axis) can be observed with these NRAO research facilities as a function of redshift (x-axis).

Green Bank Telescope

The GBT is the world's premiere single-dish radio telescope operating at meter to millimeter wavelengths. Its enormous 100 meter diameter collecting area, unblocked aperture, and excellent surface accuracy provide unprecedented sensitivity across the telescope's full 0.1 - 116 GHz (3.0m – 2.6mm) operating range. A unique and powerful telescope that is used by hundreds of scientists each year, the GBT is fully steerable, and 85% of the entire celestial sphere is accessible to it. Its operation is highly efficient, and it is used for astronomy ~ 6500 hours per year.

The GBT's filled aperture has comparable collecting area and sensitivity to ALMA and the EVLA, but with the image brought to a single focal plane. This provides the GBT with extraordinary sensitivity to extended, low surface-brightness objects such as diffuse molecular clouds or SZE distortions of the cosmic microwave background (CMB), as well as high sensitivity to point-source radiators such as pulsars. The single focal plane is ideal for rapid, wide-field imaging systems – cameras. The GBT thus serves as the wide-field imaging complement to ALMA and the EVLA. The single focal plane also provides an accessible development platform and allows much of the advanced, instrumentation to be provided by university-based laboratory groups. The GBT's high sensitivity imaging and point-source capabilities enable a large and varied program of key science projects. In addition, the GBT often joins the VLBA for interferometry observations to provide a critical threshold of sensitivity for a number of important projects, including, for example, the megamaser cosmology experiment.

Part of the scientific strength of the GBT is its flexibility and ease of use, allowing for rapid response to new scientific ideas. It is scheduled dynamically to match project needs to the available weather. The GBT is also readily reconfigured with new and experimental hardware, adopting the best technology for any scientific pursuit. Facilities located on the Green Bank site are also used for other scientific research, as well as for an extensive array of programs in education and public outreach, and for the training of science and engineering students and teachers. The complex is a large site with laboratories, utilities and support facilities that makes it an attractive location for staging a variety of research experiments. In addition, because of the National Radio Quiet Zone (NRQZ) and the West Virginia Radio Astronomy Zone (WVRAZ) it is uniquely protected from many forms of man-made radio frequency interference.

The GBT was designed to readily allow upgrades and changes to all aspects of its hardware and software. A specialty (or principle investigator-driven) instrument can be installed on the telescope with relative ease, making it feasible for an individual or group of researchers to outfit the telescope to meet their particular science goals. The GBT also has a vigorous development program in collaboration with college and university groups to take advantage of the latest technology and provide our user community with a constantly improving facility. In concert with the community, development projects for the GBT will continue through the coming decade and have already led to important discoveries in a number of areas, from discovering the most massive neutron star yet known, which has had great impact on our understanding of physical equations of state in dense matter, through making the highest resolution, most sensitive images of the SZE yet known, to provide a rare observational window into the actual formation process of clusters of galaxies.

Primary science goals for the GBT include the following:

- Detect nano-hertz gravitational waves through precision timing of millisecond pulsars;
- Study the large-scale structure of the universe and map the Baryon Acoustic Oscillations (BAO) using the technique of HI Intensity Mapping;
- Measure galaxy cluster properties, including gas pressure and the presence of shocks, for up to 100 clusters, with the best sensitivity and resolution to date, through surveys of the SZE;
- Determine the origins of low-mass star formation in Interstellar Dark Clouds (IDCs) via measurements of temperature, density, turbulence, etc., in a large survey of cloud cores;
- Study the chemical origins of life in interstellar and cometary gas clouds through observations of pre-biotic molecules and their precursors.

Very Long Baseline Array

The VLBA is the premier ultra-high resolution radio-wavelength array in the world, with applications ranging from sub-millarcsecond resolution imaging to micro-arcsecond astrometry. The instrument consists of ten 25m-diameter radio telescopes spread across the contiguous United States, Hawaii, and the U.S. Virgin Islands, and a state-of-the-art software correlator facility in Socorro, NM. The VLBA operates at observing frequencies from 300 MHz – 90 GHz (wavelength: 1.0 m – 3.3 mm).

The VLBA will continue to evolve throughout FY 2013-2017 so that the strongly supportive (U.S. and International) user community can exploit its capabilities and make major contributions to high priority science frontier discovery areas identified by NWNH, particularly astrometry and time domain astronomy, where the VLBA will play leading roles in the coming decade and beyond.

In FY 2013, the VLBA will operate at a bandwidth of at least 256 MHz per polarization, a factor of 16 over its initial capabilities, providing a factor of four in increased sensitivity. Improvements to sensitivity will continue to be made in the future through receiver upgrades, further improvements to the digital electronics, and eventual replacement of the analog electronics path with one similar to that used on EVLA telescopes.

Survey science at milliarcsecond resolutions is now becoming practical via advances in correlator technology recently deployed by the NRAO. The next decade will see, for the first time, deep Very Long Baseline Interferometry (VLBI) imaging of tens of thousands of galaxies being studied at other wavelengths with deep exposures and will shed new light on the origin of the radio emission.

The value of the VLBA as a collection of individual 25-meter radio telescopes will be increasingly exploited. The VLBA will be used in multi-static observations of asteroids in conjunction with the Goldstone or Arecibo radar facilities to determine asteroid spin properties via the speckle tracking technique. The state of spin of an asteroid is otherwise difficult to determine but plays an important role in predicting its future path and Earth-impact potential. The individual VLBA telescopes will also be used for spectroscopic single-dish observing with applications ranging from stand-alone neutral hydrogen intensity mapping at low redshift to total power supplementation for ALMA observations of molecular species in star-forming regions.

VLBI has long been recognized as a potent tool for tracking spacecraft, and fundamental science questions can also be addressed with such observations. The VLBA and several other radio telescopes tracked the path of the Huygens probe as it descended through the atmosphere of Saturn's moon Titan, providing critical information about Titan's winds. The solar system ephemeris will continue to be improved via VLBA observations of spacecraft in orbits around other planets; the measurement accuracy of Saturn's orbit will be improved considerably over the next two or three years as observations of the Cassini spacecraft start to span a larger fraction of a full solar orbit.

The VLBA will also continue to be a major contributor to the geodetic observations that construct and maintain the fundamental reference frame used by all astronomers. This International Celestial Reference Frame (ICRF) is a grid of quasars with positional accuracies better than 1 milliarcsecond. Maintenance of the reference frame is important given source evolution and the VLBA will continue to contribute high quality data towards future ICRF updates. The VLBA will also continue to play a critical role in extending this reference frame to higher radio frequencies. The relevance of the radio reference frame will increase at mid-decade when the Gaia satellite is expected to launch and connect the radio and optical reference frames to high precision using many of the same sources. Geodetic observations also greatly impact geology via measurements of the deformation of the Earth's crust that results from Earth-Moon-Sun tidal interactions and from earthquakes.

Major science goals for the VLBA include:

- A 3-D astrometric image of the entire Milky Way;
- Measurement of the relative motions of the Local Group of galaxies – determining the past and future locations of the Milky Way relative to its neighbors;
- Time domain astronomy of transients, including cosmic movies of jets in gamma-ray emitting Blazars and in micro-quasars, such as SS433;
- Precision determination of the Hubble Constant, based on angular diameter distances of circum-nuclear mega-masers in the Hubble Flow.

1.6 One Observatory

With four forefront telescopes located in North and South America, operated by staff based in Charlottesville, VA, Green Bank WV, Socorro NM in the US, and Santiago, Chile, the NRAO operates as a single Observatory. This One Observatory approach is the most cost effective, because the complementary suite of telescopes provides the astronomy community unsurpassed scientific capabilities, especially when the telescopes are used in combination, at a cost per telescope that benefits from the economy of scale. Specifically, the science and telescope operations, development and administrative services all share and benefit from the collective expertise, resources and infrastructure across the Observatory.

An important example of an Observatory-wide resource is the collective, deep and extensive expertise of radio interferometry accumulated across the NRAO over more than 50 years. It is critical to the success of ALMA, EVLA and VLBA, all based on interferometry, as well as most next-generation facilities. NRAO provides critical inputs to the design, planning, construction, science commissioning and the eventual science operations of the international ALMA. Such depth and breadth of interferometry expertise at the NRAO is rare in astronomy; the NRAO staff embodies a significant fraction of the world's expertise in this critical area.

2. Key Community-Driven Science Goals

Radio astronomy in the coming decade is poised for revolutionary advances and exciting discoveries, many of which will be enabled by the transformational capabilities provided by the NRAO facilities. While it is difficult to predict exactly where such dramatic improvements will lead, NRAO builds this vision around the primary science themes identified by the American science community in NWNH.

NRAO's strength is its flexibility, and the high impact of its telescope discoveries. The most important science may come from projects not yet conceived. NRAO telescopes will also be key to much of the science outlined in the NWNH as shown in Table 2.1.

Table 2.1: "New Worlds, New Horizons" Science and NRAO Research Facilities

Astro2010 Science Discovery Areas & Questions	ALMA	EVLA	GBT	VLBA	Radio-wavelength research foci
Discovery					
Habitable exoplanets	X	X			Protoplanetary disks, planetesimal formation and gaps
Gravitational wave astronomy		X	X	X	Pulsar timing arrays for gravity wave detection; pulsar distances
Time-domain astronomy	X	X	X	X	Surveys and rapid follow-up
Astrometry	X	X	X	X	Milli- to micro-arcsecond astrometry
Epoch of reionization	X	X	X	X	Low freq studies of neutral IGM; high freq studies of gas, dust in galaxies
Origins					
How did the Universe begin?	X	X	X		Cosmic Microwave Background supporting observaitons
First light in the Universe	X	X	X		Observations of gas, dust, star formation, and AGN in the first galaxies
How do cosmic structures form & evolve?	X	X	X	X	Large scale structure research via surveys and intensity mapping
Dark & luminous matter	X	X	X		Dynamics of galaxies from z=0 to z=10 CO, [CII], HI
Fossil record of galaxy assembly	X	X	X		Mass distribution in galaxies from molecules and HI
How do stars form?	X	X	X	X	Probing deep into the optically obscured, earliest epochs of star formation
Cirumcumstellar disks & planetary systems	X	X	X		Protoplanetary disks in dust and gas, outflows
Understanding the Cosmic Order					
How do baryons cycle in & out of galaxies?	X	X	X	X	Large scale flows around galaxies in HI and CO
Matter and energy in the circumgalactic medium	X	X	X	X	Wide field surveys in HI and radio continuum
Mass-energy-chemical cycles within galaxies	X	X	X	X	Studies of obscured star formation; molecular and atomic gas
Stellar rotation and magnetic fields	X	X	X		Polarization studies of stellar radio emission
Massive stars/Type Ia supernovae	X	X	X	X	Radio studies of SNe, SNe remnants, and GRBs
Planetary systems diversity	X	X	X		Protoplanetary disks and surveys of dark clouds
Habitable worlds & signs of life	X	X	X		Prebiotic molecule searches
Frontiers of Knowledge					
Why is the Universe accelerating?	X	X	X	X	Cosmological parameters via intensity mapping, megamasers, large scale surveys
What is dark matter?	X	X	X	X	Imaging of galaxy dynamics using HI; Local Group galaxy dynamics
Compact stellar remnants			X		neutron star physics using pulsars

The following sections outline the many key science areas identified in NWNH in which NRAO will play a fundamental role in enabling progress. These areas are arranged according to the four paramount science themes highlighted by NWNH: Discovery (Section 2.1), Origins (Section 2.2), Understanding the Cosmic Order (Section 2.3) and Frontiers of Knowledge (Section 2.4). The sections demonstrate the broad range of science that will be afforded users by the NRAO facilities.

2.1 Discovery

Of the five science frontier discovery areas highlighted in NWNH, radio astronomy observations play a crucial role in four: gravitational wave astronomy, time domain astronomy, astrometry and the epoch of reionization.

Gravitational Wave Astronomy
NRAO Facilities: GBT, EVLA

One of the most important pending discoveries in Astronomy and Astrophysics is the direct detection of gravitational waves. An important and competitive method to detect the stochastic background of nano-Hertz gravitational waves, generated by the ensemble of merging super-massive black hole (SMBH) binaries throughout the universe and by individual SMBH binaries, is via high precision timing of milli-second pulsars. Such detection requires the measurements at two observing frequencies, over 5 - 10 years, of the pulses from at least 20 millisecond pulsars spread across the sky at ≤100 ns timing accuracy. The pulsars act as the far ends of the arms of a Galactic-scale gravitational wave detector. A direct detection of these gravitational waves is likely during the next 10 years using current facilities.

As the world's premier telescope for pulsar observations, outside the range of Arecibo, the GBT is the central instrument for the North American effort, known as the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). NRAO played a key role in establishing NANOGrav in order to devote long-term commitment of GBT observing time for this important scientific goal, developed the ultimate timing backend (GUPPI), and will develop a wide-band timing system essential to the eventual success of NANOGrav. NANOGrav was ranked by the NWNH survey as a compelling project for funding through the proposed Mid-Scale Innovations Program. NRAO is committed to continue applying its scientific and technical expertise to facilitate the implementation of the future goals of NANOGrav, e.g. to go beyond detection to using gravitational waves to probe the physics of the gravitational wave sources.

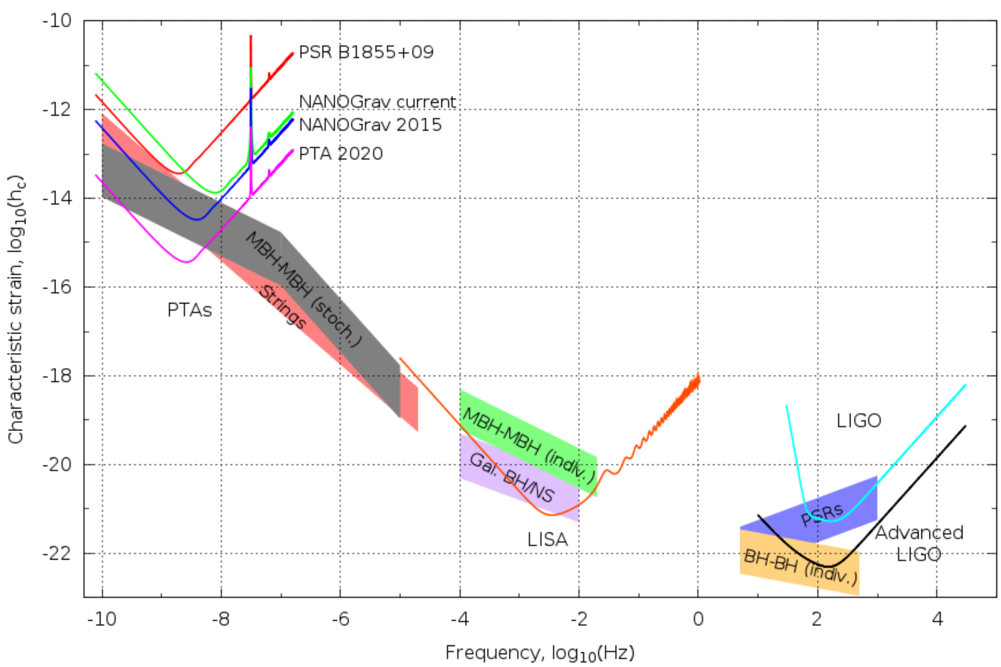

Figure 2.1 Gravitational Wave Radiation Discovery Space / Gravitational Strain versus Frequency: The predicted gravitational wave strain spectrum from astrophysical sources (colored bands) and the sensitivity curves of current or future gravitational wave detectors (colored lines) as a function of gravitational wave frequency. The three primary "instruments" are pulsar timing arrays (PTAs, including NANOGrav in the nHz regime), LISA (in the mHz regime), and LIGO/Advanced LIGO (in the kHz regime). The instruments are completely complementary to each other and will see different classes of sources. The improvement of PTAs with time is evident in the greatly improved sensitivities as the next decade progresses.

The phased EVLA, with very wide bandwidth and a collecting area slightly exceeding the GBT, will be an important part of the timing network for the detection of nano-Hertz gravitational waves.

NANOGrav's objectives and technology will complement the laser interferometer searches such as Advanced Laser Interferometer Gravitational Wave Observatory (LIGO) and Laser Interferometer Space Antenna (LISA) to detect higher frequency gravitational waves.

Opening the time domain: Making Cosmic Movies
NRAO Facilities: EVLA, VLBA, ALMA, GBT

The dynamic sky was specifically called out in NWNH as a rich area ripe for discovery. Thanks to new technical developments there are a new generation of synoptic optical and radio imaging telescopes working or under development (e.g., Pan-Starrs, Palomar Transient Factory, Large Synoptic Survey Telescope (LSST), Australian Square Kilometre Array Pathfinder (ASKAP), Westerbork Synthesis Radio Telescope (WSRT/Apertif, MeerKAT). While NRAO facilities are capable of carrying out large-scale time domain surveys, their superb sensitivity, broad frequency response, and ability to make spatially resolved "movies" of evolving objects, make them optimally suited as follow-up instruments.

The radio discoveries made in the last decade underline this point: coherent emission from flaring brown dwarfs, bursting and transient pulsed emission from magnetars, bright nanosecond timescale bursts from pulsars, fading afterglows from short-duration gamma-ray bursts, a mysterious burster at the Galactic Center, a new population of sub-relativistic supernova, and transient jet production from the tidal disruption of stars passing near super-massive black holes. Transient processes, which sample full range from the nano-second, hourly, daily and monthly scales, give us insight into the nuclear equation of state, relativistic particle acceleration, accretion physics and jet formation, the death of massive stars, and the birth of black holes.

In the coming decade, NRAO will partner with synoptic imaging facilities to maximize the science yield of all experiments. Important new discoveries may include the detection of the radio afterglows of gamma-ray bursts from the earliest stars ($z>7$) and the radio detection and imaging of the electromagnetic counterparts from gravitational wave experiments (e.g., Advanced Laser Interferometer Gravitational-wave Observatory, Virgo).

At a more institutional level of collaboration, the NRAO was invited, and has applied, to join the LSST Corporation as an institutional member. Such an affiliation will ensure the NRAO is closely engaged in this key discovery area of time domain astronomy and to provide multi-wavelength capabilities to the exploratory and discovery potential by the entire astronomy community. Panchromatic, wide field synoptic surveys will be a major scientific thrust in the coming decade, and NRAO will be contributing to these studies in a fundamental way.

Owing to its ultrafast antennas, unmatched sensitivity, excellent snapshot imaging and quick access to frequencies spanning a decade or more, ALMA can provide high resolution imaging of evolving events in the sky. The first stars seeded the early Universe with the heavy elements as they died in supernovae, some visible to us as gamma ray bursts. Faint millimeter wave emission from these bursts has been imaged with current instruments only with long integrations, masking, for example, reverberations from reverse shocks that might map the density structure of the evolving remnant. ALMA's sensitivity and flexibility will increase by orders of magnitude the number and character of stellar explosions that can be studied, allowing users to connect variations in the host galaxies and progenitors to the energy and characteristics of the explosions. ALMA's high sensitivity to low surface brightness emission should enable time-resolved studies of shock processes in the nearby interstellar medium—observers will be able to witness the chemical transformation as cold icy material is transformed into warmer, kinematically active gas as a shock is driven through it.

Astronomical transient sources tend to be compact objects that emit synchrotron radiation from high-energy particles, radiation best observed at radio wavelengths. The EVLA is ideal for studies of variable sources because of its high sensitivity, its ability to observe day and night under most weather conditions, and the rapid response enabled by dynamic scheduling. The EVLA sensitivity enables observations at higher frequencies, providing improved spatial resolution. The EVLA can image novae and relativistic jets anywhere in the Milky Way, and measure the sizes of many tens of gamma-ray bursts (GRBs) each year. Transient processes that sample timescales from nanoseconds to months will yield insights into the nuclear equation of state, relativistic particle acceleration, accretion physics and jet formation, the death of massive stars, and the birth of black holes.

EVLA will partner with synoptic imaging facilities to maximize the science yield of all experiments. Important new discoveries may include the detection of the radio afterglows of gamma-ray bursts from the earliest stars ($z > 7$) and the radio detection and imaging of the electromagnetic counterparts from gravitational wave experiments.

The VLBA will continue to support programs of at least two distinct types of time domain astronomy. The first type includes programs that monitor the source and polarization structure of compact non-thermal radio sources produced by super-massive black-holes. The ultra-high angular resolution of the VLBA shortens the relevant timescale of many distant structure evolution phenomena to time durations of a few years. The long-term MOJAVE project, for example, will continue to monitor a large collection of such sources at 15 GHz (2 cm), providing new insights into the functioning of active galactic nuclei. Scientists will also continue to use the VLBA to monitor micro-quasars, such as SS433, that vary on a daily time scale, and the radial oscillations of the maser envelope of stars such as TX Cam.

The other major type of VLBA time domain astronomy will be conducted via transient searches. The ten VLBA telescopess will be used for commensal transient searching in parallel with most scientific observations.

Opening the Time Domain: Dynamic Imaging of the Sun
Future Facility: FASR

The Sun is in some ways the ultimate in time domain astronomy, producing phenomena across the electromagnetic spectrum on time scale of milliseconds to centuries and longer. Due to its proximity the Sun not only represents a touchstone against which to measure our understanding of the structure and evolution of main sequence, it is an extraordinary laboratory for exploring fundamental astrophysical processes—from magnetic dynamos to magnetic energy release to particle acceleration; it represents the driver of so-called space weather phenomena, phenomena that can have a direct impact on the interplanetary medium, on the Earth's magnetosphere, its ionosphere, and its atmosphere. These can have a profound impact on our technological society both on the ground and in space. For example, powerful radio bursts (more than 100 million Janskys!) in December 2006 jammed the GPS network for an extended period of time; a violent outburst of activity caused a collapse of Quebec's electrical grid in 1989; in January 2005 a flare produced hard particle radiation that would have exposed an astronaut on the moon to 50 rem, a dose sufficient to cause severe radiation sickness.

The Frequency Agile Solar Radiotelescope (FASR) will revolutionize the study of the Sun at radio wavelengths. The FASR innovation is to perform ultra-broadband (0.05-21 GHz), dynamic, imaging spectroscopy. In so doing, it will image the Sun's entire atmosphere, from the mid-chromosphere to well out into the corona, in less than one second. In other words, it will image the Sun's dynamic atmosphere and the myriad processes occurring therein, in 3D, every second. These wholly unique observations will enable a number of powerful new diagnostic techniques that will reveal phenomena that were previously inaccessible. These include: quantitative measurements of coronal magnetic fields, magnetic energy release, particle acceleration and transport, shock formation and propagation, and insights into the heating of the solar chromosphere, corona, as well as solar wind acceleration. FASR will, moreover, make significant contributions to understanding the drivers of space weather, a critical need for space weather prediction. FASR represents an apt example of next generation instrumentation that will exploit fundamentally new data types and new analysis techniques to enable new science using large data sets.

The NRAO staff has played an important role in developing the FASR science case and instrument concept. NRAO / AUI is a founding member of the FASR consortium, which could act as a model for future university/facility collaborations. FASR is in a high state of technical readiness and can move forward to construction quickly. The NRAO will lead the FASR proposal development in FY 2012 to position the project for a construction start in FY 2013 or early FY 2014.

Ultra-high precision astrometry

NRAO Facility: VLBA, GBT, EVLA, ALMA

The VLBA is a unique instrument for precision astrometry. The VLBA astrometric accuracy of <10 μarcsec, for example, is better than what the European Space Agency (ESA) Gaia mission will achieve for most of its catalog stars (the catalog will be released no earlier than 2015). Precision astrometry at the VLBA will continue to improve as new receivers are installed and its sensitivity by expanding its recording bandwidth, and continue to extend the capabilities of its software correlator. For reference, a parallax of 3 micro-arcsecond corresponds to a distance of 1/3 Mpc, and a proper motion of 3 micro-second/year corresponds to 0.15 km/s at a distance of 10 Kpc, or 150 km/s at a distance of 1 Mpc. This is why the NWNH report (p 2-7) pointed out that "Direct geometric measurements of distances to the Galactic Center, to major regions of star formation in the Milky Way, to nearby galaxies, and, most importantly to galaxies at cosmological distances are possible using precision radio astrometry."

In the next five years, scientists will directly map for the first time the spiral structure and dynamics of the Milky Way to unprecedented precision, via VLBA measurements of the distance and proper motion of the 6.7 GHz methanol masers in massive star-forming regions throughout the Galaxy, in the Key Science observational program called "Bar and Spiral Structure Legacy Survey (BeSSeL)".

Closer to the solar neighborhood, a key project to measure the parallax and proper motion of all Pre-main-sequence (PMS) stars with detectable radio emission in the Gould's Belt will provide accurate distances and velocities that will place the study of PMS stars on a much firmer theoretical footing. The VLBA will also continue searches for exoplanets around M-dwarf stars and PMS stars.

VLBA astrometry will unlock secrets of the extreme physics of pulsars via accurate velocity and distance measurements that will probe supernova energetics and allow absolute luminosities to be determined across the electromagnetic spectrum.

Beyond the Galaxy, the VLBA will also directly measure the relative motions of the Local Group galaxies, determining the past and future configurations of the Milky Way and its neighbors, and whether the Milky Way will experience a future merger. Angular diameter distance determinations to galaxies in the Hubble Flow, without resort to the extragalactic distance ladder, have been demonstrated with the VLBA and GBT observations of mega-masers, and they will continue to improve the accuracy of the expansion rate of the Local Universe – the Hubble Constant to place high precision constraints to cosmological parameters and the equation of state parameter of Dark Energy.

Astrometry precision is directly proportion to the S/N ratio. Therefore, the use of the GBT and the phased EVLA together with the VLBA, which greatly increases the total collecting area, will be critical to achieving the best possible astrometric measurements.

The VLBA has also long been a mainstay in the establishment and maintenance of the International Celestial Reference Frame (ICRF). The ICRF, anchored by dual-frequency VLBI observations at 2.3 and 8.4 GHz, provides the angular framework for all position measurements in the Universe, including practical applications such as spacecraft navigation and the understanding of the true orientation of the GPS satellite constellation. As part of a potential partnership with NASA for spacecraft navigation, the VLBA will enable the ICRF to begin a transition to the higher 33 GHz frequency. This will significantly reduce the reference-frame errors caused by propagation through the Earth's ionosphere and the intrinsic structure of the quasar radio sources.

ALMA's high site, with a stable atmosphere, a small synthesized beam on long baselines (10 milli-arcsecond at 1mm) and great sensitivity endow it with the ability to do excellent astrometry at sub-milli-arcsecond level. This is the amplitude of the astrometric wobble of a Solar System analog viewed at ten parsecs. With short observations spaced several months apart, the motion could be measured. For example, Pollux should be easily detected and its astrometric motion measured, providing solid constraints on the nature of its planetary system. Because of its great sensitivity at submillimeter wavelength, ALMA can detect directly the stellar thermal radiation for astrometric studies, and therefore not limited to a subset of stars with non-thermal emission. There are a number of masers in the ALMA spectral range that will be useful for astrometric studies.

High Energy Astrophysics
NRAO Facility: VLBA, GBT

The NASA Fermi Gamma-ray Space Telescope was launched in mid-2008, and its first gamma-ray source catalog was released in early 2009. This catalog will likely include several thousand active galactic nuclei (AGNs) by FY 2011 – 2012. The VLBA provides a key imaging capability lacking in gamma-ray telescopes, and is the only instrument that can regularly image the gamma-ray emitting regions of AGNs. Several key VLBA programs are in progress that are aimed at relating gamma-ray and radio emission under the hypothesis that imaged radio knots are the key particle-acceleration sites that also produce gamma rays. As the Fermi all-sky survey reaches an integration time of several years, many more weak AGNs, such as Seyfert galaxies, will likely be detected. These gamma-ray results should become available just as the VLBA achieves frequent observations at 2 Gbps and enables regular imaging of these radio-weak objects.

Fermi has been unexpectedly prolific in aiding the discovery of millisecond pulsars through the radio pulsar searches towards unidentified Fermi sources far off the Galactic plane. Point source detections made by Fermi will continue to be searched for pulsations using the GBT, which has already discovered more than 20 millisecond pulsars in these sources, several of which will be crucial for projects such as NANOGrav. Many of these milli-second pulsars are bright sources that can serve as timing sources in NANOGrav, and they will be targets of VLBA astrometry to determine their distances.

2.2 Origins

Deciphering the origin of the first stars, galaxies and black-holes, planetary systems and life itself all has to do with understanding the mechanisms of their formation from gas and dust. Radio astronomy techniques are essential to answering the questions involved because the spectral lines from ionized, atomic and molecular gas, and the dust emission in the regions of formation at high redshift fall within a range from meter-wave, such as the 21 cm HI emission line from the Dark Ages and Epoch of Reionization, to submillimeter-wave, from redshifted far-IR line and continuum emission from the first galaxies.

Centimeter through submillimeter wavelength observations play crucial roles in the studies of the molecular lines that probe the fuel for star formation in galaxies, the atomic fine structure lines that are the principal coolants for the interstellar medium gas in distant galaxies, the thermal dust continuum emission that is a key star formation rate estimator, and the radio synchrotron emission that measures star formation and signals the presence of relativistic jets. The "inverse-K" correction due to the shape of the far-IR radiation distribution and lines means that it is possible to detect the gas and dust in the first galaxies beyond $z \sim 10$ with the GBT and image them at sub-kpc resolution with ALMA and EVLA.

The origin of the Universe itself can be probed via the detailed studies of the cosmic microwave background and via the detection of gravitational waves from the inflationary era by pulsar timing.

NRAO provides the community with four major radio astronomy facilities with the requisite capabilities, and continues to develop forward-looking techniques and next generation experiments and facilities, to help understand our origins.

First Sources of Light and the End of the Cosmic Dark Ages
NRAO Facilities: ALMA, EVLA, GBT
Future Facilities: PAPER, HERA

NRAO is a leader in the study of cosmic reionization, and the preceding Dark Ages, through the HI 21cm line of neutral hydrogen. Reionization corresponds to the earliest epoch of galaxy formation, when the first stars and accreting black holes ionized the neutral IGM, and represents the last frontier in the study of cosmic structure formation. The HI 21cm line is widely recognized as the most direct and powerful method with which to probe this epoch, and the study of the HI 21cm signal from reionization was called out as one of the science areas with 'extraordinary discovery potential' by the NWNH survey.

NRAO is working closely with community groups to develop the hardware and observational techniques for the first generation pathfinder experiments. While the NRQZ served as a site for initial hardware testing of Precision Array to Probe the Epoch of Reionization (PAPER), senior members of the NRAO staff continue to be key scientific and technical participants to the PAPER project. The same NRAO staff also helped prepare the highly rated Hydrogen Epoch of Reionization Array (HERA) A2010 white paper, and are playing crucial roles in the deployment of the 128-element PAPER in South Africa. For a realization of the subsequent full HERA program, the NRAO will play a proactive and leading role in facilitating this next generation instrument through university and international partnerships.

In parallel, the GBT, ALMA and the EVLA will detect and map the atomic and molecular gas, and dust, in the first generation of galaxies within the epoch of reionization. A particularly exciting prospect is the use of the atomic fine structure lines to determine redshifts for the first galaxies ($z = 8$ to 10). Getting redshifts for candidate galaxies during cosmic reionization is extremely difficult in the near-IR, but should be straightforward with ALMA using the atomic fine structure lines.

Origin of Galaxies, Supermassive Black Holes, and Large Scale Structure

NRAO Facilities: ALMA, EVLA, GBT, VLBA

ALMA opens a new window on the cold universe, imaging the dust and cold gas that are the building blocks for stars, planetary systems, galaxies, and life itself. Complementary to ALMA, with a continuous frequency coverage between 1 and 50 GHz and a powerful new correlator, the EVLA has already demonstrated its capability to image the molecular gas around quasars at z~6.42. Astronomers will carry out high-resolution spectroscopic imaging, which is only possible with EVLA and ALMA for normal galaxies at high redshift, revealing galaxy dynamics and star formation on sub-kiloparsec scales. Using ALMA, astronomers will image the redshifted dust continuum emission from evolving galaxies at formation epochs as early as z ~ 10.

At the highest redshift, the atomic fine structure lines, the dominant coolant of interstellar gas, promise to revolutionize studies of the intersteller medium (ISM) in the first galaxies. These far-IR lines require space observations for nearby galaxies, but redshifted into the submm bands, they are accessible to ALMA for distant galaxies.

These observations will be an essential complement to the near-IR observations that will probe the stars and ionized gas, and the X-ray observations that will reveal the AGN. Together, next generation observatories operating from centimeter to X-ray wavelengths in the coming decade will provide the requisite panchromatic view of the processes involved in the origin of the first generation of galaxies, SMBHs and cosmic reionization.

The availability of bolometer arrays on the GBT has opened a discovery window into the properties of gas in galaxy clusters through high resolution measurement of the SZE. The GBT provides an unequaled combination of surface brightness sensitivity and high angular resolution for SZE measurements. The GBT SZE measurements, combined with X-ray data, will determine the cluster gas pressure and indicate the presence of shocks hidden from the imaging X-ray telescopes. The data will reveal evidence of past merger activity or ongoing subcluster mergers. The GBT is the most sensitive instrument in existence for such high-resolution SZE measurements and will provide extensive information on the merging history and processes of galaxy clusters, not easily accessible by other means.

Origin of Stars and Planets

NRAO Facilities: ALMA, EVLA, GBT, VLBA

The study of the origin of stars and planets is entering a new regime in which the stages of star and planetary formation will be observed directly, given the outstanding sensitivity and resolution of ALMA and the EVLA, instead of being based largely on theoretical modeling on the computer. ALMA will revolutionize the study of the dynamics of the whole collapse process in star formation, including the rate of accretion and infall from nascent molecular clouds, the mass distribution across such disks, and their molecular outflow structure and the dust-obscured protostellar accretion disks,

The beautiful proplyds, showing the dusty shadows of protoplanetary disks, as imaged in the optical, will be imaged directly to observe the actual processes of planets in formation. Astronomers will use ALMA to image the gas kinematics in protoplanetary disks around young solar-type stars at a resolution of AU scale out to ~ 150 pc, the distance of the Ophiuchus and Corona Australis star-forming regions. These ALMA images will enable detailed analyses of the physical, chemical and magnetic field structures in protoplanetary disks and detect directly the warm dust associated with forming Jupiter-like planets.

The EVLA will be crucial for probing the most optically thick inner regions of protoplanetary disks and is sensitive to large dust grains. The GBT will perform large-scale surveys for dark, protoplanetary disks, and study the composition of debris disks.

Recent astrometric observations of the low-mass star-forming regions in Taurus and Ophiuchus, and the high-mass star-forming region in Orion, have begun to chart the three-dimensional structure of these stellar nurseries. VLBA observations of weak continuum stellar radio emission from recently formed low-mass stars in Taurus have provided astrometric distances to 1% accuracy, and the ρ Ophiuchi molecular cloud has been found to consist of two star-forming regions along the same general line of sight but separated by as much as 40 pc. With the expansion of the VLBA bandwidth to a peak data rate of up to 4 Gbps, the number of stars accessible in these regions will be increased by a factor of 5 - 10, so that each region will have distances for 30 - 50 stars. These markers will provide the first 3-dimensional measurements of the distribution of star formation in Gould's Belt, and will also provide more accurate stellar masses for use in a host of applications. A higher sensitivity VLBA will detect exoplanets by their astrometric signatures on nearby radio-emitting pre-main-sequence stars.

There are many mysteries about star formation. It occurs on the scale of a solar system, but can be triggered by events at the scale of a galaxy, through density waves, tidal encounters, AGN activity, feedback from earlier star formation, and cloud collisions. Advances in our understanding of star formation require observations on all angular scales. The wide-area, high sensitive mapping capability of the GBT is an essential complement to the detailed high-resolution data provided by ALMA, the EVLA, and other interferometers. The GBT is ideally suited for measuring physical conditions in infrared-dark clouds, the likely progenitors of stellar clusters. Although thousands populate our Galaxy, their physical conditions and evolution are poorly understood. A 7-pixel GBT camera operating at 18 GHz to 26 GHz will be used to image and measure the temperature, density, turbulence, and kinematics of a large IDC sample, providing new quantitative insights into star formation and the initial conditions (interactions, shocks, self-gravity) that control dark cloud evolution.

The GBT will also extend molecular observations to nearby galaxies, providing critical information on the large-scale evolution of galactic systems. By measuring the properties of molecular clouds in galaxies, both nearby and distant, the GBT can also link large-scale processes with star formation in a necessary complement to local studies.

2.3 Understanding Cosmic Order

The dynamic interplay between stars and the interstellar medium, galaxies and quasars and the intergalactic medium, influences how stars and galaxies evolve and underlies the complex cosmic order.

The NWNH posed the following frontier science questions under this scientific theme:

- How do baryons cycle in and out of galaxies?
- What are the flows of matter and energy in the circum-galactic medium?
- What controls the mass-energy-chemical cycles within galaxies?
- How do black hole work and influence their surroundings?
- How do rotation and magnetic fields affect stars?
- How do massive stars end their lives?
- What are the progenitors of Type Ia SN and how do they explode?
- How diverse are planetary systems and can we identify the telltale signs of life on an exo-planet?

Again, many of the answers require radio observations enabled by NRAO facilities.

Evolution of Galaxies and Black Holes
NRAO Facilities: ALMA, GBT, EVLA, VLBA

The GBT and the EVLA provide imaging of the neutral gas around nearby galaxies, and the Milky Way, with unprecedented resolution and surface brightness sensitivity. The GBT mapping of the Magellanic Stream has already revealed crucial information about the recent evolution of the Galactic Neighborhood, and the study of high velocity clouds in our Galaxy and nearby galaxies, will revolutionize our understanding of the lifecycle of gas in and around galaxies, and how it relates to, and possibly drives, star formation. These telescopes will also explore the critical frequency regime between 30 GHz and 50 GHz, which is dominated by free-free emission from star forming galaxies.

ALMA, EVLA, and GBT will image nearby galaxies in CO, HCN, and numerous other molecular species to unlock the processes of star formation.

The chemical composition of star-forming gas in galaxies similar to the Milky Way will be traceable via molecular and atomic spectroscopic observations to $z \sim 3$ in less than 24 hours of observation. Scientists will quantify the kinematics of obscured galactic nuclei on spatial scales smaller than ~ 100 pc and assess the influence of chemical and isotopic gradients in galactic disks on the formation of spiral structure.

The EVLA in early science (see the ApJL special issue to be published in August 2011) is already revolutionizing studies of the molecular gas in distant galaxies, revealing the last major piece in the galaxy formation puzzle—the gaseous evolution of galaxies—in unprecedented detail. The ultra-wide bandwidth allows for blind surveys of molecular gas over substantial cosmic volumes, as well as direct redshift determinations for dusty, star-forming galaxies, otherwise impossible to obtain at optical wavelengths. The EVLA provides unprecedented resolution for studies of the gas distribution and dynamics, as well as probing the lower order transitions of critical mass determinants, for both the total (CO) and dense (e.g., HCN, HCO^+) molecular gas. The redshift ranges probed extend through the "epoch of galaxy assembly," when most of the stars in the Universe formed ($z \sim 1 – 3$), back to first light and cosmic re-ionization ($z > 6$). Simultaneously, the cool dust and free-free continuum emission will be observed with sufficient sensitivity to detect typical star forming galaxies, out to the epoch of galaxy assembly, in a single synthesis observation.

In the optical deep field studies of the universe, establishing the presence of AGN or supermassive black holes in the distant young galaxies has been a challenge, hampering the comparative study of the epochs of formation of black holes and galaxies. The new software correlator of the VLBA can now be configured to perform searches for compact radio sources over hundreds of galaxies in such deep fields within a 0.5-degree field of view simultaneously, which will make the important comparative study of the AGN and galaxy formation possible.

The numerous and diverse instruments on the GBT give insight into galaxies at all redshifts. By measuring the properties of hot gas in galaxy clusters via the SZE, to detect cold dust at high redshift, the GBT probes the evolution of gas and dust in the Universe on large scales across cosmic time. Measurements of nuclear black hole masses, with the GBT as a single instrument and as part of the High Sensitivity Array (HSA), contribute to the understanding of the role of mergers in galaxy evolution. Surveying the raw material of star formation in CO, HCN, and HI reveals the flow of baryons in and around galaxies and the processes by which galaxies evolve. The GBT will survey thousands of galaxies for their HI content, rotation, and mass. It can detect HI emission an order of magnitude fainter than any other telescope, revealing patterns of interaction and accretion in nearby systems.

Solar System, Stars and Exoplanets
NRAO Facilities: GBT, ALMA, EVLA
Future Facility: FASR

NRAO facilities play a major role in the study of the solar system. The development of a large field camera at 90 GHz at the GBT will, if funded, provide a unique tool that could transform cometary research. Comets contain primitive material from the Solar System's formation. Their study is critical to our understanding of problems from Solar System formation to the origin of life on Earth. Observing comets requires an instrument that can make rapid measurements with high angular resolution over a wide field of view and have high sensitivity to low surface-brightness lines. Researchers now depend on the occasional spectacular comet (e.g., Comet Hale-Bopp, C/1995 O1) to produce sufficient signal for the detection of numerous molecular species. A 90 GHz GBT camera would provide such capability for several comets per year, each detectable for ~ 3 – 4 weeks. In parallel, ALMA will greatly expand our knowledge of the Solar System by providing unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs and Kuiper-belt objects, along with images of the planets and their satellites. The GBT is also a fundamental component of bi-static radar studies of solar system objects including Mercury, Venus and Europa.

ALMA will be able to detect and study stellar photospheres throughout the Hertzsprung-Russell diagram, and it will resolve the photospheres and chromospheres of giant and supergiant stars within a few hundred parsecs. ALMA will also provide new solar physics insights as it images active solar regions and enables the study of particle acceleration physics on the Sun's surface.

Continuum observations at tens of gigahertz will enable dramatic new studies of stars. One exciting possibility is imaging the photospheres of known red supergiant stars. The EVLA will have the sensitivity and resolution (~ 1 μJy rms at 40 mas resolution) to image the photospheres of stars such as Betelgeuse in unprecedented detail. Such observations reveal the physical processes (quiescent thermal brightness temperatures and active regions) in stellar photospheres on scales approaching the optical photosphere.

The field of extrasolar planets is entering a new age with the discovery of hundreds of planets. ALMA will make substantial contributions to the observations of extra solar planetary systems at all evolutionary stages. Multi-wavelength imaging over wide fields will identify regions of planet formation. These can then be investigated over broad bandwidths to identify the molecular and dust characteristics of the natal disk. High spatial (hundredths of an arcsecond or better) and spectral resolution (~1km/s) can resolve kinematics of planet-forming disks. With very high spatial resolution, astrometry (to tenths of milli-arcseconds) can reveal the presence of planets about many nearby stars, through active regions on late type stars or thermal emission from a cross-section of stars of any spectral type. Furthermore, rotation of many disks may be directly observed.

The VLBA has initiated a long-term program to assess a nearby dwarf star sample for compact radio emission of sufficient strength and duration to enable careful position measurements over several years. These observations will be used to search for the reflex motions of giant planets orbiting the target stars. More than a thousand hours are being devoted to this pilot program. It will be followed by a more extensive long-term project once the VLBA sensitivity upgrade has been completed and a much larger sample of stars is detectable.

Life
NRAO Facilities: GBT, ALMA, EVLA

How did life arise on Earth? This question is as old as humanity, and the answer will require research across many fields, from biology and chemistry, to physics and astronomy. The GBT has had a leading role in this research, detecting many new organic molecules in space through its ability to measure weak, spatially extended spectral lines over a wide range of frequencies. It will become an increasingly important facility as its capabilities are extended into the lower part of the 3mm band, outside the current ALMA coverage and in a region of the spectrum where no large telescopes operates.

Interstellar molecular clouds are host to chemical reactions that occur under conditions of temperature and density not accessible in terrestrial laboratories. Studies of chemistry in clouds give fundamental information on the nature of the chemical bond in gases and on surfaces, over time scales not achievable on Earth. The GBT will measure interstellar chemical processes and their variation throughout the Milky Way, determine the characteristics of pre-biotic chemistry in star-forming regions, and study the components necessary for the formation of life. Such observations may shed light on the provocative question of the connection, if any, between organic chemistry in space and life on Earth. With wide-field cameras, the GBT will allow rapid imaging of cometary molecules, revealing the content of the building materials of the Solar System.

The chemistry of life on Earth most likely originated in the protosolar nebula, and analogous chemical processes may be observable in interstellar clouds around the Galaxy. More than 160 molecules have already been identified in interstellar and circumstellar sources. Many of these are complex species of ten or more atoms, and they include biologically significant molecules such as formic acid (HCOOH), acetic acid (CH_3COOH), ethylene glycol ($HOCH_2CH_2OH$), and the simplest member of the sugar family, glycolaldehyde (CH_2OHCHO). The complexity of interstellar chemistry and the existence of plausible delivery mechanisms such as comets and meteorites suggest that some part of pre-biotic chemistry on the early Earth and similar planets occur in interstellar and proto-solar gas clouds.

NRAO has the perfect suite of telescopes to pursue this fundamental area of research, the first step of astrobiology. The GBT has sensitivity both to molecular cores and extended emission fields, and the frequency agility to cover the rich molecular bands from centimeter through 3 millimeter wavelength. It is the most capable instrument for initial identification and characterization of sources and species in these wavebands. The high resolution imaging afforded by the EVLA and ALMA allow detailed astrochemical studies of the emission distribution of various molecules, while lowering the "spectral confusion" of observations. Such images show how the gas temperature varies across a proto-planetary region. Ices containing complex molecules survive the throes of planetary formation in cold distant reaches of proto-planetary systems, and are delivered to formed planets via orbital disruption and planetary impact. Large scale variations in chemistry may lend different characters in proto-planetary systems in diverse parts of the parent molecular cloud. Such differences may lead, in turn, to different chemistry on the surface layers of inner planets. This fosters planetary diversity as well as variation in general proto-planetary disk properties and evolution, in the environment and in the dynamics of the new planetary systems.

Collectively, NRAO's new generation of instruments are poised to unlock key processes of this earliest phase of astrobiology. The GBT/EVLA/ALMA synergy is essential for this science, with the interferometers providing spatial resolution and the GBT wide-field imaging and added sensitivity to diffuse emission.

2.4 Frontiers of Knowledge

The NWNH report describes the following high priority science questions under the broad theme "Frontiers of Knowledge":

- Why is the Universe accelerating?
- What is dark matter?
- What are the properties of neutrinos?
- What controls the masses, spins, and radii of compact stellar remnants?

This theme and these science questions address how new, fundamental physics, chemistry and biology can be revealed by astronomical measurements, experiments, and theory and advance the frontiers of human knowledge. Key science relevant to this theme includes the nature of inflation, the accelerating Universe, the nature of dark matter, neutrinos, the nature of compact objects and probes of relativity, and the chemistry of the Universe. The astronomy community will probe and make progress on these frontiers of knowledge using modern, multi-wavelength research programs that will include state-of-the-art radio wavelength observations acquired at NRAO telescopes. The following sections provide a detailed description of the scientific impact of the NRAO facilities on two of these science questions: the accelerating (expansion of the) Universe, and the nature of compact objects and probes of relativity.

The Accelerating (expansion of the) Universe
NRAO Facilities: GBT, VLBA, EVLA

A precise determination of the Hubble Constant, H_0, allows for a new, robust and independent constraint on the equation of state of dark energy and other cosmological parameters, complementing other precision cosmology programs, such as Planck and the Joint Dark Energy Mission. Such a measurement is possible using H_2O mega-maser disks around SMBHs in galactic nuclei at distances where the Hubble flow dominates the peculiar motions. Reaching the 1% goal entails a search for H_2O masers in $>10^4$ galaxies out to $z \sim 0.06$ using large single-dish centimeter-wavelength telescopes - principally the GBT. A resulting sample of order 100 sources is expected with properties adequate for follow-up with very long baseline interferometry and time-series spectroscopy to measure centripetal accelerations, from which the angular diameter distances to the host galaxy can be derived to obtain an accurate determination of H_0. This study requires intercontinental 22 GHz VLBI arrays with sensitive telescopes (VLBA, GBT, EVLA, Effelsberg, Large Millimeter Telescope, and the new Shanghai Astronomical Observatory 65m telescope). The NRAO development program will greatly enhance the GBT's ability to perform this science. This is described in detail within Chapters 4 and 5.

Because of its collecting area and appropriate resolution, the GBT is being used to study the large scale structure of the Universe at $z \sim 1$ through the novel technique of 'intensity mapping.' This technique entails observing the integrated HI 21cm emission from distant galaxies on Mpc scales, thereby bypassing the need to detect individual galaxies (which is currently impossible at $z \sim 1$). The initial results demonstrate the viability of the technique, provide the measurement of the mean HI mass in optically selected galaxies at $z \sim 1$, and point the way to performing large scale structure studies using this technique. A key goal will be to map the Baryon Acoustic Oscillations (BAO), echoes of sound waves from the Big Bang, at intermediate redshifts, thereby constraining the acceleration rate of the Universe, and the equation of state of Dark Energy, w(z). An important practical advantage of the intensity mapping approach to BAO is it avoids the great cost involved in detecting HI from galaxies at high redshift.

The intensity mapping approach can also be applied to detecting carbon monoxide (CO) emission from high redeshift star forming galaxies using the GBT. While the main impetus is to detect the BAO signature, the GBT observations will also provide unique information regarding the neutral hydrogen and carbon monoxide within the regions observed: the former is a tracer of star formation potential, the latter of star formation activity. NRAO will support further exploration of the technique at the GBT using multi-pixel phased-array receivers via collaborations with the University of Massachusetts and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan, and foster university collaboration with the goal of a dedicated facility for Intensity Mapping.

The Nature of Compact Objects and Probes of Relativity

NRAO Facility: GBT

Neutron stars, and their radio incarnations as pulsars, have been laboratories for testing strong gravity and other exotic physics since their initial discovery over 40 years ago. The GBT is widely considered the world's best pulsar telescope due to its ability to see 85% of the sky and its impressive instantaneous sensitivity. Over the next decade, the GBT has the potential to measure for the first time higher order relativistic effects from the double pulsar, leading to a determination of the neutron star moment of inertia. In addition, ultra-high-precision timing observations of previously known millisecond pulsars—such as resulted in the recent measurement of a two solar mass neutron star—as well as of a fraction of the dozens of new systems the GBT has uncovered over the past five years, will reveal exotic systems whose masses challenge nuclear physics or whose orbital characteristics allow tests of gravity in much stronger gravitational regimes than are possible here in the Solar System. A prime example of the latter will occur when the GBT—the best telescope for this project in the world, given the requirements for high frequencies (10-20 GHz) and high sensitivity—finds the first pulsars in human-timescale orbits around the super-massive black hole Sgr A* in the center of our Galaxy. The periodic signals from such pulsars will provide unique probes of the space-time, plasma, and dark matter around the central black hole.

In the coming years, the GBT's sensitivity will also be exploited to make the most sensitive search yet for pulsars around the black hole at the Galactic Center. The periodic signals from any detected pulsars will provide unique probes of the space-time, plasma, and dark matter around the central black hole. Precise timing of radio pulsars by the GBT can be used as well to derive information on the nature of matter at the highest densities, densities that exceed those of atomic nuclei and which cannot be studied in any other fashion. Finally, measurements of atomic and molecular lines at high redshift will continue to place stringent limits on possible temporal variation of fundamental physical constants in early epochs of the Universe.

3. Optimizing Science Impact: Observatory Science Operations

Enabling astronomers to conduct forefront research by using the NRAO telescopes effectively and efficiently is the Observatory Mission. Observatory Science Operations (OSO) facilitates coordinated access to NRAO facilities, expands access to new users, enhances services provided to users to enable their scientific objectives, and maximizes operational efficiencies across the Observatory. This 'One Observatory' approach provides uniform user support and takes advantage of the collected expertise across the NRAO to support efficient use of all facilities, shares resources across telescopes whenever practical and cost effective, and leverages new or improved support capabilities planned for one telescope for the rest of the Observatory, while minimizing duplication of effort.

Such economies of scale and improvements in shared user services are possible due to the largely common nature of the NRAO facilities: three are interferometric arrays of radio telescopes (ALMA/EVLA/VLBA) and one single-dish radio telescope (GBT), all using very similar hardware and software technologies for heterodyne detection, signal processing and transmission, requiring essentially the same calibration, data and image processing and archive solutions.

All user support activities are carried out by staff at three science centers within the NRAO - the North American ALMA Science Center (NAASC) in Charlottesville, the Array Science Center (ASC) in Socorro (which covers both the EVLA and VLBA), and Green Bank Science Operations Center (GBSO) for the GBT, but closely coordinated under OSO. The impact of this approach has already been felt in the user support activities for the early science efforts of ALMA and EVLA.

The integrated efforts that OSO will provide to and on behalf of the scientific community, and our plans to enhance OSO services into FY 2013-2017, are described below. They fall into three categories: (1) Shared Services, (2) Facility-based Activities, and (3) Training the Next Generation.

3.1 Shared Services

In the timeframe of this LRP, EVLA and ALMA will enter full science operations. This provides exciting opportunities to continue integrating and cross-training staff at the NAASC, ASC and GBSO and to leverage operational efficiencies and provide robust user support.

The services described in this section are site-based OSO deliverables coordinated across the science centers. Many staff at all three sites cross-train between sites and instruments to maximize operational flexibility and enhance user support. For example, a large fraction of ASC staff use the EVLA and VLBA for their science, and are able to support users of both facilities.

The services operate under Observatory-wide standards and include User Support (User Portal and Helpdesk), Data Services (Data Archives and Virtual Astronomy Observatory [VAO]-related functions), Post-processing Software, and Science Support Software. OSO also maintains user metrics and statistics. OSO strives to make NRAO telescopes accessible to all astronomers, regardless of radio-wavelength expertise, working with the scientific community to engage and assist new users, especially early career scientists, while also providing direct access to detailed technical material for expert users.

Our development plans follow for the User Portal, Helpdesk, Proposal Handling, User Support, Science Community Outreach, Archival Access & Storage, Virtual Astronomical Observatory, and Metrics and Statistics.

User Portal

NRAO maintains two User Portals: one that provides access to applications supporting NRAO's northern facilities, and one to provide access to information and applications supporting the international ALMA project. A goal during the period of this plan is to provide NRAO users with integrated access to these two portals.

The EVLA, GBT, and VLBA share access via a single portal (https://my.nrao.edu). Once signed on users can configure their preferences, access proposal and observation preparation tools, determine the status of on-going projects, and obtain information on observing and technical support, data services, and access to the data archive.

The ALMA Science Portal (http://almascience.org) is an internationally organized portal with instances maintained at each of the ALMA Regional Centers (ARCs) in Europe, Japan and North America. (The North American ARC is nested within the NAASC.) The ALMA science portal "look and feel" is standardized between the three regions, and includes web content that is common across the project as well as single-sign-on registration for access to the ALMA Observing Tool, Helpdesk, and Project Tracker and the ALMA archive.

While the ALMA Science Portal must remain distinct due to the international nature of ALMA, NRAO will develop a common interface from which users can access information across all of its facilities. To accomplish this goal, a global single sign-on for NRAO-ALMA users will be developed. In this system, a registered ALMA user will automatically be an authenticated NRAO user and vice-versa. The planning needed to realize these goals is well underway and will be implemented by the time ALMA enters full science operations in early FY 2014.

Helpdesk

The NRAO operates and maintains two Helpdesks – one supporting NRAO's northern facilities, and another supporting the international ALMA project. Both helpdesks use the Kayako system, a commercial knowledge-base solution that was selected owing to its success at the Herschel and Spitzer data centers. Both helpdesks support Observing Preparation, Proposal Submission, Proposal Review, Archive Access, Data Processing, and Observer Support. The helpdesks s are staffed NRAO-wide, so tickets are answered by NRAO support staff with the best knowledge, regardless of facility.

During FY 2013-2017, the NRAO will develop an integrated helpdesk interface for both users and NRAO support staff and will institute a common NRAO-wide triage process. The Frequently Asked Questions (FAQ) and "knowledge base" repository of the Helpdesk will be combined so solutions to user queries will be suggested spanning all four facilities considerably improving the efficiency of user support.

Proposal Handling

The NRAO organizes a semi-annual proposal evaluation process that includes unified support for proposal preparation, proposal management and review, and time allocation for the GBT, VLBA, and EVLA. Eight Science Review Panels (SRPs), each composed of members of the scientific community, conduct proposal reviews. The Chairs of each SRP comprise the Time Allocation Committee (TAC), which makes recommendations for proposal time allocation and scheduling priorities to the NRAO Director. In addition, the TAC makes recommendations for large proposals (those requesting 200+ hours of telescope time) and Key Science Projects.

The ALMA proposal evaluation process, while closely aligned with the proposal evaluation process used for the North American facilities, is lead by the Joint ALMA Observatory (JAO) in concert with our international partners. OSO will work with the JAO on implementing a plan to ensure that users will be able to apply for joint observations between facilities before ALMA reaches full science operations at the beginning of FY 2014.

OSO staffing for these efforts includes software support for the Proposal Submission Tool (PST) plus scientific assistance to provide user support for proposal preparation, technical assessment of all proposals, and administration of the peer review processes.

User Support

OSO will communicate NRAO capabilities and community opportunities via our established training programs, including the bi-annual NRAO-National Astronomy and Ionosphere Center (NAIC) Single Dish Summer School and NRAO Synthesis Imaging School. The successful North American ALMA Science Center Community Day training model will be extended Observatory-wide, incorporating EVLA, GBT, and VLBA content and training. OSO will design and repackage the face-to-face tutorials and training to also be available as customizable on-line, on-demand programs. OSO will oversee the development of user training materials for instrument and technique-specific workshops, observation preparation, data reduction/analysis, online and live demos, and online courses and teaching materials. Some of these materials will apply to multiple NRAO facilities; others will be specific to a site or instrument. OSO will track quantitative metrics of program effectiveness, user community size, and diversity. Periodic surveys of the user community will be conducted in consultation with the NRAO Users Committee and other advisory committees to assess the effectiveness of our training program.

An important component of NRAO user interaction is dedicated face-to-face support to users traveling to any of NRAO's facilities for data reduction visits. Support is provided both for investigators and students associated with successful projects. OSO coordinates logistic support for these visits, and the cross training of staff over the FY 2013-2017 timeframe will ensure that users will receive the necessary support at whichever site they wish to visit.

Science Community Outreach

The Communications team works with OSO scientific staff and management to enable timely, accurate, two-way communication with astronomers and the broader scientific community about NRAO research opportunities, priorities, plans, and accomplishments. These communications seek to maximize our community's understanding of and access to research opportunities with NRAO telescopes while also enabling the Observatory to understand and meaningfully respond to the community's needs and interests. One of our challenges and priorities is to make NRAO telescopes accessible to all astronomers, regardless of radio-wavelength expertise. NRAO works to develop the community through the engagement and assisting of new users, especially early career scientists.

Face-to-face communication is the richest, and taking full advantage of the communication opportunities offered by major scientific meetings is vital. The semi-annual American Astronomical Society (AAS) meetings will be NRAO's highest priority face-to-face communication opportunities, and multiple events at each AAS meeting will be organized to serve users. A Town Hall will broadly inform the membership about the status of our science, operations, and projects, and allow us to field and answer many user questions. One or more topical Special Sessions at each AAS meeting will convey the latest science results and our evolving research capabilities. An increasing number and variety of community tutorials and training sessions will be offered as AAS Splinter Sessions, covering topics such as proposal preparation, observing strategies, instrument-specific techniques, data reduction and analysis. The NRAO exhibit at AAS meetings provides a welcoming space for members to informally visit and interact with our scientific staff. To communicate with the broader science community, the NRAO will organize one or more science symposia at venues such as the Annual Meeting of the American Association for the Advancement of Science, the largest science meeting in North America; the annual International Conference for High Performance Computing, Networking, Storage and Analysis; and the tri-annual International Astronomical Union General Assembly.

Effective development, operation, and maintenance of the NRAO Internet site for the science community—http://science.nrao.edu—will always be a priority. As Internet technologies evolve, the NRAO will determine the most effective communication methods for our users and will implement technologies into our Internet environment that improve two-way communication between and among our users and staff. NRAO will create more flexible forums for on-line communication between and among our staff and the broad community of users. Our science Internet content management system will evolve to offer more flexible, adaptable workflows with improved security and extensibility. OSO will also create and manage documentation appropriate to the science web, including observer "cookbooks," user manuals, and expert documents.

Archival Access and Storage

Archives for EVLA and VLBA will be readily accessible to the community by FY 2014, along with products from the new GBT spectrometer and selected surveys. Due to the diversity of instrumentation and observing modes, community access to a validated set of historical GBT data products will be completed prior to FY 2017. For ALMA, each ARC will maintain a mirror copy of the archive. The ALMA project will deliver an archive interface that is common across the international project. OSO will provide an integrated interface to archives across to all four instruments – GBT, VLBA, ELVA, ALMA that leverages technology developed for the Virtual Observatory. These archives will contain a complete copy of all observational data and pipeline products.

A challenge to OSO is the fact that NRAO telescopes will produce science data volumes of the 10s-100s of terabytes. By FY2014 each of the three facilities will need storage capacities in the petabyte range. To enable long-term storage and access to these data, NRAO is continuing to establish external partnerships in pivotal areas of technology. NRAO will leverage commodity storage with the Next Generation Archive System (NGAS) developed by ALMA and will be an active participant in high-performance computing forums such as the annual TeraGrid, ADASS and SuperComputing conferences.

Virtual Astronomical Observatory

The VAO will make it easy for researchers to connect large data sets with high performance computational resources to aid analysis, and detect and visualize hidden patterns. It provides the data discovery, access, and an integration framework that enables researchers to navigate through this daunting sea of information.

OSO will provide scientific and technical support for comprehensive NRAO participation in, and data availability through, the VAO. The NRAO archive will be accessible via the VAO, including access to large radio data cubes, and integration of NRAO data analysis. OSO programmers and data analysts will participate in standards development and prototyping.

NRAO will collaborate with the NSF Office of Cyberinfrastructure and the VAO to develop the capability to visualize and manipulate massive datasets. This capability will facilitate the overlay of simulation with observations which will in turn provide a way to validate theoretical models.

Metrics and Statistics

OSO will generate Observatory-wide metrics and statistics tracking the use and effectiveness of its facilities (GBT, VLBA, EVLA, and ALMA), covering proposals, observations, visiting users, remote users, community support programs, and bibliometrics. This activity includes generation of routine reports, generation of on-demand special reports, database development, report generation software, quarterly reports, annual reports, and other documentation.

3.2 Facility-based Activities

Facility-based OSO activities are specific to a telescope science center. These activities operate under Observatory-wide standards and include Pipeline Processing, Data Processing, and High Performance Computing.

Pipeline Processing

Pipeline processing is the automatic data reduction provided by the NRAO to our users. Individual pipeline heuristics (rules for processing of data) will be in place by FY 2013 for each of GBT, VLBA, EVLA, and ALMA. Pipeline data processing for EVLA and ALMA will be conducted to ensure uniform data quality analysis, aimed at producing "reference" images that can be delivered to PIs along with calibrated visibility datasets by leveraging high performance computing resources. A key focus for the GBT will be the completion of data reduction pipeline for 90% of GBT observations. GBT instruments will be integrated into a data reduction pipeline that will allow users to readily reduce their GBT data. The GBT pipeline will also take advantage of improved calibration algorithms available across NRAO and information to provide higher quality data products to all GBT users. The NRAO pipeline team will develop and test new algorithms and heuristics, and reprocess user data when necessary to diagnose problems with default/reference images or enhance the quality of the data products. These efforts will be leveraged by the ALMA pipeline development effort.

Data Processing

The Common Astronomy Software Applications (CASA) data reduction package for ALMA and EVLA will be further developed to incorporate new calibration and imaging algorithms, and to ensure that the full capabilities and sensitivities of all NRAO telescopes are realized. VLBI-related functionality and a single-dish data reduction path for the GBT will also be developed.

Increasing data processing resources will be made available to NRAO users during the time frame of this plan, including the CASA software platform, pipeline processing, and high performance computing. The NRAO will continue to develop databases of importance to observers, such as *Splatalogue*, the spectral line database. *Splatalogue* will be expanded to support observers of all NRAO telescopes, and new spectral line data will be incorporated as they become available.

High Performance Computing

The objective of high performance computing at the NRAO is to realize the full scientific capacity of every NRAO instrument, and enable our users to access, visualize, and analyze the full complexity of every dataset. The NRAO will provide access to high performance computing platforms sufficient to process ALMA, EVLA, and GBT data, and will also provide advice and guidance to assist the user community in defining and implementing computing resources at their home institutions.

Over the timeframe of this plan, OSO will review how the community is making use of these resources and consolidate/optimize them as needed. The NRAO will take a leadership role in defining methodologies for managing, analyzing and visualizing multi-Terabyte datasets. The NRAO will adopt and evolve existing software tools from other data-intensive disciplines and make them available to the user community via the NRAO science web.

Data capture and processing development will focus on the problems presented by the current and next generation of radio telescopes and arrays. High priority will be given to maximize the use of parallel processing when possible. This will provide acceptable processing capability for pipelines and for interactive use of the large datasets that will be produced by the EVLA and ALMA. Strategies for a full data center, with clusters for data reprocessing or with NRAO data stored on national supercomputing centers, will be evolved. Capabilities and tools will be developed for interdisciplinary discovery across the electromagnetic spectrum and observing platforms; and for users to access, interact with, and analyze observed and archived data.

The NAASC, EVLA, and GBT already have a number of post-processing computing clusters. These clusters have been designed to be the same to minimize maintenance overhead and to enable common interfaces for users. At the ASC, the cluster will be used for pipeline processing, batch reprocessing by users, and interactive reprocessing, primarily for the EVLA. For ALMA the pipeline processing is carried out in Chile, so its cluster will be more focused on batch reprocessing, interactive reprocessing of data, and testing new heuristics.

VLBA Resident Shared-Risk Observing Program

The NRAO RSRO program will invite users desiring early access to new capabilities (e.g., increased bandwidth, new receivers, and new software capabilities) to work with NRAO staff for two months or more to help with development and/or commissioning. This program can include observing modes that NRAO staff is not planning to develop themselves but which are natural extensions of the VLBA infrastructure (such as spectroscopic single dish observing). Large observing programs (those granted several hundred hours or more) will come with some residency requirement that would guarantee maximal scientific effectiveness and minimal operations overhead.

3.3 Training the Next Generation

The Observatory works with the university community to train the next generation of astronomers. NRAO funds an integrated suite of community support and development programs and resources through OSO, with interfaces to the science centers (GBSO, ASC, and the NAASC), the Office of Science and Academic Affairs (OSAA) and Education and Public Outreach (EPO). OSO programs focus on undergraduate and graduate students affiliated with external institutions, with members of the NRAO scientific staff serving as mentors and/or supervisors. Postdoctoral programs are administered through OSAA as described below. These programs are coordinated between OSO, OSAA, and the science centers. A variety of creative education and outreach activities involving K-12 students are conducted by NRAO's EPO department, as described in Chapter 6.

Given the constrained budgetary environment, however, difficult cuts have been instituted in FY 2012 that will recur through the FY 2013-2017 period covered by this plan. They were chosen to minimize the impact on the Observatory training mission while enabling other OSO priorities to advance to ensure the overall success of the Observatory science mission.

Student Programs

The NRAO is pursuing a broad range of student activities including undergraduate, graduate, and post-graduate programs; instrument and visitor programs to enhance university-NRAO collaborations; and workshops, schools, and conferences.

Undergraduate Programs

The successful NRAO summer student program was founded in 1959. This 10–12 week program allows approximately 25 students per year to work under the supervision of the NRAO staff members in New Mexico, West Virginia, and Virginia, carrying out original research in astronomy, computing, and engineering. The NSF Research Experience for Undergraduates (REU) program funds most of these students. Outstanding students that are otherwise ineligible for REU program support—graduating seniors, foreign students, and early-career graduate students—are supported by NRAO operating funds. The NRAO also runs 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 non-consecutive semesters. With NRAO technical staff supervision, co-op students are engaged in problems on the technological frontier. On average, three students per semester are funded through NRAO operations.

Graduate Programs

Graduating seniors, and first- and second-year graduate students, are also able to participate in the NRAO summer-student program. 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 Pre-doctoral Fellowships to students who have completed institutional requirements for doctoral candidacy so that only their thesis research remains for them to complete their Ph.D. Such fellows reside at an NRAO site, typically for two years, while they complete their research and thesis under the supervision of a member of the scientific staff.

In addition to graduate summer students and resident pre-doctoral fellows, more than 100 Ph.D. students make observations with NRAO telescopes each year. Travel reimbursement, low-cost accommodations, and computing facilities are provided on-site to assist these students during stays of one to three weeks. The Observatory also supports stays of 3 – 6 months by students who wish to collaborate with NRAO staff scientists as part of their Ph.D. research. These internships help forge valuable long-term links between the NRAO and the university community.

Financial support is also available for students performing thesis observations that use NRAO facilities. Students at U.S. universities associated with successful proposals on any of NRAO's telescopes are eligible for the Student Observing Support program, which covers salary and miscellaneous expenses such as computers and travel to a maximum of $35,000 per year.

Postdoctoral Programs

Administered through OSAA, the prestigious Jansky Postdoctoral Fellowship Program remains one of the top Astronomy postdoctoral fellowship programs in the world. Jansky Fellows carry out investigations independently or in collaboration with others. In addition to astrophysics research, the

NRAO encourages work on radio astronomy instrumentation, computation, and theory. The appointments are made for two-year terms that can be extended for a third year. Approximately half of these fellows are in residence at the NRAO; the remainders are non-resident Fellows hosted by U.S. universities or research institutes. Resident fellows are encouraged to spend time at universities working with collaborators, while non-residents are encouraged to make frequent and/or long-term visits to NRAO sites.

In addition to the Jansky Fellows, the Observatory supports the NRAO Postdoctoral Fellows. These are similar to Jansky Fellowships, but NRAO Fellows have up to half-time responsibility for Observatory facilities operation and support. The NRAO continues to develop a mentoring program for Jansky Fellows and NRAO Postdoctoral Fellows to ensure their future professional and scientific success.

NRAO Community Interaction and Support

Beyond educating and training future generations of radio users through its undergraduate, graduate, and post-graduate programs, NRAO assists and supports an active U.S. radio astronomy community. This is accomplished via staff community service, a modest visitors program, organizing and hosting scientific meetings, and providing funding assistance to university-led hardware and software projects. These activities are coordinated through OSO.

NRAO scientific and engineering staff serve on advisory committees and review panels, serve as AAS Officers and on its committees, teach university courses, serve as editors and referees for professional journals, and present colloquia and invited talks at international meetings. This interaction is further enhanced through NRAO-organized scientific meetings and workshops through which all scientists have an opportunity to discuss the current direction of astronomical research and the state of instrumentation and techniques. The Observatory also supports visits by visiting faculty, scientists, and engineers to NRAO sites so that they may interact with Observatory staff. The length of such visits is flexible, ranging from weeks (summer research) to months (sabbaticals).

These interactions keep NRAO scientists engaged in the wider astronomical community and act as an important conduit through which the community can maintain a fruitful relationship with the Observatory. A key benefit of these programs is that they allow for community-wide input into Observatory priorities for science, instrumentation, and algorithm development.

NRAO supports a number of university-based instrumentation development programs, such as those underway at the GBT and the Coordinated Development Laboratory. These programs create training opportunities for students and postdocs, as well as the opportunity to develop science and technology pathfinder instruments.

NRAO Library

The NRAO Library collections and library support functions are key research assets for the astronomical community and the NRAO scientific, computing, engineering, and education/outreach staff. The Library's primary mission is to provide research support for the explorations of scientists, engineers, students, and visitors in the field of astronomy and the information needs of all NRAO staff. The Library has the most extensive collection of radio astronomy materials in the world, requiring that this collection be maintained. In addition to maintaining this important and unique collection, the Library must manage the increasing demand for current and digital materials. This is accomplished through electronic access, with more than 300 periodical titles and over 3000 book titles available online, and the cataloguing, scanning, and posting of all NRAO publications.

The NRAO Library is motivated by the needs of its users. Our librarians strive for easy availability of current and historical information for scientists and engineers, while providing the ability to readily identify and locate NRAO holdings and publications. To ensure full access to all periodicals across the NRAO, electronic subscriptions are uniformly available across all sites. The NRAO Library continues to add to its already extensive collection of electronic books.

4. Engines of Exploration: Observatory Telescope Operations

The five-year period covered by this LRP, FY 2013-2017, will be a time of great scientific opportunity for the NRAO user community, founded on the operations of its forefront facilities. The NRAO will complete construction and commissioning for two new major research facilities—ALMA and EVLA—that will be the centimeter to submillimeter wavelength, complements to next-generation facilities at other wavelengths. Taken together, ALMA, EVLA, the GBT with focal plane arrays, and the upgraded VLBA represent an order of magnitude or more improvement in all areas of observational capabilities, including resolution, sensitivity, and spectral capabilities, from 1 GHz to 1 THz. These engines of exploration provide unprecedented advances for the astronomical community.

At the same time, ensuring all the telescope facilities are operated at their optimum performance level is a big job, constituting more than half of the Observatory budget and personnel. The suite of NRAO telescope facilities involves the daily operation of 38 telescopes, located in 9 States and 1 Territory in the US and 60 telescopes in Chile. A few more telescopes are used periodically for special projects and for education purposes.

During the full science operations phase, the research facilities are led by three Assistant Directors, one for GBT based in Green Bank WV, one for both EVLA and VLBA based in Socorro, NM, and one for ALMA based in Charlottesville, VA. Each Assistant Director is responsible for overseeing the associated science center, the telescope operations, research, development, and construction projects for each facility. As ALMA is an international joint facility, and the North American ALMA community includes those of US, Canada and Taiwan, the role of the Assistant Director for ALMA operations within NRAO is more complex and is explained further below. These Assistant Directors set operational priorities for their facility within the context of Observatory-wide operations.

4.1 Atacama Large Millimeter/submillimeter Array

Overview

The NRAO ALMA Operations includes (1) the North American share of the array operations in Chile, which is the primary responsibility of the Joint ALMA Observatory (JAO), (2) NA ALMA Science Center that is the portal to ALMA for the NA astronomy community, coordinated across the three partner regions by the JAO, (3) ALMA (off-site) repair and maintenance, and (4) oversight of the ALMA development of the future hardware and software items.

The Assistant Director for NRAO ALMA Operations is responsible for the activities listed above, except for item (1), and clearly has to work closely with the JAO, as well as the counterparts in the other Executives, to ensure ALMA as a whole functions smoothly as a joint facility. Furthermore, the Assistant Director is responsible for the entire NA ALMA community.

During the transition to operations, some staff employed in the construction phase in Chile, Charlottesville, and Socorro will transition to similar operations duties, while others will move on to different responsibilities at the NRAO or elsewhere.

Table 4.1 summarizes the ALMA capabilities that will be offered to the community for Early Science beginning in FY 2012, and for Full Science operations beginning in FY 2014.

Table 4.1: ALMA Performance Summary

Band #	3	4	5	6	7	8	9	10
Frequency Range (GHz)	84 - 116	125 - 163	163 - 211	211 - 275	275 - 373	385 - 500	602 - 720	787 - 950
Wavelength Range (mm)	3.57 - 2.59	2.40 - 1.84	1.84 - 1.42	1.42 - 1.09	1.09 - 0.80	0.78 - 0.60	0.50 - 0.42	0.38 - 0.32

	Array Completion
Antennas	At least 54 x 12m & 12 x 7m
Bands	Bands 3, 4, 6, 7, 8, 9 & 10
Maximum Bandwidth	16 GHz (2 pol x 8 GHz)
Correlator Configurations	71 configs (0.01-40 km/s)
Maximum Angular Resolution	0.02" (λ /1 mm)(10 km/max baseline)
Maximum Baseline	15 km
Continuum Sensitivity (60 sec, Bands 3 – 9)	~ 0.05 – 1 mJy/beam
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 – 9)	~ 7 – 62 mJy/beam

Operations

The ALMA array in Chile is operated on behalf of the international partnership by the JAO. The four departments of the JAO are Science Operations, Engineering, Computing and Administration. NRAO has an international obligation to maintain and repair the hardware and software delivered by North America during the construction project and used in ALMA operations.

The Department of Science Operations at the JAO is responsible for operating the array, managing the international science program including running the proposal, allocation, and scheduling processes, and handling the pipelining and archiving of the data. The interface between the user-facing aspects of JAO Science Operations and the NRAO OSO is the North American ALMA Science Center (see Chapter 3). The interface between the telescope-facing aspects of JAO Science Operations and NRAO is the North American ALMA Regional Center (a sub-division within the NAASC).

The North American ARC carries out many tasks directly supporting the JAO in its day-to-day operations by sending staff to Chile to participate as members of the JAO operations team. Duties in Chile include astronomer-on-duty shifts, data quality assurance, support for data processing and pipelining of user data, and commissioning & science verification of new capabilities and modes. The NA ARC also supports telescope operations in Chile via participation in the international management team: the Science Operations International Project Team. These activities are coordinated by the NRAO for the North American community through OSO.

The JAO Department of Engineering provides system engineering and manages engineering of the buildings, telescopes, instruments, and other general maintenance engineering needs. The interface between the JAO Engineering and NRAO Observatory Development & Programs is the NRAO Coordinated Development Lab (see Section 5.1).

The JAO Department of Computing manages software engineering, networks, database administration and general IT support for the JAO. The interface between the JAO Computing and NRAO is through both NRAO Computing and Information Systems (Chapter 7) and the Offsite Maintenance element of the North American ALMA Operations.

Offsite Hardware and Software Maintenance and Development

Software support will be carried out by personnel who wrote the software systems and transferred to the North American ALMA Operations from the construction phase North American Computing IPT. The maintenance areas include the following.

- Monitor and Control, including Correlator
- Dynamic Scheduling infrastructure
- Scheduling software
- ALMA Common Software
- Integration and Testing & Software Engineering

Personnel who transferred from the construction project Front End and Back End IPTs will carry out hardware support. Front End and Local Oscillator (LO) deliverables will be supported by staff at the NRAO Coordinated Development Laboratory (CDL) in Charlottesville. Support for Back End deliverables will be provided by a group in Socorro. Band-3 cartridge maintenance will likely be contracted to the Canadian developers. The maintenance areas include the following.

- Cold cartridges: replacing superconductor-insulator-superconductor (SIS) mixers, low-noise amplifiers (LNAs), frequency multipliers; reassembling and re-testing.
- Warm cartridge LO assemblies: replacing warm multiplier assemblies with monolithic microwave integrated circuits (MMICs) upon failure, phase-lock-loop components, power amplifiers; reassembling and re-testing.
- Board-level troubleshooting and repair of all types: power distribution, monitor & control, etc.
- All photonic LO system parts.
- All digitization and digital data transmission system parts.

ALMA Development Program

Having invested ~$1.3B to build ALMA, the biggest advance ever in ground-based astronomy, it is vital to plan to keep the facility upgraded to maintain and expand its capabilities so that it remains state-of-the-art over its projected 30-plus year lifetime. The ALMA Operations Plan envisaged an ongoing program of development and upgrade, a program endorsed by external review committees in 2007 and again in 2010. NWNH highlighted support for an ALMA Development program. The RMS panel noted particularly that although six of ten bands are included in the first light complement, adding additional receiver bands is "important for obtaining complete wavelength coverage within atmospheric windows, which is especially needed for line studies of galaxies over the full range of redshifts." The panel also highlighted the importance of providing VLBI capability to ALMA.

Both the science advisory committees of the ALMA Board and those of the regional executives have endorsed taking advantage of the rapid progress of electronic technology to provide new hardware and software components and subsystems offering improved performance and higher reliability. The Executives are issuing calls to their communities for studies of projects to be completed over the next year. These studies are expected to provide a suite of projects from which to select particularly compelling ones for incorporation into the development program. In North America, a workshop was held at NRAO in March to solicit ideas for the studies. Talks from community members detailed the science cases for the remaining receiver bands, for the higher resolution studies enabled by the addition of VLBI capability, and even for green energy sources for ALMA. It is expected that study proposals will be submitted, externally reviewed and begun in FY 2011 with the studies conducted and delivered in

FY 2012; development projects would commence in FY 2013. This cycle repeats approximately biannually, with new study calls generating new proposals from the community for further consideration. The aim of this process is to ensure that ALMA development mirrors the scientific priorities of the user community and keeps up with the latest scientific goals. The technical staff at the NRAO has expressed significant interest in these projects.

4.2 Expanded Very Large Array

Overview

By the beginning of calendar year 2013, the EVLA Construction Project will have successfully concluded, on time and on budget, delivering the following capabilities:

- All VLA telescopes retrofitted to the EVLA design.
- All EVLA electronics modules installed, including the high-speed samplers that will deliver up to 8 GHz instantaneous bandwidth.
- Continuous frequency coverage from 1 to 50 GHz, provided by 8 receivers.
- A new correlator with a suite of "standard" configurations fully commissioned and available to the community, including spectroscopic modes with up to 4.2 million channels, flexible tuning of 64 independent spectral windows, planetary and solar modes, multiple sub-arrays, phased array, and short correlator dump times ("burst mode").
- A complete suite of monitor/control software and science support software, to support full operations with dynamic scheduling, and all necessary user-facing tools.

The beginning of 2013 also marks the beginning of full EVLA science operations. At this time the array will be in its most compact D-configuration, providing up to 8 GHz instantaneous bandwidth—a factor of 80 increase over the VLA. Table 4.2 summarizes the capabilities to be offered to the community in 2013, in comparison to those of the VLA.

Table 4.2: EVLA-VLA Performance Comparison

Parameter	EVLA	VLA	Ratio
Continuum sensitivity	1 μJy beam^{-1}	10μJy beam^{-1}	10
Max. bandwidth per polarization	8 GHz	0.1 GHz	80
Frequency channels at max. bandwidth	16384	16	1024
Max. frequency channels	4194304	512	8092
Coarsest frequency resolution	2 MHz	50 MHz	25
Finest frequency resolution	0.12 Hz	381 Hz	3180
Full polarization spectral windows	64	2	32
Log(fractional frequency coverage, 1 – 50 GHz)	100%	22%	5

The dataset sizes that will be delivered by the EVLA will exceed those of the VLA by three orders of magnitude, and the way in which the community interacts with their EVLA data will be considerably different from the recent VLA past. By the end of the planning period the goal is for the EVLA to provide end-to-end data products comprising raw and pipeline-calibrated visibilities, and reference images for each spectral window, for data acquired in standard observing modes. Data reduction and analysis software, and a post-processing computer cluster, will be available for users for the re-processing of data at the beginning of full EVLA operations.

Additional software development in FY 2013 and following will concentrate on enabling advanced WIDAR observing modes that lie beyond the capabilities delivered under the EVLA construction project, such as pulsar gating. The success of the Resident Shared Risk Observing program to date makes it likely that this program will continue into EVLA operations, engaging experts from the astronomical community to assist with the delivery of specialized capabilities.

Operations

Following the completion of EVLA construction, operations will initially focus on the maintenance of the array infrastructure. Most activities relating to the operation, maintenance, and repair of the EVLA and VLBA will be carried out by groups responsible for both telescopes. The locally managed operation of these two instruments in tandem results in economies of scale and increased efficiency. The reductions in telescope operations funding at the EVLA expected in FY 2013 in order to meet budget plans will have an impact on operations and maintenance, with fewer staff available to carry out the programs. This may, in turn, affect telescope reliability and resultant science through-put. Efforts will be made to minimize any downtime increases through efficiencies to the extent possible.

Mitigation of radio frequency interference for the EVLA: RFI is a particular problem for the EVLA, 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 EVLA can operate for astronomy. The development of algorithms and tools for identification and excision of such signals from astronomical data is a high priority for the EVLA and CASA. On the timescale of this LRP it is expected that the flagging of RFI-affected data can be automated and incorporated into the EVLA's online system.

Maintenance Plans and Schedules

The EVLA maintenance plan is based on more than 30 years of VLA operations and maintenance experience, and wherever possible, is closely interwoven with the comparable service cycles for the VLBA to minimize costs and maximize efficiency. The expected lifetime of the EVLA is 20+ years, and the current age of its predominant components—the telescopes are more than 30 years old—means that effective preventive maintenance is vital for protecting this investment. As noted above, budget reductions in FY 2013 will slow the maintenance cycle which may have an impact on reliability. NRAO will mitigate these risks as appropriate.

The facility Assistant Director maintains a full list of infrastructure and operations requirements that is prioritized by site and Observatory-wide to ensure that the highest priorities activities are funded.

Telescopes: Traditionally NRAO has conducted periodic inspection and overhaul cycles in which telescopes are individually cycled in and out of the array every ~6–7 weeks. Thus, every 3.5 years, each of the 28 telescopes will be thoroughly overhauled as part of a continuously repeating cycle. Each telescope overhaul includes structural inspections, mechanical, electrical, and electronic systems upgrades, touch-up structural painting, and the repair and replacement of parts as needed. In FY 2013 and following, the time between overhauls will increase due to the projected reduction in Engineering Services Division staffing. Maintenance and repair of the EVLA receivers will also be slowed down by the projected reduction in Electronics Division staffing.

Track: The EVLA railroad tracks must be inspected continuously to assure safe travel by the maintenance vehicles (used daily by technicians to service telescopes) and the transporters that carry the telescopes 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 a plan was developed to replace approximately 5000 ties per year through 2022. This plan was developed with the assistance of a railroad maintenance consultant and is being followed on average, with priority areas receiving first attention. EVLA maintenance specialists believe that the overall condition of the track is fair, and does not pose a safety hazard to telescopes or equipment.

Execution of the EVLA track plan has varied over the years with available funding. However, in FY 2010, funding for approximately 3–5 years of rail ties, ballast and hardware was obtained from NSF under the American Recovery and Reinvestment Act stimulus bill (ARRA). This should make it possible to stabilize the raw material acquisition and replacement processes at least through FY 2013.

Correlator: The EVLA correlator will require routine yearly maintenance on its HVAC (heating, ventilating, and air conditioning), fire suppression, and dedicated UPS systems. The level of maintenance and repair for the EVLA correlator boards, racks, fans, power supplies, and other parts will be carefully assessed and quantified through FY 2015; it is expected to exceed the maintenance and servicing required for the VLA correlator.

EVLA Developments

Most of the development work for the EVLA within this plan focuses on ensuring the most effective delivery of EVLA science, and in particular, the new algorithms and software needed to provide thermal noise limited, full polarization, full primary beam imaging at all EVLA operating frequencies. Note that in many cases the algorithms and data processing platforms needed for the EVLA are similar to those required by other radio interferometers around the world (e.g., ALMA and the Netherlands astronomical foundation ASTRON's Low Frequency Array (LOFAR)), and that many of these instruments are working closely with, and relying on, NRAO staff to solve many of the computing challenges that lie ahead in this area.

Major proposed EVLA enhancements that could broaden the EVLA capabilities even more are being reviewed as part of the annual NRAO prioritization process but are currently not funded under this plan.

4.3 Green Bank Telescope

Overview

The 100-meter GBT is the world's premiere single-dish radio telescope operating at meter to millimeter wavelengths. Its enormous (2 acre) collecting area, unblocked aperture, and active surface accuracy provide superb sensitivity and spectral stability across the telescope's full 0.1 - 116 GHz operating range (with 35% efficiency at 90 GHz). The GBT is fully steerable, and 85% of the entire celestial sphere is accessible to it. Its operation is highly efficient, and it is used for astronomy approximately 6500 hours every year. Part of the scientific strength of the GBT is its flexibility and ease of use, allowing for rapid response to new scientific ideas. It is scheduled dynamically to match project needs to the available weather. The GBT is also readily reconfigured with new and experimental hardware, adopting the best technology for any scientific pursuit. It sets the scientific and technical standards that new telescopes in the rest of the world aim to achieve or surpass.

With comparable collecting area and sensitivity to ALMA and EVLA, the GBT is the wide-field complement to the high angular resolution interferometers. Facilities in Green Bank are also used for other scientific research, as well as for an extensive array of programs in education and public outreach, and for the training scientific and engineering students and teachers.

Table 4.3: GBT Performance Summary

RECEIVER BANDS

Band	P	L	S	C	X	Ku
Frequency Range (GHz)	0.29 - 1.2	1.2 - 1.7	1.7 - 2.6	4.0 - 8.0	8.0 - 10	12 - 18
Wavelength Range (cm)	102 - 25	25 - 17	17 - 12	7 - 3.7	3.7 - 3.0	2.5 - 1.7
Resolution (arcmin)	25	10	5.8	2.5	1.4	0.9
Number of beams	1	1	1	1	1	2
Continuum Mapping Sensitivity (mJy rms on deg² in 12 hr	0.10	0.14	0.29	0.60	1.61	1.31
Extragalactic Continuum Confusion Level (mJy rms)	590	50	12	1.2	0.25	0.09
Spectral Line Sensitivity (mJy in 12 hrs, 300 km/s resolutic	0.04	0.04	0.02	0.02	0.02	0.02

Band	K	Ka	Q	W	MUSTANG2	W*
Frequency Range (GHz)	18 - 28	26 - 40	38 - 50	68 - 92	82 - 98	82 - 116
Wavelength Range (cm)	1.7 - 1.1	1.2 - 0.8	0.8 - 0.6	0.4 - 0.3	0.4 - 0.3	0.4 - 0.3
Resolution (arcmin)	0.53	0.37	0.27	0.17	0.17	0.17
Number of beams	7	2	2	2	160	100
Continuum Mapping Sensitivity (mJy rms on deg² in 12 hr	1.77	0.53	4.8	N/A	0.10	N/A
Extragalactic Continuum Confusion Level (mJy rms)	0.02	<0.01	<0.01	N/A	<0.01	N/A
Spectral Line Sensitivity (mJy in 12 hrs, 300 km/s resolutic	0.02	0.04	0.06	0.07	N/A	0.07

Reflector: 100-m fully steerable reflector; largest steerable telescope, largest telescope working at mm wavelengths
Telescope Performance: 70% aperture efficiency at 15 GHz; 35% aperture efficiency at 90 GHz
Tracking: 1-2" pointing accuracy across 85% of celestial sphere (-46° to +90)
Scheduling: Dynamically scheduled to match science requirements with weather conditions
Signal Processing: High time and spectral resolution systems with full polarization information; Instantaneous bandwidth from 0.1 - 10 GHz

Operations

A wide variety of activities fall within general operations all of which are necessary to maintain the safety and integrity of the site—its telescopes, buildings, and visitor facilities. Maintenance within these areas include all site buildings, roads, vehicles, wells and the site septic system, maintenance and inspection of the site water tank, regular monitoring of all site water systems, monitoring and inspection of site wastewater systems, repair and maintenance of all HVAC systems, within both the buildings and the site telescopes, and field cutback and mowing on site for fire protection. Green Bank operations are also responsible for maintaining the radio frequency integrity of the site and for administering the NRQZ.

Mitigation of radio frequency interference for the GBT: Cosmic radio signals are easily masked or confused by man-made interference. For example a cellular telephone on Mars would produce a signal on Earth stronger than most astronomical sources studied with the GBT. The GBT is located within two RFI protection zones—the NRQZ and the WVRAZ. Together these provide protection against sources of terrestrial interference, a protection which is administered by staff at the Green Bank site.

The NRQZ was established in 1958 to minimize possible harmful interference to NRAO's Green Bank telescopes and the radio receiving facilities at the Navy Information Operations Command in Sugar Grove, WV. The NRQZ encloses a land area of approximately 13,000 square miles near the state border between Virginia and West Virginia and protects both sites from all fixed radio transmitters licensed by the Federal Communications Commission (FCC). The WVRAZ is a 10 mile radius region around the GBT within which the telescope is protected from harmful man-made radio transmissions.

Together these two zones provide the GBT and other site telescope with an unprecedented view into the radio spectrum. These radio quiet zones allow scientists to make the new and oftentimes unexpected discoveries which often provide the most fundamental understanding of the Universe.

Working with our colleagues at the Navy Information and Operations Command in Sugar Grove, WV, NRAO staff in Green Bank administers all FCC applications within the 13,000 square miles of the radio quiet zone, working with transmitting applicants to find a solution for their needs which does not interfere with our ability to obtain excellent, unpolluted, radio astronomy data. Similarly, NRAO staff monitor the WVRAZ around the GBT, looking for potentially harmful interference and working with the community to find solutions for their needs that do not interfere with GBT observations.

Maintenance Plans and Schedules

The GBT is a large and complex structure, with over 2000 actuated surface panels and 16 million pounds of moving weight. Structural painting is performed annually, structural inspections on a two-to-three year cycle, and preventive maintenance is performed weekly. NRAO expects that the budget reductions planned for FY 2013 will have an impact on operational up-time for both electronics and maintenance: tasks take longer to complete with fewer staff, and there are fewer staff to respond to unexpected faults. Efforts will be made to minimize any downtime increases through efficiencies and dynamic scheduling to the extent possible.

Operations Upgrades: The majority of the work in GBT operations across the FY 2013-2017 period will be routine and preventive maintenance of the GBT. However there will be a small number of improvements made to ensure the telescope performance remains optimal throughout this period.

Replacement of software libraries for GBT: This work consists of two main activities. (1) NRAO is standardizing on 64-bit architecture for Linux computers and upgrading to a 64-bit Red Hat Enterprise operating system. The GBT monitor and control (M&C) system must also be ported to 64-bit consistent with Computing and Information Services' (CIS) timeline for 64-bit standardization. (2) The GBT M&C system is currently using an out of date Python version. An upgraded version is required in order to leverage a number of library bug fixes, gain access to advanced language features, and facilitate integrations of third party libraries that require a more recent Python version.

Replacement of the actuators on the GBT's secondary mirror: The age of the actuators on the GBT's secondary mirror require the replacement of those actuators in the FY 2012-FY 2013 timescale to ensure continued accuracy of the GBT's pointing and focus.

Monitor and Control Software upgrade: The data analysis programs for the GBT M&C system are limited to gathering data from the Flexible Image Transport System (FITS) files written during an observation. This method of interprocess communication through files is not scalable to the ever increasing data volumes. An upgrade to our data system will make data available directly from the software responsible for data acquisition, allowing observers significantly improved efficiencies while paving the way for improvements to allow massive datasets (100 terabytes or more) to be processed.

Installation of multi-frequency Tipping Radiometer: A multi-frequency tipper will provide overall improvements for GBT observers, both directly (through calibration efficiency measurements) and indirectly (through improved performance within Precision Telescope Control System (PTCS) and Dynamic Scheduling). In FY 2012 the instrument would be set up for use in expert mode only, allowing the local staff to monitor both the information received and use it to better understand the overall weather at the GBT and the performance and scheduling of the GBT in light of the measured weather conditions. Once understood, NRAO will produce a plan to incorporate the information obtained into the existing observing infrastructure, from scheduling and telescope performance through data calibration.

GBT Receiver Room Upgrades study: There are more receivers than can be fit into the current GBT receiver room. As a result there is significantly decreased scheduling flexibility and severe limitations on projects that can be run concurrently. The GBT is also in need of space for tertiary optics and improved mounting for high frequency receivers. Finally, it is possible improvements can be made in the overall optics at high (and low) frequencies with an upgrade. In FY 2012 NRAO will undertake a study to determine possible upgrade plans for the receiver room, both their cost and their scientific benefit, which will then be evaluated to determine the best path forward for the GBT. This may result in a number of changes and improvements to the existing receiver room.

GBT Development

The GBT was designed to readily allow upgrades and changes to all aspects of its hardware and software. A specialty (or principle investigator (PI)-driven) instrument can be installed on the telescope with relative ease, making it feasible for an individual or group of researchers to outfit the telescope to meet their particular science goals. The GBT also has a vigorous development program in collaboration with college and university groups to take advantage of the latest technology and provide our user community with a constantly improving facility.

As outlined below, optimizing the path forward for new discoveries with the GBT is built upon the collaborative development of new instruments which will open new scientific capabilities. All new instrumentation and development for the GBT is built in collaboration with research groups at universities and colleges throughout the country. This not only leverages efforts of Observatory staff and supports university faculty, it provides a valuable training ground for students to become future instrument builders. The program has been highly successful both in training excellent scientists and engineers and in providing the instruments necessary to provide the best possible scientific results from the site telescopes.

During this LRP timeframe, existing development projects will come to a natural close, and new development for GBT will be initiated if ranked scientifically highly enough in the Observatory-wide prioritization process to meet the constrained budget. While NRAO will continue to develop focal plane arrays for the GBT, the efforts will increasingly depend on collaborations with university and other institutional groups in the US and abroad.

Digital Signal Processing: With existing funding from the NSF Advanced Technologies and Instrumentation (ATI) program the Configurable Instrument Collaboration for Agile Data Acquisition (CICADA) collaboration is building a new backend for the GBT to replace the existing GBT spectrometer and spectral processor, instruments based on technology more than 20 years old. The new backend will provide vastly improved dynamic range, higher time resolution (for off-line RFI excision and rapid maps), and greatly improved observations of multiple lines through the ability to create high frequency resolution sub-bands across a 1.4 GHz bandwidth, modes crucial for the GBT's exciting astrochemistry studies. The instrument will permit the GBT's focal plane array instruments to reach their full science potential by providing significantly increased bandwidth for the individual feeds. The instrument will also provide an instantaneous 10 GHz bandwidth vital for both detection of highly redshifted lines such as CO and also for the search for millisecond pulsars in the center of the Milky Way.

Camera development: The camera development program is a collaboration with more than 20 university, college, and industry groups. The first prototype instruments in this program are already on the GBT—a 64-pixel transition edge sensor (TES) bolometer array (81-98 GHz) and a 7-pixel 18-26 GHz traditional focal plane array. Under the guidance budget, the camera development program will continue primarily through work at the university groups with some additional effort gained through NRAO's Coordinated Development Laboratory. As the research development progresses, prototype systems will be placed on the GBT. The first three of these instruments will include a 200 MHz bandwidth cooled phased array feed in the 1-2 GHz range, an 8-pixel 82-116 GHz prototype integrated feed horn system, and a 100-pixel bolometer array using Microwave Kinetic Inductance Detectors (MKID) technology. Delivery of these instruments is expected before FY 2016 if funding allows.

Optimized Single/Dual Pixel Feeds: In addition to cameras, is it important to develop receiver systems optimized to a given science case which can be rapidly put into operation on the GBT. Currently there are three such instruments in development—a 4mm two-pixel receiver for molecular line and VLBA studies, a wide-bandwidth receiver spanning from 0.5 to 3 GHz optimized for pulsar timing for NANOGrav, the long-term gravitational wave detection project, and a broadband receiver covering 12-18 GHz for the detection and study of pulsars in the Galactic Center. All three instruments should be completed within the time frame of this plan.

Software, Algorithm Development, and High Performance Computing: The NRAO will continue to work with University and other research groups around the world to develop and test new concepts in data intensive computing. The first of these initiatives will be to work with the Hierarchical Data Format (HDF) community to explore and develop new high density data files formats. NRAO will also be working with a number of university and national laboratories to test new visualization software developed for large datasets. By the end of this period it is anticipated the GBT will be readily able to store, visualize, and analyzed datasets of 50-100 TB in size. Research and funding efforts for this will be led from outside the NRAO.

4.4 Very Long Baseline Array

Overview

The VLBA is the foremost instrument in the world for precision astrometry, capable of sub-10 μarcsec accuracy measurements. During FY 2013-2017 the array will use these astrometric capabilities to continue delineating the structure of the Milky Way via measurements of maser parallaxes in massive star-forming regions, providing unprecedented insight into our Galaxy's structure. The VLBA, in conjunction with the phased EVLA as part of the High Sensitivity Array, will begin to focus on maser astrometry in M31. Measuring the 3-dimensional velocity and rotational parallax of M31 will resolve the largest outstanding unknowns in the dynamical evolution of the Local Group. The VLBA will also be used to chart the three dimensional structure of the stellar nurseries in Orion and Ophiuchus, and will be used with the GBT in the Megamaser Cosmology project to measure H_o and to make a direct measure of the central black hole mass of the AGNs in the galaxy sample.

Movies of maser motions in the disks and jets of protostars, and in the envelopes of evolved stars, will reveal the dynamics of stellar formation and evolution. Movies of jet ejection from AGN will elucidate the role of supermassive black holes in galaxy dynamics and evolution, as well as the coupling of the jet formation process with very high energy outburst events. The expanded tuning range of the VLBA will enable water megamasers to be used as probes of dark energy and the Hubble Constant over a much larger range in redshift than has previously been possible.

The time available for astronomy on the VLBA will be substantially devoted to large, key-science projects that will employ the array's unique, high-resolution capabilities. Several of these highly significant scientific programs will be carried out in conjunction with partners who will contribute to VLBA operations and upgrades funding.

Table 4.4: VLBA Performance Summary

Receiver Bank Designation [cm]	Nominal Frequency Range [GHz]	Baseline Sensitivity [mJy]	Image Sensitivity [μJy/beam]
90	0.312 - 0.342	29	196
50	0.596 - 0.626	81	553
21	1.35 - 1.75	1.9	18
18	1.35 - 1.75	2.0	19
13	2.15 - 2.35	2.1	20
6	3.9 - 7.9	1.4	13
4	8.0 - 8.8	2.0	19
2	12.0 - 15.4	3.6	34
1	21.7 - 24.1	2.9	28
0.7	41.0 - 45.0	13	90
0.3	80.0 - 96.0	52	447

Baseline sensitivity = rms noise on a single VLBA baseline

Image sensitivity = 8 hour integration

Operations

Since the 2006 NSF Senior Review, the NRAO has been working diligently on securing non-NSF funding partners for VLBA operations. Several agreements on providing non-NSF funding of the VLBA operations have been signed. The USNO will provide $1M/yr for 5 years starting FY2012 towards operating costs in exchange for daily 1.5 hour observations using the Mauna Kea and Pie Town telescopes for rapid determination of UT1-UTC, a parameter describing the spin phase of the earth required for maintenance of the GPS reference frame. One agreement recently signed with the Shanghai Astronomical Observatory will initially yield $100k/yr with the intention of increasing that to at least $200k/yr. Other 5-year contributions yet to be concluded include those from the Max Planck Institute for Radio Astronomy (MPIfR), the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taipei, National Astronomical Observatory of Japan (NAOJ), and CSIRO Astronomy and Space Science (CASS) in Australia. The contributing institutions are "subscriber" institutions and will be accorded top priority in the VLBA operations.

The VLBA is now operating with minimal staff, reflecting the necessities of a limited budget. NRAO is maximizing scientific potential at the expense of ease of use: the VLBA is primarily an expert facility and gives first priority to the subscriber institutions. Thus, daily USNO observations preempt astronomical observing. However, the impact on the traditional user community is expected to be minor, but NRAO will work with our affected users to minimize the impact of such operations on their science. In addition, the NRAO is developing staff exchanges with the subscriber institutions as an effective way to augment the scientific staffing needed to optimize the operation of the VLBA.

Mitigation of radio frequency interference for the VLBA: RFI is less of an issue for the VLBA compared with other NRAO facilities because the RFI environment is typically local to the individual stations, and does not correlate from one telescope to another. Thus the main effect of interference is to increase the noise at the frequencies of the interference, unless the RFI is particularly strong and makes the receiver amplifiers become non-linear in their responses.

Maintenance Plans and Schedules

VLBA maintenance plans and schedules are based on 15+ years of NRAO experience in operating the instrument. Wherever possible, maintenance activities will continue to be closely interwoven with comparable EVLA service cycles to minimize costs and maximize efficiency.

Traditionally, three VLBA telescopes are scheduled for a major maintenance overhaul each year, usually between April and September. This may be reduced to two per year in FY 2013 due to budget reductions, probably resulting in decreased reliability and increased telescope downtime. An expert team of 2-3 telescope mechanics, a servo technician, an engineer, the VLBA site technical supervisor, and the two resident site technicians conduct each major maintenance visit. The cycle currently repeats approximately every three years, which will increase to four years in FY 2013 and following, with the Pie Town, NM station serviced as time and resources become available outside of the schedule. These maintenance visits include azimuth wheel assembly and elevation bearing replacement when needed, upgrades to mechanical and electronic equipment, repair to azimuth tracks, and other key maintenance. Routine preventive maintenance and repairs to each site's mechanical, electrical, HVAC, servo, cryogenic, and Local Oscillator and Intermediate Frequency (LO/IF) systems are conducted daily by the two site techs.

The Saint Croix, Hancock, and North Liberty stations require additional maintenance owing to their exposure to corrosive and/or severe weather environments. These stations require more frequent structural painting, azimuth track repair, replacement of deteriorating subreflectors and dichroic panels, and the replacement of rusting stairways and ramps.

VLBA Developments

The continued prominence of the VLBA will require ongoing upgrades to offer enhanced and new capabilities and to ensure maintainability. The philosophy used in planning VLBA upgrades is to lean heavily on commercial off-the-shelf (COTS) computing hardware and to make extensive use of EVLA hardware and infrastructure. These will have the combined effect of minimizing operating and maintenance costs and providing future upgrade paths with minimal engineering overhead.

The VLBA is adopting the monitor and control software from the EVLA. The ongoing bandwidth and receiver upgrade projects are funding the initial deployment of this new software system. The legacy monitor and control system and the aging computers on which it runs will be completely replaced within the timeframe of this Plan. This combined EVLA and VLBA infrastructure reduces maintenance costs and provides an ideal base from which to pursue development work for future arrays.

An ongoing bandwidth expansion project is nearing a major milestone of doubling the continuum sensitivity by increasing the system bandwidth by a factor of 4 to 256 MHz of bandwidth per polarization (MHz/pol), to give a data rate of 2 Gbps. It is hoped that an extension of this to 512 MHz/pol (4 Gbps) or better will be available within the timeframe of this LRP through improvements in data recorder technology.

Increasing data rates to 4 Gbps would be a natural extension to the 2 Gbps capability already achieved and will require relatively small improvements. Deployment of 4 Gbps recorder technology will require down-selection from two viable options followed by production and integration at a cost of approximately $250k. Full time recording at this peak rate will require a doubling of the media (hard drives) used to transport data to the correlator at a cost today of $750k but with an expected decrease in cost by a factor of two every two years. While funds for this effort have not yet been identified, it is of high enough priority to expect ODP resources to complete this upgrade well before FY 2017 begins.

One of the most highly ranked projects in a cross-observatory prioritization process is the design of a new pulse calibration (PCAL) generator. The PCAL system on the VLBA is designed around semiconductor devices that are no longer available; NRAO is expected to have difficulty maintaining these systems. New techniques using digital techniques would lead both to better maintainability and increased flexibility. This development project is expected to be completed by NRAO by the end of FY 2013.

5. Towards Future Discoveries: Observatory Development and Programs

Astronomical science advances through the iterative interplay between theory and empirical data, and calls for ever-increasing powers of observation. It cannot be predicted what the precise status of today's most compelling scientific questions—or, indeed, of questions emerging from the next-generation optical/infrared observatories such as James Webb Space Telescope (JWST), LSST, and European Extremely Large Telescope (EELT) as they come on line—will be as the third decade of the millennium dawns. However, it can be predicted with high confidence that in addressing them, we will be pressing current radio/millimeter tools beyond their existing limits.

Continued development of the hardware and software required to advance observational capabilities enables future discoveries. A forward-looking Observatory-wide R&D program that is aligned with the recommendations of NWNH and in partnership with other institutions and groups in the US and international community will be conducted under Observatory Development and Programs (ODP). The goals are: (1) continually developing critical capabilities for upgrading all the NRAO facilities and for next generation facilities; (2) helping the community to realize mid-scale projects recommended by NWNH; (3) identifying and pursuing collaborations that lead to new scientific initiative, advancements in the state-of-the art technology, as well as possible additional funding opportunities.

The Coordinated Development Laboratory (CDL) is now organized to deploy the Observatory-wide expertise and resources in order to spearhead and coordinate all development efforts, preferably in partnership with university groups, to implement goals (1) and (2) above, and the New Initiatives Office (NIO) is charged to form new science and technology partnerships with U.S. and international groups, to reach goal (3) above.

NRAO staff from all NRAO sites work on projects in a way that best matches technical capability to project requirements, regardless of the geographic location of the individuals involved. There is an established process for introducing and evaluating new technical concepts and allowing fair internal competition for resources, based on scientific merit. This process includes an annual review of all current and proposed new development proposals. Each project submits a brief proposal that is scientifically and technically reviewed through a process overseen by the Observatory Science and Technical Council. The resulting prioritized list is submitted to the NRAO Users Committee for review and comment, and the NRAO Director provides the final strategic guidance. Once the review and prioritization process is complete, projects are considered for execution based on priority and the available budget, as part of the annual Budget Summit of NRAO senior administrative staff.

Some projects have relatively short (1-2 year) timescales and are primarily connected with a specific NRAO instrument. These projects are funded and executed through the specific facility, as already described in the “Developments” overviews in Chapter 4 of this report. Other projects have longer timescales, and broad applicability to a wide variety of projects and applications, in support of the long-term scientific goals as outlined above. These are executed under the auspices of the Coordinated Development Laboratory or the New Initiatives Office as appropriate, and are described below.

In short, ODP aims to evolve critical capabilities for all the NRAO facilities and to help realize the next generation facilities and experiments for advancing capabilities for future discoveries, an NRAO function that is as important as operating the existing facilities.

5.1 Coordinated Development Laboratory (CDL)

The crucial research and development of radio astronomy technologies necessary for the future advances of astronomy and for maintaining the state-of-the-art of technologies for the near term requirements of the NRAO mission are carried out in the CDL.

Specifically, the scope of the CDL focuses on hardware development and includes the following:

- Coordinate engineering R&D activities across all NRAO sites.
- Manage the process by which new concepts are selected for further consideration, and relative priorities are set between new and existing project areas.
- Perform basic engineering R&D activities to advance the state of the art of the technologies needed to support the Observatory's mission.
- Perform initial R&D and prototyping activities required to proceed from initial concept to executable project.
- Assist with EVLA, GBT and VLBA infrastructural and telescope-specific projects.
- Assist with key engineering activities for other New Initiatives.
- Perform ALMA development design studies and execute ALMA development work.
- Undertake ALMA maintenance activities that are synergistic with ALMA development work and the core engineering competencies of the CDL.
- Perform essential maintenance activities for NRAO telescopes and other institutes, where these activities are synergistic with the core engineering competencies of the CDL.

CDL activities are driven by the need to address the highest priority science questions, following closely the recommendations of NWNH.

The specific research areas addressed by the CDL currently planned over the timescale of the LRP are described below. However, the long-term research directions at the CDL (and therefore specific projects) will be reviewed periodically and, if necessary, redirected.

Phased Array Feed Development

Radio astronomy receivers are approaching a fundamental limit in sensitivity so other methods for increasing the efficiency of a radio telescope must be sought, and one of those ways is greater use of the focal plane, i.e., radio cameras. Just adding more conventional feed horns at the focal plane under-samples the focal plane by about a factor of 16 because of the physical size of the feeds, and the farther the feed is from the telescope axis the less efficient it becomes. A focal plane phased array feed (PAF) can electronically synthesize multiple, simultaneous beams on the sky for complete coverage of the field of view without loss of sensitivity in each beam. However, a substantial amount of signal processing is required to form each PAF beam and phased arrays need considerably more development work to achieve system temperatures comparable to the best single-beam and conventional horn arrays.

Scientifically, an efficient, high-speed radio camera will facilitate high-sensitivity mapping of large areas of the sky to detect low-surface-brightness neutral hydrogen in the outer reaches of our own galaxy and in nearby groups of external galaxies. A phased array feed will also enable more efficient surveys for new and exotic pulsars that will be laboratories for the study of extreme physics in the interiors of neutron stars and in the high-intensity electric and magnetic fields surrounding these rapidly rotating objects. Similarly, the emerging field of radio transients is expected to uncover new and exciting science. This field depends heavily on much higher survey speeds and sky coverage that will be enabled by phased array feeds.

The NRAO has a long-standing collaboration with Brigham Young University (BYU), via NSF funding, on RFI mitigation and phased array feeds. The BYU-NRAO team has successfully demonstrated high-efficiency beam forming with both uncooled and cryogenic 19-element arrays on the 20-meter Telescope in Green Bank. The current prototyping instruments are 19-element, dual polarization uncooled and cryogenic arrays in the 1.3-1.7 GHz frequency range targeted toward spectral line and pulsar science. This development includes a prototype digital data link between the GBT receiver room and the GB lab, development of a low-profile receiver module that will digitize the signals at the array receiver box, and development of beam-forming firmware for the Center for Astronomical Signal Processing and Electronics Research (CASPER) field-programmable gate array (FPGA) system. The three-year goal is a 37-element cryogenic array on the GBT with system temperature less than 25 K. Preliminary results on the latest 20-meter campaign with the first cryogenic array have demonstrated a system temperature of about 35 K (the best achieved anywhere in the world thus far), and specific areas for improving upon this have been identified.

Advanced Receiver Technology Development

The extreme demands of future large-scale radio astronomy instruments require entirely new receiver architectures. NRAO is a world leader in this development area. The CDL is developing an end-to-end integrated receiver that incorporates a state-of-the-art digital orthomode transducer. In this integrated receiver, the astronomical signal will be digitized very close to the telescope output and sent via optical fiber to the central processing facility. Hardware polarizers and polarization splitters will be largely replaced by more accurate digital signal processing, and multiple frequency conversions will be replaced by a single sideband separating mixer with high-isolation, stable, digital sideband separation. A unique device has already emerged from this work: a triangular waveguide-to-low-noise-amplifier transition with much wider single-mode bandwidth than has been previously achieved.
Scientific observations would benefit from receivers which provide better performance, in terms of noise temperature, polarization purity, instantaneous bandwidth, and sky coverage, particularly if this can be achieved at a lower cost than is possible at present. For example, one of the features of the developments described here is the ability to calibrate the polarization response of the receiver in the laboratory (or by test signals injected when the receiver is mounted on an telescope) and provide arbitrary polarization reconstruction (linear at any angle, circular) with high accuracy. This effectively removes the polarization errors contributed by the receiver from that of the dish, improving the accuracy of, for example, measurement of magnetic fields using the Zeeman effect. Wide instantaneous bandwidths (e.g., 0.5-3 GHz) will significantly improve high-precision pulsar timing observations of the sort required by NANOGrav to search for gravitational waves. The wide bandwidths allow pulsar astronomers to remove or mitigate the strongly frequency-dependent effects of the ionized interstellar medium such as dispersion and scattering on a per-observation basis. Reducing the cost per pixel on the sky will speed observations at higher frequencies using arrays of conventional feed horns.

Low-noise Cryogenic Amplifier Development

The CDL has long been a world leader in the development and production of the best performing LNAs used at cryogenic temperatures. The sensitivity improvements made in the last few decades using new types of transistors have been central to scientific advances. For example, essentially all Cosmic Microwave Background experiments have depended on NRAO either directly providing LNAs (or SIS mixers) or sharing the designs and assembly and testing know–how. These include not only the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck spacecraft Low Frequency Instrument (LFI) spacecraft, but also ground- and balloon-based experiments. NRAO's LNA production capability is not only vital to the ALMA, GBT, EVLA and VLBA, but also to many other telescopes in the U.S. and the world.

Since 1994, the Indium Phosphide (InP) Hetero-structure Field Effect Transistor (HFET) has been the device of choice for cryogenic receivers and continues to offer the lowest receiver noise to ~100 GHz. In ground based applications, such as EVLA or VLBA, the current state of the art receivers contribute only a fraction of the total system noise (for example a recently constructed C-band VLBA receiver exhibits 5 K noise temperature out of which 3.5 K can be attributed the amplifier). Although, it would be unrealistic to expect further large improvements in the receiver performance using cryogenically cooled InP HFET's, there still exist significant gaps in understanding of their cryogenic behavior. These include not only its dependence on the device structure but also natural performance limits, repeatability of noise performance, 1/f gain fluctuations and a number of issues in the design and fabrication of MMIC's.

Recently Silicon-germanium (Si-Ge) Hetero-structure Bipolar Transistors (HBTs) have been demonstrated to offer a competitive noise performance at cryogenic temperatures at low microwave frequencies (less than 4 GHz). Such devices can be used in lower frequency amplifiers as well as in IF amplifiers for SIS mm-wave receivers, offering in principle an order of magnitude lower 1/f-like gain fluctuations and large instantaneous receiver bandwidths, improving continuum radiometer sensitivity for CMBR and S-Z effect observations and enabling competitive receiver temperatures for the wide-bandwidth pulsar timing systems needed for gravitational wave studies by NANOGrav. The first cryogenic phased array feed uses HBTs obtained from Caltech, and new, lower-noise devices are being readied for use in this array and other projects at the CDL. So far, however, only one type of device from one foundry offers cryogenic noise performance that is competitive with HFETs. Consequently, the research needed to advance the understanding of cryogenic SiGe HBTs is very similar to that already mentioned for HFETs.

The individual receivers are ever closer in performance to what is physically possible, and therefore the future science goals can only be addressed by building array receivers, both conventional focal plane arrays and phased array feeds. Any future radio astronomy facility currently contemplated would require a large number of receivers and therefore the research issues listed above would have to be addressed. The CDL staff is uniquely qualified not only to address these research issues, but also to carry out development as well as production.

MMIC (Monolithic Microwave Integrated Circuit) Development

Because only 100-200 cryogenic LNAs are needed by radio telescopes worldwide, current demand is satisfied by manual production using intensive labor, as this is the route proven to result in the best possible performance. However, for future arrays of telescopes or feeds with thousands of receiving elements, this becomes impractical.

MMIC devices, long used at room temperature in many types of electronics, will provide the means for large-scale LNA production in the future. In this approach, all circuit elements are combined onto a single macro-scale chip instead of one-at-time under a microscope. This chip, typically a few millimeters in dimension, is simply glued into a metal block and wire-bonded to interface circuits in a few hours rather than a few days. Attempts have been made for the last two decades to develop MMIC amplifier chips with competitive noise performance at cryogenic temperatures to the best chip-and-wire designs. In the last few years, some success has been seen, and NRAO will pursue this technology vigorously.

Some MMIC chips for the frequency range 60-95 GHz were manufactured in 2009 by Northrop Grumman Space Technology (NGST, successor to TRW) in a collaborative project with JPL and California Institute of Technology (CalTech) and show great promise, with achieved noise temperatures that are among the very best ever recorded for this frequency range. A new wafer run has just been completed and is under test. NRAO plans to continue this work in order to develop a practical means of building arrays requiring very large numbers of cryogenic receivers, in order to meet the science objectives at an affordable cost. This work has broad application across nearly all fields of astrophysics.

Millimeter and Sub-millimeter Technology Research and Development

The electromagnetic spectrum above 1 THz is extremely rich and highly rewarding for molecular radio astronomy if sensitive wideband heterodyne detectors can be developed. The exciting science which would be enabled is described in detail in the "ALMA" Astro2010 white paper. Recent developments in devices, materials, and fabrication technology suggest that nearly quantum-limited sensitivity with greater than 10 GHz bandwidth should be possible in the next decade. The long-term goal of the NRAO millimeter and sub-millimeter receiver research and development program is to develop submillimeter receiver technology for frequencies beyond the useful operating range of niobium-based SIS mixers (~700 GHz). In the shorter term, the goal is to develop the technology for a nearly quantum-limited receiver at 350 microns (~850 GHz). This is a joint effort of NRAO and the University of Virginia Microfabrication Laboratory (UVML).

NRAO and UVML have an established record of successful instrument development. The SIS mixers for ALMA Bands 3 and 6 were developed by NRAO and UVML. The UVML has recently acquired major new fabrication equipment that puts them in an excellent position to undertake the proposed fabrication work. With the suspension of SIS Mixer development at JPL/Caltech, NRAO/UVML is now the only research facility in the U.S. capable of producing such devices.

The 350 and 200 micron atmospheric windows (ALMA bands 10 and 11) are important for the next generation of terrestrial radio telescopes as well as for instruments in space. The NRAO goal is to develop reproducible, reliable, inexpensive, quantum-limited SIS receivers based on NbTiN technology that has given promising, though not yet consistent, results in other laboratories. The mixers will be designed to support a wide IF bandwidth which is desirable for both spectral line and continuum measurements, and in a form suitable for sideband-separating and balanced operation.

The new technology will be suitable for focal-plane and phased-array receivers as well as conventional single element receivers and interferometers. It complements the continuum and relatively narrow band spectral line capabilities of bolometer detectors and will have use in ALMA, SOFIA, balloon-borne experiments, and possibly spacecraft in the future.

Digital Signal Processing

Essentially all new instrumentation development requires advanced digital signal processing (DSP), and in many cases DSP development is a dominant part of the project. NRAO has been a key member of the CASPER Consortium for some time, and has built up a substantial expertise in this area. In addition, NRAO is collaborating with the CASPER community to develop fully reconfigurable computing; using FPGAs, Graphics Processing Units (GPUs) and multi-core, clustered Central Processing Units (CPUs) to provide signal processing capability in the most flexible and cost-effective way. Examples of recent and current DSP development include the new Green Bank GUPPI pulsar searching / timing backend that is essential to reaching the goals of NANOGrav to detect nano-Hz gravitational wave background, the new GBT Spectrometer, and the VLBI Digital Backend. Future projects include wide-bandwidth beam-formers for phased array feeds; high-speed digital links that will enable large numbers of data channels to be efficiently transmitted from the telescope focus to central processing stations; new firmware and GPU algorithms for science-specific applications, such as pulsar search strategies and more accurate pulsar timing; greater use of distributed, real-time, signal processing through the use of new commercial signal routing hardware; and expansion of the new technique for efficient multi-field processing if VLBI signals. This technology will also be a vital component of the PAPER and the FASR. As these projects develop they will spawn new ideas for signal processing in the time frame of this long-range plan. This work has broad application across nearly all fields of astrophysics.

In addition to the application of existing DSP technology, NRAO will continue to extend the state of the art in areas such as heterogeneous computing and model-based FPGA development. Application-specific integrated circuits (ASICs) will continue to play a role in the core of high-speed signal processing where operations per unit power consumption is crucial, and we will be on look-out for instances where FPGA code will warrant an ASIC implementation.

Electromagnetic Components

The CDL designs and builds passive electromagnetic components for specific applications: feeds, polarizers, orthomode transducers, dichroic mirrors, etc. This work requires extensive design, analysis, computer-aided modeling, prototyping, testing, and finally production. Units such as feeds are tailored to match the optics of the target telescopes. The basic idea in these activities is to solve Maxwell's equations with very complex boundary conditions. This work will continue at a steady pace through FY 2013-2017, as new receivers are required.

Fabrication will be done in NRAO shops or, depending on workload and size of parts, by outside contractors. Test of production units will be performed either by CDL staff or by receiver production staff at the telescope sites. For parts that must be electro-formed, the mandrels will be manufactured like other parts, and the electro-forms will be grown in the NRAO chemistry laboratory.

5.2 Key Partnerships: New Initiatives Office (NIO)

The NIO pursues, develops, and manages strategic partnerships and collaborations with academic, government, and non-profit organizations in the US and internationally. The NIO is also specifically charged with establishing collaborations with community groups to respond to the NWNH Survey Report recommendations, a central component of the NRAO mission: to enable forefront science by the scientific community.

In FY 2013 and beyond, NIO will continue to pursue, develop, and manage partnerships and collaborations that have the potential to lead to additional funding and/or that benefit the mission of the Observatory. It is expected that viable collaborations may follow the so-called FASR model, in which NRAO will function as a key institutional partners by bringing its unique scientific, technical, and managerial expertise to the planning, design, construction, and operational phases of these new instruments or facilities, especially on a scale that is too big for a university group to manage.

To engage the community in an ongoing discussion of long-term (>10 year horizon) development of astronomy, NRAO will sponsor a series of workshop on future science and technology in radio astronomy, but in the context of multi-wavelength and time domain approach.

Some of the emerging projects that already enjoy NRAO collaborative participation and that will be carefully examined by NIO for further integration and partnership opportunities are briefly described below.

Large Synoptic Survey Telescope (LSST)

With its application for institutional membership submitted in our FY2011 Program Year, NRAO anticipates an increasing engagement in the LSST project over the period covered by this Long Range Plan. The LSST will profoundly transform the practice and scope of astronomical research; the quality, cadence, spatial coverage, and accessibility of the core LSST data set will be a resource of unprecedented richness for all astronomers. Toward the end of this decade, when LSST begins end-to-end commissioning and science verification at the end of this decade, NRAO will already be operating a complementary suite of four fully commissioned, state of the art radio facilities for the community.

NRAO sees its early institutional participation in the LSST project as a natural platform for encouraging the synergistic use of both the LSST and NRAO telescopes by the widest possible cross section of the research community. Although ALMA's virtually identical sky coverage makes it an obvious resource for coordinated or follow-up observations with LSST, the EVLA, GBT and VLBA all have appreciable overlap with the Southern sky, (particularly at low frequencies where atmospheric attenuation is low), and expect those telescopes to be no less pressured to carry out coordinated and follow up observations.

NRAO's institutional membership in the LSST will develop and promote better understanding of LSST's extraordinary capabilities to the traditional NRAO user communities, as well as keep the OIR communities informed of science opportunities that could be enhanced through radio observations. Through the close linkages that exist with our several-thousand-strong global user community, NRAO expects to play an active role in convening workshops to promote such cross-fertilization.

NRAO will also collaborate with the LSST in the development and testing of software packages that would translate primary LSST data products into specialized metrics that could be of particular interest to our user community (e.g., the construction of multicolor star count and extinction maps for user-selected fields). NRAO also will have gained considerable experience in the archiving and analysis of large data sets, although not at LSST's projected data rates and volumes. Nonetheless, as the EVLA and ALMA move toward achieving the full data rate, several IT areas will be of common interest and of use to the LSST project. These include our experience in archiving and distributing multi-Terabyte data sets to users, developing data mining capabilities that are optimized for the exploration of our archives, dealing with the ongoing challenges of maintaining access to those archives, supporting a set of general tools for the analysis of astronomical data (the CASA platform), and maintaining an optimal balance between local and remote high-end computing resources. NRAO also expects that the important issue of optimizing mutual access to the NRAO data archives for LSST users will be an important area of responsibility for the Observatory.

Frequency Agile Solar Radiotelescope (FASR)

FASR is an ultrabroadband (0.05 - 21 GHz) radio imaging array designed specifically for observing the Sun. It will be the most powerful radioheliograph in the world. Composed of three complementary sets of radio telescopes, the instrument will image radio emission from the middle chromosphere to the outer corona in three dimensions once every second, providing unique measurements of the Sun's coronal magnetic fields, of magnetic energy release and particle acceleration in solar flares, and chromospheric and coronal heating. Given that the Sun is the driver of heliospheric, geophysical, and atmospheric phenomena that can have adverse impacts on modern space-based and ground-based technological systems—as well as on manned space flight—FASR is well positioned to make significant contributions to understanding the physics of space weather, as well as contributing to monitoring and forecasting space weather phenomena.

FASR will be a facility for the solar and space physics community, a significant scientific constituency. The FASR project has been conceived as a partnership between the NRAO and multiple universities under AUI management. The NRAO will provide the crucial scientific and technical expertise for design and planning, as well as management of the eventual construction and operations.

NWNH ranked FASR highly as a mid-scale project, reinforcing the top recommendation from the independent solar and space physics decadal survey (*From the Sun to the Earth – and Beyond*: A Decadal Research Strategy in Solar and Space Physics). Moreover, NWNH recommended that the NSF develop the Mid-Scale Innovations Program as a means of funding projects like FASR, a project characterized by the NWNH as "compelling." FASR is now at a level of readiness that will enable it to ramp up to the construction project quickly; the construction project has a nominal duration of five years but the project can respond flexibly to fiscal realities, building out as quickly, or gradually, as budgets permit.

Current plans call for the development of a full FASR construction proposal during FY 2012, a process that NIO will facilitate and is largely funded by the NRAO. This will position the project well for funding consideration in FY 2013-2014. With a funding start in FY 2013-2014, the project could be complete by the end of FY 2017-18, a timeframe commensurate with the completion of NSF's complementary O/IR Advanced Technology Solar Telescope.

NANOGrav

Though predicted by Einstein's 1916 theory of General Relativity, gravitational radiation—energy propagated at the speed of light via waves in space-time—has not as yet been directly detected. However, one detection approach—using masses suspended *in vacuo* and measuring their displacement with precision laser interferometers to detect the passage of a gravity wave—is approaching fruition with the upgrade of NSF's LIGO facility. Another technique, proposed to the Astro2010 Decadal Survey by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) envisioned using the naturally occurring population of millisecond precision pulsars in the Galaxy as "clocks" that could detect very low frequency gravitational waves. Although the NANOGrav consortium first anticipated that upgraded capabilities at the Arecibo and GBT would form the backbone of the pulsar timing array, as the concept evolved, the value of using other telescopes (such as an augmented MeerKAT array) became evident. Given a sufficiently large reference frame of millisecond pulsar standards, timing measurements should be able to detect the formation and collision of massive black holes with signals of periods of months to several years. A dedicated NANOGrav facility will be able to detect relic gravitational waves from the very early universe, a regime that is otherwise inaccessible to direct observations.

The Decadal Survey's strong endorsement of the NANOGrav science goals has reinforced NRAO support for the development of technologies critical to the NANOGrav mission. Over the next several years, NRAO telescopes will be used as test beds of these technologies, as well as for primary platforms in pursuit of NANOGrav science. Examples include the development of very wideband feeds and high-speed digital signal processors specialized for pulsar observations on the GBT. In addition, the EVLA has already been used to demonstrate the feasibility of wide-band "on the fly" pulsar signal de-dispersion within the WIDAR correlator itself. When fully implemented on the completed EVLA, this will make it possible to apply the full power of the EVLA for pulsar observations at very wide bandwidths.

PAPER-HERA

Characterizing "Cosmic Dawn"—the emergence of the very first stars and their host galaxies from the fabric of the largely featureless infant Universe—is one of the key scientific goals recommended by

NWNH. The Hydrogen Epoch of Reionization Arrays (HERA) roadmap presented to the Survey one strategy for reaching that goal, proposing to build out a staged sequence of increasingly powerful radio arrays to unveil and parameterize in increasing detail the physical processes that led to the contemporary Universe. The roadmap was strongly endorsed by NWNH, in part because of its scientific focus, and in part because it is to be heavily leveraged through partnerships and proposes to build upon existing world-class radio astronomical infrastructure.

PAPER, the Precision Array to Probe Epoch of Reionization, a partnership between NRAO and scientists at UC-Berkeley, the University of Virginia, the University of Pennsylvania, and Curtin University in Australia is one of two HERA-I class instruments cited as currently under development. PAPER has completed its expansion to a 64-telescope array at its South African site, and has been awarded $4.5M (to UC Berkeley, UVA and NRAO) from NSF to expand this to a 128-element array that will attempt detection of an EOR signature.

NRAO will continue to participate as a major institutional partner in PAPER/HERA and will continue to devote its scientific, technical and managerial expertise to ensure the success of the PAPER/HERA program.

Lunar Radio Astronomy

The NRAO has been collaborating with the University of Colorado and others in the Lunar University Node for Astrophysics Research (LUNAR) program. LUNAR involves development of concepts for performing astrophysics using the Moon as the observing platform for low-frequency cosmology and astrophysics, gravitational physics and lunar structure, and radio heliophysics. NRAO participation will include the development of concepts for low frequency telescopes and a refinement of the science case while defining the corresponding instrument requirements.

During the past year, activities have been centered on the Dark Ages Radio Explorer (DARE) mission, a lunar orbiter concept designed to detect the strongly-redshifted (40-120 MHz) emission of primordial hydrogen atoms at the end of the so-called Dark Ages, a time when the Universe was less than 200 Myr old and the first stars were beginning to light up. DARE will orbit the Moon, using the lunar rock to shield the sensitive detectors of the spacecraft from the radio interference that abounds on the Earth in the 40-120 MHz radio band. NRAO has participated in an initial funding proposal to NASA, submitted in February 2009. If the proposed program is successful in moving toward the construction phase, the Observatory will play a key role in the design and fabrication of the DARE satellite's antennas and radio receivers.

The North American Array

In early 2011, the NSF declined to contribute to the pre-construction phase of the international Square Kilometer Array (SKA) project. Consequently, the US SKA Consortium decided to dissolve at the end of 2011. It is therefore necessary for U.S. radio astronomy to take a fresh look at the case for new meter and centimeter-wave instruments that will be more closely aligned with the NWNH science goals, as well as providing new capabilities that will go beyond the U.S. flagship facilities (EVLA, GBT, VLBA) this decade.

During the period covered by this Plan and in partnership with the U.S. astronomical community, NRAO intends to lead the development of a new and finely focused science case to build logically upon and extend the current capabilities. This emerging concept, the North American Array (NAA), is envisioned as a natural, science-driven evolution of the EVLA, GBT, and VLBA that will begin to take shape in the decade of the 2020s. To start the project definition process, NRAO will be sponsoring a series of workshops to bring together the US and international community to formulate the science case that determines the technical requirements.

Discussions between the NRAO and the US SKA Consortium have led to an agreement that NRAO will manage the Dish Verification Antenna (DVA-1) project of the US Technical Development Project (TDP) and would host the test telescope at the EVLA site. If this arrangement goes forward and the project passes its initial design reviews and moves through to construction, an innovative, lightweight 15m, off-axis mid-frequency (ν < 20 GHz) telescope will be built and subjected to basic performance tests at the EVLA site by mid-2013. Such a prototype will also be a valuable starting point for the NAA telescopes.

MeerKAT

The NRAO collaboration with the South African SKA Project Office (SASPO) includes an engineer and scientist exchange program that will continue in FY 2012 and beyond, and will become more structured and formalized beginning in FY 2012. This collaboration has fostered the adoption of the NRAO CASA package as MeerKAT's post-processing software, and has lead to algorithm development in South Africa that is expected to be also applicable to EVLA and ALMA. This collaboration is also developing direct digital sampling, which will be critical to maintaining low cost and reliability for an SKA of several thousand dishes.

Long-Wavelength Array

Led by the University of New Mexico (UNM), the Long Wavelength Array (LWA) is a low-frequency (10-88 MHz) antenna array designed to produce high-sensitivity, high-resolution images and open a window on a poorly explored part of the electromagnetic spectrum. When fully realized, this interferometric array will be located primarily in New Mexico with baselines extending up to at least 400 km. The first LWA station has been completed at the EVLA site, and with first light, has demonstrated the soundness of the basic telescope, receiver, and correlator designs. Although funding problems have continued to prevent the build-out of the array, new avenues of support are being explored, and it is possible that construction of the array may resume. Although the EVLA will host the core LWA stations, all work performed by the NRAO on behalf of the project will continue to be on a cost-reimbursed, available-personnel basis.

SOFIA Second-Generation Instrumentation

The NRAO plans to submit a proposal to NASA to build a second-generation receiver for Stratospheric Observatory for Infrared Astronomy (SOFIA). Instrument development and commissioning is planned to span three years. Development of such an instrument would be synergistic with ALMA development activities. The NRAO substantial experience in meeting the rigorous program management, quality control and documentation standards position us well to deliver a flight-qualified instrument.

The proposed instrument is an 8-pixel array receiver covering 1200-1500 GHz using NbN HEB mixers. The 8-pixel SIS receiver would offer up to a 10x increase in mapping speed over the SOFIA GREAT receiver currently used in this frequency range. New results from the Herschel HIFI instrument verify that simple hydrides are major constituents of the interstellar medium (ISM). These simple hydride molecules are of great importance in astrophysics and astrochemistry. Physically they dominate the cooling of dense, warm phases of the ISM, such as the cores and disks of Young Stellar Objects. The developed receiver is being proposed as a work horse mapping instrument in this critical frequency range.

Submillimeter-wave VLBI Imaging of M87 and SgrA*

The FY 2013-FY2017 period will see marked improvement in millimeter and sub-millimeter wavelength VLBI capability, largely as a result of the upcoming capability to observe with ALMA as a single large phased-array aperture of 84-m equivalent diameter. Reaching the exciting goal of directly probing and perhaps imaging the event horizon of a black hole as it changes on hour to week timescales would simultaneously advance the study of black holes and captivate the public. In addition to ALMA, the Large Millimeter Telescope near Puebla, Mexico and an ALMA prototype telescope that is being retrofitted and moved to Greenland are expected to come online as significant additions to a global array of telescopes that can work together in this wavelength range to form the Event Horizon Telescope. Through its technological and scientific expertise, NRAO will play a large part in developing and exploiting submillimeter-wave VLBI. A collaborative Major Research Instrumentation (MRI) proposal submitted by MIT Haystack Observatory seems, at this writing, likely to provide most of the funding needed.

Space Very Long Baseline Interferometry

Russia's RadioAstron satellite has been successfully launched on July 19, 2011. Following on-orbit checkout, it is expected that the VLBA, GBT, Effelsberg, and Arecibo, as well as several ground-based Russian radio telescopes will search for fringes and explore performance on a range of baselines. Following this fringe-detection period, we anticipate the continued participation of the GBT, EVLA, and VLBA in response to the normal NRAO proposal cycle. The Socorro DiFX correlator and the MPIfR correlator are being prepared to handle data from the space-ground baselines.

The Astro Space Center at Moscow's Lebedev Physical Institute has recently expressed interest to fund NRAO to establish a tracking station for RadioAstron at the Green Bank site. The 43m telescope will become available for a new contract in November 2011, and could be readily refurbished. A multiyear usage contract for tracking and downlinking RadioAstron data is being considered.

5.3 Long-term Computing Development

Over the timescale of this plan, NRAO will develop and implement data processing, storage, and communications architectures that will enable our user community to handle raw and post-processed products in the petabyte/year range. These capabilities will also enable the next generation of radio instruments through increased and improved data processing capability. Petascale architectures (computing capability on the order of 10^{15}) will be required for storage, compute cycles/second and, most challenging, communications throughput; Exascale (10^{18}) architectures will be required for instruments envisioned for the 2020 decade.

Parallel Processing

For the past 40 years, Moore's Law has been the bellwether for the exponential scaling in performance with time, yet it only tracks component density and not communications throughput or data storage, which have been lagging, and present key concerns for observational astronomy. As such, understanding data management and transfer needs for the science under investigation is essential to minimize data movement, improve signal extraction, and avoid unnecessary data replication.

NRAO will continue to invest heavily in and adopt parallel processing techniques, and the increasing availability and suitability of High Performance Computing technologies – multi-core clusters, parallel file systems, non-blocking system area networks – and diverse programming practices will guide our future community support strategies.

NRAO's computing research will be necessarily focused on the two complementary areas of data generation and data analysis. The former is naturally driven by the real-time requirements of the observation—spectrometers, correlators, etc. —while the latter is more general, since meaningful analysis of complex data requires the union of numerical manipulation, visualization, and iterative comparison to other data, both from simulation and other observations. Our ability to automate and standardize key activities such as data flagging and editing, calibration, and the excision of radio frequency interference in real time for streaming data, present fundamental challenges which must be overcome, predominantly in software.

The Power Wall

Beyond ALMA, power and associated cooling will limit scientific computing, with multi-megawatt facilities being increasingly expensive and impractical to co-locate with the observational instruments at geographically remote locations. A researcher can effectively interact with and analyze megabyte and gigabyte datasets on their own computer by retrieving the data over a high latency (>30 millisecond) shared link. For terabyte or larger datasets, alternative options for interacting become a requirement due to the cost (in time and resources) of moving, then storing the data is unsupportable.

These challenges will mandate the movement of data to the location of cheap power and shared computational resources for the most challenging observations. The co-location of the data repository (archive + user storage) and the computational resources to re-process and visualize massive datasets will become prevalent, facilitated by transparent remote access through remote rendering software to web-based clients. This will require a major break with the traditional model of an observer being provided with a copy (or in some cases the only copy) of the observed data, source code for data analysis, and then relying on their institution to provide power, storage and supported computing resources. NRAO will continue to investigate options to mitigate these risks during this plan period by partnering with organizations that have subject matter expertise and/or resources to improve the power efficiency of our HPC systems.

Software Challenges

The challenge of supporting and extending 100,000+ lines of interferometry analysis software (e.g., CASA) for the community, on a diverse set of architectures and operating systems, will require substantial resources. In addition, to scale this code efficiently to highly parallel systems (>1,000 CPUs) is a challenge. It would be prudent to embrace the insights gained from research into Open Grid (and even Cloud) solutions that allow for the rapid deployment of software to large numbers of virtual hosts. This enables code portability, by hiding system dependencies, but is still constrained by the overhead of efficiently accessing data. To date, commercial grid and cloud products do not offer an attractive price-point for storage or computer cycles, other than to help drive the standards for "software as a service" solutions.

Internally, excellent traction has been realized with software developed for commodity hardware such as the DiFX correlator and signal processing solutions, such as pulsar de-dispersion using GPUs. Continued work will be needed to enable semi-automated processing pipelines for the ever-increasing volumes of data in a consistent and reproducible way so that reference images and other data products can be delivered to the community via VAO defined protocols.

Hardware Opportunities

NRAO will continue to lead where appropriate and follow where applicable. Opportunities for digitizing and optically encoding receiver signals earlier and more efficiently will simplify and improve instrumentation, while the use of low power, mass produced, components can dramatically reduce development time and operating costs.

NRAO baseline strategy will ensure there are sufficient in-house computing resources to support the community during any data proprietary period. Thereafter, the NRAO will enable researchers to leverage external resources, such as the high performance computing capabilities offered via systems such as NSF funded XSEDE, with data being replicated on demand over high speed backbone networks to science gateway systems. The NRAO will work with the community to determine how best to preserve user generated products, and how to re-ingest them into the archive for future citation.

The Observatory will shift to 10Gbps connections for key servers and on-site networks, while leveraging Infiniband (currently 40Gbps) for parallel file system access and low latency (~microsecond) inter-node communications. Likewise, over the next 5 years, all three major NRAO sites in the US will increase their long-haul network to support 10+Gbps over the national research networks by partnering with regional educational institutions.

The fundamental question remains as to how NRAO should invest in cyber infrastructure beyond that needed for the initial data capture and validation. It is already clear that the continued use of commodity disk drives will continue to strike the best price/performance balance for frequently used data. It is expected that the current trend in drive capacity will continue through the mid-decade with 10+terabyte units being readily available, though access speeds per disk spindle are unlikely to keep pace with capacity. Disruptive technologies such as Solid-State drives will bridge the performance gap between RAM and disk as a large cache or application accelerator.

Summary

The critical concerns of the FY 2013-2017 period for computing development will be to ensure timely software and the related data management and manipulation strategy to the community. The high priority projects recommended by NWNH will yield opportunities to clearly define and address these long-term computing development challenges and enable new science.

6. Broader Impact: Radio Astronomy and Society

Science exists to satisfy deep curiosity about nature, curiosity highly refined in the professional scientist but present in everyone. So the public provides money on a vast scale to support science. They expect benefits, both tangible and intangible, such as interesting insights into nature (interpreted so that they can understand them), opportunities to leverage today's scientific and technical expertise for the educational advancement of the rising generation, and, as is practical, direct improvements to other aspects of their lives.

6.1 Radio Astronomy Technology and Society

The state-of-the-art technical developments that have enabled progress in radio astronomy have also contributed to our national technology base and fostered progress in a variety of fields. A basic science such as radio astronomy does not exist primarily to develop technology, but the cumulative contributions over the last 25 years are impressive.

Table 6.1: NRAO Contributions to the U.S. Technology Base

Application	Radio Astronomy Technique
• Wireless Local Area Network technology • Position location of wireless sensor nodes • Radio location of cell phone 911 calls	Radio Interferometry
• Hydrogen maser time standards for space communications, satellite navigation, and defense applications • International celestial reference frame, terrestrial reference frame, Earth orientation parameters • Global Positioning System time and position reference frames	Very Long Baseline Interferometry
• Precision communication and radar antennas.	Homologous Antenna Design
• "Pospieszalski" noise model for amplifier design • Improvements to commercial cryogenic cooling systems	Low Noise Amplifiers
• Significant development of Maximum Entropy reconstruction techniques • Medical-imaging tomography techniques • Image de-blurring	Radio Image Reconstruction
• Development of open source middleware for volunteer and grid computing.	Processing of Massive Datasets
• Image reconstruction	Self-calibration
• Interplanetary spacecraft navigation	Precision astrometry
• "Thinned aperture" imaging radiometry in earth sciences	Aperture synthesis

6.2 Radio Astronomy for Everyone: Education and Public Outreach

NRAO's EPO mission is to engage the American public, including students, in the adventure and fruits of radio astronomy, the wonders of the natural phenomena that it reveals, and the roles that radio/mm/submm astronomy play in the larger multi-wavelength context.

EPO strives to:

- Make radio astronomy accessible to everyone, serving as a dependable, authoritative source of interesting, accurate, informative, and educational resources about the science for the interested American public and students.
- Lead efforts nationwide to promote public awareness and understanding of important science results achieved by NRAO users.
- Promote and effect STEM learning and careers among students.
- Contribute to the sustaining of public support for continued American participation and leadership in radio astronomy, with particular emphasis on communities where NRAO operates telescopes.

NRAO endeavors to reach and involve diverse participants in many of these activities.

Resources

NRAO core-funding (via the Cooperative Agreement) resources for EPO are modest. Divided among the four major telescopes that NRAO operates, our average per-telescope EPO budget is approximately 16% of Spitzer's, 12% of Chandra's, and 6% of Hubble's (and none of those space-based telescopes' Earth-based EPO programs operate visitor centers and tour programs). Despite these limitations—and indeed, spurred on by them—NRAO aggressively works to increase the productivity and efficiency in the use of available resources, and to secure additional resources.

EPO strategies include:

- Having a single, although geographically dispersed, EPO team for the entire observatory.
- Seeking opportunities for partnerships that leverage and amplify our efforts.
- Soliciting contributed time from staff scientists and engineers to EPO events and projects.
- Increasing earned revenue from science center operations.
- Securing in-kind and monetary support from non-traditional (e.g., not the NSF) sources.
- Competing successfully for federal grant funding for educational programs.
- Expanding technical and creative skills of the EPO staff (so that they can carry out multiple technical functions).
- Selecting projects carefully, with an eye toward those that will deliver the greatest impact.

Given the funding prospects for the period covered by this plan, continuing success will depend upon such ongoing increases in productivity and external revenue.

Overview

NRAO's EPO program contributes to the fulfillment of the NSF's mandate for the achievement of Broader Impacts via work that is arranged in two broad categories:

- **News & Public Information:** Informing the science-interested public (including students) about the NRAO (its purpose, capabilities, technologies, and people), the celestial phenomena that radio astronomy studies, and new science results. Since each NRAO telescope constitutes the state-of-the-art within its type, our users tend to generate many *newsworthy* science results.
- **STEM Education:** Using radio astronomy as an inspiring vehicle by which to teach about the nature of science, the process of scientific research, the technology and math disciplines applied in the field, and associated educational and career pathways.

The imaginary membrane that separates these categories is quite permeable, and in reality most of our activities contain attributes of both; a good science news story is typically educational for the reader and a good learning activity is often informative. Further, materials created as part of a project in one category often find subsequent application in the other.

At present EPO allocates roughly 47% of its core (NRAO & ALMA Ops) resources to News and Public Information, and 53% to Education. This does not tell the whole story, however, for the education efforts are significantly supplemented with grant funding; for FY 2012 educational grant expenditures will amount to an additional ~71% of the funds allocated to education from core funding.

Within each of the aforementioned categories, a carefully-chosen mix of activities within two types is undertaken in a given year:

- **Programs:** On-going core activities having no specified beginning or end dates, but that evolve to adapt to changing conditions and opportunities. Example: As long as NRAO telescopes remain scientifically best-of-breed, we will operate a news program driven by the discoveries made by our users. How that news is conveyed to the public, however, is continually changing.
- **Planned Projects:** Fixed period efforts to achieve particular goals. Once that goal is attained, resources are freed for other projects. Example: An online virtual tour of an NRAO facility. Once completed, it can successfully "reach out" without needing to be substantially revised for a number of years.

A third type of activity exists that is outside of our ability to specifically plan: Responsive Projects. Experience shows that unexpected opportunities always arise. The way to plan for these is simply to make sure NRAO is equipped with the necessary skills, tools, and materials to take advantage of them as they appear.

Activities

As the period covered by this plan opens, scientists using the completed EVLA will be producing new science, ALMA will be commencing full science operations, specialized instruments on the GBT will be generating unique results, and VLBA key science projects will be bearing fruit.

By this time EPO will have completed a new core public website that features an elegant, luminous, "app-like" design and extensive associative (non-hierarchical) content cross-linking. Our social media networks will have continued to expand. Our educational offerings will be available to more—and more widely located—students than ever before.

EPO will work to achieve the public recognition and understanding that NRAO's new facilities, and the resulting science conducted by our users, deserve, and continue to work to engage students in our evolving educational opportunities.

Science News Dissemination & Publicity

The ongoing revolution in media and communications will affect how NRAO get its messages out to the world, with the traditional, relatively unadorned "press release" yielding to the reality of an ever-declining traditional press. As the number of science reporters and media personnel continues to shrink with consolidations, EPO will, it is likely, increasingly become the direct primary source of information to the public about science impacts. EPO will adapt to new information infrastructures as they develop, staying abreast of technology and trends in its use, and making necessary upgrades to hardware, software, and training. Text, in this age of the brief tweet, will have to get tighter and punchier. Graphics will continue to rise in importance. Intensive collaboration between text creators and visualizers will become the norm, with the resulting integrated media products aimed directly at the public (rather than at dedicated science journalists), and for direct adoption by online news aggregators and reference by online science commentators.

Social media networks will grow in importance as means of alerting interested parties to our users' science results, and to the availability of online resources and opportunities related to the news. Such opportunities will include virtual interactions with (willing) science users who have made newsworthy discoveries.

EPO will continue also to disseminate press releases (and other select media) via the ViewSpace network. ViewSpace, a product and service of the Space Telescope Science Institute's Office of Public Outreach, is an ever-growing network of 220+ science museums, planetariums, nature centers, observatory visitor centers, and other public venues that collectively draw some 10 million visitors or more annually. Each venue is equipped with a continually-refreshed large-screen display that presents a cycling loop of astronomical and earth science multimedia presentations written in a museum exhibition text style. By agreement with STScI, NRAO is a ViewSpace Content Creation Partner.

Finally, EPO will undertake as a special project an integrated public awareness campaign, in coordination with our international ALMA partners, for the formal inauguration of ALMA.

Public Information

A vast gulf of unawareness, and misconception separates the public from an understanding of radio astronomy, the branch of astronomy that, as Smithsonian historian David DeVorkin has said, has been the most neglected by science popularizers. The new NRAO public website that will be up and running by the beginning of 2013 will become a locus of well-interpreted information about radio astronomy, the amazing telescopes that NRAO operates, the scientists who use them, the engineers and technicians who enable them, and the wide range of natural phenomena they explore. Extensive, richly visualized articles and media modules will delight our online visitors, and we will undertake significant efforts to promote the availability of these resources. The unique characteristics and scientific contributions of each of NRAO's telescopes will be presented. For example, the GBT will be shown to be not merely "America's largest steerable telescope," but an instrument unique in its contribution to research in ways that complement, and compensate for the limitations of, arrays.

EPO will continue to make use of our ever-growing social media networks to inform NRAO's followers about interesting events and other information that falls below the threshold of a "press release." We will also continue to pursue as discrete projects the creation of science communication programs with major media, such as broadcast documentary networks, large-format film networks, popular science and technology webcasts, digital fulldome planetariums, and popular science & technology publications and websites.

STEM Education

The NRAO offers unique opportunities for students to learn-by-doing through hands-on use of research-grade radio telescopes. Students by the thousands each year avail themselves of these opportunities by visiting our education facilities in Green Bank, where they can directly use a large, 40-foot diameter radio telescope that is dedicated entirely to education. Some students remain at Green

Bank for extended periods, living in on-site housing and working in proximity with (and sharing meals with) NRAO scientists, engineers, and technicians.

These opportunities will continue to be offered, but as the period of this plan opens, and subject to the receipt of pending grant funding, the NRAO, in cooperation with the University of North Carolina Chapel Hill, The University of Chicago's Yerkes Observatory, and the Astronomical Society of the Pacific, will be offering students "mouse-on" remote-control of our 20-meter radio telescope, which is being renovated for remote-control use as this plan is written. The *Radio SkyNet Jr. Scholars* program will engage students and informal educators around the country in desktop-controlled scientific research. EPO will also pursue expansion of the successful *Pulsar Search Collaboratory* program, which provides students with opportunities to learn about and discover pulsars using GBT drift scan data.

EPO will continue to develop educational classes, special events, and school visits at all sites, and to seek opportunities to participate in community events and science expositions.

An important aspect of education is training educators. One way in which NRAO will continue to do this is by participating in the University of Dayton's Chautauqua course program. Chautauqua courses are an annual series of forums in which scholars at the frontiers of various sciences meet intensively for several days with non-research undergraduate teachers of science. In the summer of 2011, for example, NRAO presented two such courses. The one in Green Bank was entitled "The Radio Universe and the Green Bank Telescope." The one in Socorro was entitled "Exploring the Frontiers of 21th-Century Astrophysics with the VLA and VLBA".

Informal STEM Education (Visitor Centers and Tour Programs)

NRAO's facilities in New Mexico and West Virginia are bona fide science tourist destinations, attracting some 20,000 and 45,000 annual visitors respectively. These facilities are highly accessible to visitors, inspirational simply to see, and there's no need to worry about ascending treacherous mountain switchbacks, or about waking up sleeping astronomers in the daytime! At each of these facilities a visitor center with exhibits and other amenities (the Green Bank Science Center and the VLA Visitor Center) is operated. Each provides an introductory film, a gift shop, and a tour program. The Green Bank facility also offers a quality food service. These high-impact experiences to visitors who venture out to our locations, will continue to be provided for during this plan period. Additional actions will be undertaken to secure funds to increase our effectiveness in promoting visitorship, in repairing and upgrading the exhibits at both, and improving the richness and meaningfulness of the interpretive programs offered to visitors. EPO will strive for increased numbers of visitors, and for ways to enable special events at each location to be enjoyed by virtual visitors online. EPO will also continue to offer a range of special events meant primarily for residents of the communities where NRAO operates facilities. These events, in addition to being informative and enjoyable, will help to express NRAO's commitment to the betterment of our immediate neighbors (who sacrifice certain of civilization's modern amenities to enable our operations to be relatively free from radio frequency interference), and help them understand the significance and importance of the work NRAO and our many users accomplish with the tools in their midst.

Outreach in Chile

As part of our North American ALMA Operations funding NRAO maintains an EPO Officer at the NRAO/AUI offices in Santiago. This officer's responsibilities entail disseminating NRAO/ALMA news to the Chilean public, representing NRAO at public and educational events, seeking opportunities to promote and teach astronomy, and train teachers, and participating with the JAO's and other ALMA partners' local EPO representatives on joint educational and outreach projects and events.

Connections to the broader astronomy EPO world

NRAO EPO actively participates in the broader astronomical EPO community, presenting and acquiring knowledge of best practices, drawing upon specialized expertise found in other organizations, and seeking opportunities for collaborations and partnerships. NRAO EPO staff routinely attends astronomy education and communication meetings, such as the annual meeting of the Astronomical Society of the Pacific. EPO staff members also receive specialized training to improve their own specialized skills.

A New Focus: Radio Astronomy Visualization

In collaboration with OSO, NRAO will be working with a dedicated data visualization scientist to develop new tools for translating radio astronomy data into such formats, and injecting them into such distribution/amplification networks, as will enable the visualized data (accompanied by audience-appropriate interpretation), to be understood and enjoyed by students and other members of the public who attend digital planetarium programs or use online tools such as *Microsoft's World Wide Telescope* or *Google Sky*.

6.3 Diversity

The NRAO is fully committed to creating a culture and environment that is rich in diversity. The NRAO seeks to have diversity thrive in all aspects of its operations—senior management to site operations—so that its objectives, values, and benefits are readily and continually a part of every NRAO staff member thinking, decisions, and behaviors. NRAO intends to effectively attract, employ, nurture, and retain a diverse workforce that will serve as a role model to other research facilities. In addition, we intend to expand our broader impact initiatives throughout our science community. The NRAO will achieve its diversity objectives in FY 2013-2017 via the initiatives described below.

Figure 6.1 Seven NRAO Jansky Fellows, eight NRAO postdoctoral Fellows, and six University of Virginia postdoctoral researchers delivered talks on a wide variety of science topics at the 7th NRAO Postdoctoral Science Symposium, 11-13 April 2011 in Charlottesville. This annual event rotates among the NRAO research facilities and brings together postdoctoral researchers from across the Observatory to present their work, discuss ideas, and form new collaborations.

A "Bottom Up" Approach

The NRAO will follow a "bottom up" approach in implementing its diversity strategies and initiatives, as detailed in the AUI Broadening Participation Plan. NRAO will continue building and supporting the successful Diversity Advocate model where each NRAO site has an Advocate who provides leadership and promotes the advancement of diversity within the respective sites. Human Resources (HR) will broaden this support and establish well-defined Employee Diversity Groups who will enthusiastically promote diversity and inclusion activities and assist in creating a safe environment for diversity discussions and awareness.

Diversity Training

Diversity Training will be conducted across the Observatory and be customized to each site's local culture and goals. This training will incorporate a wide-ranging discussion on diversity and how it relates to NRAO and its employees, as well as a comprehensive review of the NRAO Diversity Plan and the AUI Broadening Participation Plan.

Community Outreach

NRAO Diversity will actively seek colloquium speakers and lecturers from diverse engineering and scientific staff at other institutions, and craft opportunities for NRAO scientific staff to visit and collaborate with minority institutions, their faculties, and students.

Communications Strategy

HR will design an effective diversity communication strategy for the Observatory. A robust communication campaign will be implemented across the NRAO that promotes and supports the role and purpose of Diversity Advocates, Employee Diversity Groups, and the Diversity Council. Timely and interesting Internet content will be developed and periodically updated for the NRAO staff, public, and science community web sites.

Partnerships

The NRAO will continue to establish and develop effective partnerships with Historically Black Colleges and Universities (HBCU) and Minority Serving Institutions (MSI). We will strive to increase the participation of underrepresented minorities in Science, Technology, Engineering and Mathematics (STEM) disciplines via a well-designed program of education, mentoring, and research experiences for HBCU and MSI students. The NRAO has been successful in hosting Howard University students engaged in scientific and engineering projects. Research collaborations with underrepresented minorities have been established with students from Norfolk State University, West Virginia University, as well as the University of Maryland and University of Virginia. We will seek partners to promote STEM education opportunities to schools within our community and plan to explore international STEM projects.

Recruiting and Hiring

Diversity is also a central element in all NRAO recruiting and hiring. HR will continue to enhance recruitment policies and ensure that search committees and candidate pools for every open NRAO position—scientific, technical, management, administrative, etc.—include a diverse cross section of available talent.

7. Efficient Operations: Administration and Services

7.1 Director's Office

The Director's Office provides executive management for all aspects of the Observatory, long range planning, leadership for scientific research, and community relations. It houses the Director, Deputy Director & Chief Operations Officer, Associate Director for Administration and Chief Business Officer, Associate Director for Programs, and other communication, outreach, and administrative functions. In addition, it includes the OSAA, the Chief Scientist, the Chief Technologist, and the Science and Technology Council.

Office of Science and Academic Affairs

Scientific Staff

The OSAA will continue to have primary responsibility for the scientific productivity and research environment at the NRAO, overseeing the research aspects of all astronomers, and research engineers at all sites. The responsibilities of the OSAA for FY 2013-2017 also include: scientific staff research travel budget, annual scientific performance appraisals, scientific staff hiring and academic promotions, and scientific sabbaticals and leave. The OSAA also oversees adjunct appointments at NRAO, all NRAO colloquia, and the Jansky lectureship.

A productive and active scientific staff is fundamental to the successful operation of cutting-edge research facilities. The scientific staff is key to telescope operations, user support, and long-range development and planning. NRAO has a world-class staff of astronomers, computer scientists, and engineers, who are internationally recognized for their excellence in telescope design and support, as well as their technical and scientific knowledge and production. Recent awards, including Guggenheim, Max-Planck, and AAS Warner prizes, and international engineering awards from the IEEE and International Union of Radio Science (URSI) demonstrate this staff excellence. The NRAO staff is often invited to serve and/or chair key international committees in astronomy.

The scientific staff will continue to be fully integrated into Observatory operations, with clear functional duties relating to the NRAO mission, users, and facilities. In parallel, the scientific staff will continue to be leaders in scientific and technical endeavors on a global scale. NRAO staff will lead large observing programs at NRAO facilities, as well as multi-wavelength programs using other space and ground-based telescopes. NRAO staff will continue to play key roles in planning for the future of radio astronomy, such as the implementation of the relevant recommendations of NWNH. NRAO staff will work with the community to plan and implement future radio programs in key discovery areas, including leadership roles in gravitational wave detection with NANOGrav, studies of cosmic reionization with PAPER, and heliophysics with the FASR.

NRAO staff will lecture at graduate summer schools in radio astronomy and related science and technical areas, including the NRAO aperture synthesis and single dish summer schools that are recognized as the definitive courses in radio astronomy. During FY 2013-2017, NRAO staff will design and provide a short course in millimeter astronomy, and a longer lecture course in general radio astronomy. NRAO scientific staff will be actively engaged in the NRAO REU program, a pre-doctoral fellows program, and a graduate internship program. Scientific staff will also be involved with a range of public outreach programs.

Postdoctoral Fellows

OSAA will continue to oversee NRAO postdoctoral fellowship programs, including the Jansky Fellows and other postdoctoral appointments, fostering development and research opportunities for early career scientists. NRAO will support a diverse group of postdocs, ranging from technologists who build cutting-edge instrumentation to astronomers publishing ground breaking research based on observations with NRAO facilities and other major international telescopes.

NRAO will typically support 12 Jansky Fellows and 4-6 project appointments, as well as resident postdocs with external funding (such as Hubble fellows).

The Jansky program will continue to be NRAO's prize research fellowship program. Jansky Fellows will have no formal NRAO functional duties, though they will be encouraged to contribute, when appropriate, to activities such as telescope commissioning. Jansky Fellows will formulate and carry out their research either independently or in collaboration with others within the wide framework of interests of the Observatory, including instrumentation, computation, and theory.

NRAO facility and project-related postdocs will continue to have functional duties while they also conduct research. These functional duties will range from archive development to telescope commissioning to hardware development.

The NSF has established guidelines for postdoctoral mentoring and reporting for NSF-funded postdocs, and the NRAO will continue to follow and periodically review these guidelines, supporting programs and activities that foster the professional development of its postdocs, such as an annual symposium that provides a valuable forum for all postdocs, including external Jansky Fellows, to present their research and establish collaborations with their colleagues.

International Spectrum Management

NRAO's spectrum management effort is the buffer between the user community and the wider world of commercial radio communication. New astronomy instrumentation allows observations in an ever-increasing swath of the spectrum just as commercial applications await permission to exploit the radio spectrum more widely for their own purposes.

The intersection of these competing interests occurs at many levels in many venues. NRAO filed comments with the FCC about the use of millimeter-wave radars to measure fluid levels inside containers, and on cars for cruise control. But NRAO also explained to U.S. manufacturers why the Chilean FCC equivalent would forbid their use on a proposed fleet of robotically controlled mining vehicles near the ALMA site. Learning the rules and intervening in such a wide range of environments requires a degree of attention to detail that is well suited to the work of a national observatory.

Indeed, representatives of several observatories and their national administrations—including, importantly, NSF—have gathered each year since 1960 in Geneva to coordinate their spectrum management activities at the International Telecommunications Union-Radiocommunication Sector (ITU-R) conference, and at the assemblies of International Astronomical Union, the Committee on Space Research (COSPAR), and the URSI. NRAO has played a large role in this effort, on its own behalf and through the international Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) that is jointly funded by IAU, URSI and COSPAR (www.iucaf.org).

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.

7.2 Observatory Administrative Services

Observatory Administrative Services is home to these NRAO groups: Environmental Safety & Security, Human Resources, Computing & Information Services, Business Services, Fiscal, Contracts & Procurement, and Management Information Systems.

Environmental Safety & Security

The NRAO Environmental Safety & Security (ES&S) group ensures that the Observatory meets the requirement of the Occupational Safety & Health Act to provide a "safe workplace". ES&S will discharge this responsibility in FY 2013-2017 by ensuring that our staff remains competent & capable of delivering a world-class safety program. Training essential to the missions of the Observatory will continue to be made available to all employees of the Observatory, and will be delivered, documented, and tracked by ES&S. Routine and unscheduled audits/inspections will be conducted to ensure this function is being met effectively. ES&S will track and chart lagging metrics as performance indicators and will carefully investigate any incidents that do occur so they can be prevented from recurring.

The ES&S group is responsible for ensuring that the Observatory has clarity and detail in its emergency response plan. Routine and unannounced drills will continue to be conducted to ensure that ES&S is addressing any weak spots that may have developed in the plan or in our ability to execute against it. ES&S will continue to mitigate operating risks in the NRAO facilities by examining risks presented by the work performed within our facilities and identifying the risks and necessary mitigations. ES&S ensures these mitigations are in place when the work begins as well as that they stay in place until the hazard is eliminated.

Human Resources

The HR group is key to enabling the NRAO to be America's premier astronomical observatory by employing and developing people with the critical skills required to continually conceptualize, design, develop, construct and operate the world's most sophisticated radio astronomy instruments. Developing the next generation of astronomers, scientists and engineers, while embracing diversity and capturing the interest of top students from around the globe, are critical elements of the HR long-term strategic plan. NRAO scientific staff pushes the envelope of science and existing technology, ensuring that the Observatory continues to be an exciting and dynamic organization for its workforce.

HR responsibilities include diversity, employee relations, recruitment, employment, compensation, benefits, training and development, regulatory and policy compliance, and HR oversight and guidance of NRAO/AUI's Chilean Local Staff and International Staff supporting the Joint ALMA Observatory in Chile.

In the period covered by this LRP, NRAO's transition from construction to operations for EVLA and ALMA presents unique workforce challenges and opportunities, which the strategic, success-driven objectives and actions below address. These objectives and actions are consistent with NRAO's Workforce Management Plan, Diversity Plan, and the AUI Broadening Participation Plan.

Ensure critical skills retention during the ALMA/EVLA construction ramp down

ALMA and EVLA are entering the completion stages with staff reductions occurring 2011 through 2013. HR has therefore initiated several short and long-term actions to ensure that NRAO retains critical skills among the personnel affected by the ALMA and EVLA construction to operation ramp down. NRAO budget challenges during these years and beyond add to the retention challenge.

To identify critical skilled staff across the Observatory, a Critical Skills Inventory was conducted via an employee survey in 2010 to identify those staff members with the skills necessary for NRAO's ongoing success. High participation from staff was assigned to construction projects.

The next step involved two voluntary Early Retirement Programs, in fall 2010 and spring 2011, to reduce NRAO personnel costs and provide opportunities for critical skilled ALMA and EVLA staff to apply for the limited backfill opportunities that were permitted. A nominal additional cash incentive and three-year minimum moratorium on future Early Retirement Programs was included in the spring 2011 Early Retirement Program to encourage participation. These measures also reassured staff that NRAO was doing all that it could to reduce staff before contemplating the use of an involuntary staff reduction program.

A process was instituted throughout NRAO to ensure that ALMA and EVLA construction staff are afforded every opportunity to apply for open positions throughout NRAO, including open ALMA positions in Chile. HR instituted a "push" recruitment communication strategy that alerts all employees of job vacancies quickly and effectively as soon as a job is posted internally. NRAO employees are therefore provided an opportunity to apply for open positions prior to external candidates. HR takes this process one step further by reviewing the skills of ALMA/EVLA construction staff included in the Critical Skills Survey to identify and contact potential candidates. Finally, for critical skilled ALMA/EVLA construction staff that leaves the Observatory at the end of their assignment, HR will maintain an active post-employment contact list for future opportunities. A complete Workforce Management Plan, which includes an Observatory Staffing Plan is maintained outside of this document.

Enable the successful transition of NRAO's impending workforce generation changes (retirement), including the ability to attract, develop and retain the next generation of astronomers, scientists, and engineers.

The changing workforce demographics require a strategic and planned approach in pay and benefits to attract, develop, and retain a highly skilled staff in the future. HR has developed an NRAO Total Rewards Strategy (TRS) that values all rewards (compensation, benefits, etc.) employees receive and enables NRAO to make informed benefit and compensation decisions. Understanding NRAO's competition for talent is a critical component of the TRS, so a comprehensive review was conducted to identify benchmark peer and competing organizations that NRAO will use in assessing its compensation and benefits programs. Supplementing this information are periodic employee surveys that measure and benchmark employee engagement and satisfaction. Employee surveys were conducted in 2007 and 2010, with the next survey scheduled for 2013 to coincide with the final year of the ALMA/EVLA construction ramp down.

Two critical TRS initiatives started in 2011 and will continue through 2017. First is ensuring that NRAO is paying its employees appropriately, which is critical in attracting and retaining top talent, especially considering the Observatory's expanding international hires for ALMA. The most critical initiative involves compensation whereby HR is conducting a thorough review of NRAO's compensation program, including a compensation policy update, career paths (job families), and updated job descriptions for all NRAO jobs (reviewed annually by employee and supervisor.) Much of the credit for NRAO's increasing success in attracting top talent to ALMA in Chile is a direct result of this initiative. In this case, HR's ability to assess and effectively communicate a candidate's total compensation package relieved the pressure on past demands for high base salaries. Finally, tying compensation to the achievement of NRAO goals and objectives will be enhanced though the use of an electronic performance evaluation process. NRAO will beta test a new software program in 2011 that could enable this process and provide NRAO with a means of evaluating individual skills. The implantation of such a system should be fully transitioned into the organization over a two-year period.

Medical coverage is the second and most complex critical initiative. NRAO's mature workforce will be retiring in increasing numbers over the next decade. This will open opportunities for a new generation of diverse employees that have different needs. Maintaining compliance with the myriad of regulations mandated by Health Care Reform vastly increases the complexity of major modifications to NRAO's medical plans over the next five to seven years. Limited financial resources, increasing medical costs, and the looming increase in retirees in the coming years has prompted the need for NRAO to move away from traditional health care programs to ones that accommodate the future needs of the workforce and Observatory. The strategic planning process is well underway and incorporates a phased approach to transition NRAO's medical plans to individual Heath Savings Accounts for all employees. The transition process will span FY 2013-2017 and beyond.

Cultivating future diverse scientists and engineers and enable and empower employees to play an integral role in NRAO's diversity and broadening participation programs.

As described in the section Diversity & Broadening Participation (Section 6.2), HR is involved in supporting both programs with direct responsibility for the majority of Diversity initiatives.

As with many organizations with diversity programs, HR leads the Observatory's effort to search and hire diverse employees. Search methods include reaching out to known diverse sources. However, NRAO stands apart in finding and nurturing future female and minority scientists and engineers. NRAO is aggressively recruiting interns and co-op students and plans to establish two new partnerships by 2017 with minority-based education institutions similar to its successful, ongoing partnership with Howard University. Besides offering internships to students, NRAO scientific and engineering staff will conduct colloquia and lectures at Minority Serving Institutions and invite scientific and engineering students to visit NRAO.

Diversity will be successful if it becomes a part of the Organization's culture. It is imperative that employees become enabled and empowered to play an integral role in NRAO's Diversity and Broadening Participation Plans. HR is leading this effort through NRAO's site-based Diversity Advocates who are empowered to organize their respective diversity employee work group volunteers. HR works with the Diversity Advocates and provides training and development support to them, their work group members, and employees at the sites.

Develop the next generation of leaders

Meeting the future challenges NRAO faces as an international observatory requires a new breed of leaders. To meet this challenge, NRAO has initiated in 2011 a leadership development program that is customized for scientific staff. The rationale behind this approach is to address the reality that scientists rarely, if at all, receive any training in leadership during their education. The program will be offered to all potential leaders, be expanded to cover non-scientific staff, and include refresher training over the course of this Plan.

Enable the success of NRAO International Staff and AUI Chilean Staff working for ALMA Chile, through JAO Human Resources or direct support of staff

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, so 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.

In 2013, 2015 and 2017, HR will oversee the Chilean staff collective bargaining process. Helping ensure that a positive labor relations environment is maintained during this period is a top priority. HR will work collaboratively with the NRAO Office of Chile Affairs and JAO HR team to make this happen.

HR will work in conjunction with JAO HR and the ALMA Executives to maintain the successful integration of all staff working for ALMA in Chile and to enhance the International Staff experience. As NRAO International Staff return home from their assignments, HR will ensure they are fully supported in integrating back into NRAO's U.S. workforce.

Computing & Information Services

Overview

CIS oversees operational computing support needs for the observatory sites. This includes planning, policy, standards, computer security, allocation of the shared central budget, web services, computer staff training, inter-site computing related travel, procurements, and software/hardware maintenance contracts. CIS periodically upgrades computing infrastructure for desktop and servers, as well as printers and the storage systems required to provide archived observation data to the community. NRAO telecommunications infrastructure within the observatory is also a CIS responsibility.

In the next 2-4 years, unprecedented staff and infrastructure demands will be addressed by CIS via a close partnership with OSO that provisions critical services such as Archive, High Performance Computing, next generation networks, and web content management solutions.

CIS will adapt and exploit advances in the computer and communications industries. Within FY 2013-2017, the increased data flow from the EVLA, ALMA, and GBT will mandate that NRAO substantially enhance its computational and data management resources. The opportunity to partner with national computing research centers is an essential CIS strategic goal, given the data and compute intensive nature of new and enhanced observatory instruments. Partnership with national computer centers and telecommunications providers is essential to ensure appropriate sharing of knowledge and infrastructure to support a distributed user-base.

NRAO sites and major projects each have a computing division charged with providing local user support and reporting to the site director. CIS coordinates the activities of the computing divisions through the Common Computing Environment.

The following sections outline the FY 2013-2017 CIS activities that will assure an optimum computing, storage, and communications environment for staff and users of NRAO telescopes, and a proactive development program.

Computing Standards and Policy

To provide a uniform structure to carry out the mission, CIS has the responsibility to develop, evolve, and enforce standards, policies, and conventions designed to maximize consistency between sites, while enabling the diversity and agility needed in an active research environment. Policies address computer use, information security, major software procurements, computer hardware purchasing, etc. Standards include supported computer hardware configurations and application software suites. The evolution of web-based applications, Software as a Service, mobile access, and distributed computing will require CIS leadership to inform, and be informed by, the user community. A major long-term commitment is seen in ensuring observatory-wide alignment for archive access, especially for data processing driven by OSO in collaboration with the Virtual Astronomical Observatory (VAO).

CIS supervises the maintenance of all computer equipment and software observatory-wide. This role must shift to integrate the NRAO portion of ALMA via the North American ALMA Science Center (NAASC) and be cognizant of the challenges imposed by the close collaboration with a global organization (JAO) with divergent standards, policies, and support expectations.

Common Computing Environments (CCE)

CCE minimizes and leverages the differences between site-specific computing environments within the observatory. It is important to ensure that the NRAO-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. Early within this plan's timeline, NRAO will adopt System Center to better coordinate the centralized management and administration of our Microsoft systems. The key CCE areas of mobile access, distributed computing and web-based applications will be leveraged heavily over the next 5 years.

Information Infrastructure (Web Services)

The Observatory continues to improve its web services in collaboration with Communications and Education & Public Outreach. This team will implement a web-based content management system (CMS) and user portal applications development environment to provide reliable information with high availability to a diverse audience with integrated workflows and content version control. The successful implementation of the science.nrao.edu into the new CMS will be leveraged for the internal staff site as well as archive access and user documentation support.

Web-based collaboration software will continue to be a key tool across the observatory, helping individuals, groups, and projects perform collaborative tasks including project management, reporting, documentation, and software development. CIS is committed to improving the interactive nature of these tools to include presence, video and real-time information sharing between NRAO users and systems but, as always, needs to strike the balance between accessibility and security.

Integrating the NRAO Helpdesk and User Portal is a major initiative that will improve the quality and transparency of access to observation support as we push to broaden the audience to key services and data repositories, as well as analysis tools developed in conjunction with the VAO and others.

CIS provides web and mail-client interfaces enabling staff to access their e-mail in a safe and secure manner, but the increasing ubiquity of mobile devices presents an opportunity of enhanced communication and inter-personal interactions better suited to modern life.

Networking and Telecommunications

CIS has consolidated many of our long-distance phone services under a single contract through the General Services Administration (GSA) Federal Telecommunication Service Networx contract that will be in place for most of FY 2013-2017. CIS also provides web meetings, audio conferencing, international and domestic toll-free service, and calling cards to key employees under this program. This consolidation results in easier account management, lower overhead, and lower overall cost. CIS will migrate other services, such as cell phones and mobile data access as appropriate. NRAO completed the shift to a Multi-Protocol Label Switching (MPLS) WAN in 2011 to better support the prioritization of critical data-flows between the sites, and to enable the expansion of High-Definition video conferencing in the next 3 years.

The NRAO is a sponsored participant in the Internet2 from all major locations, with access to National Lambda Rail. NRAO must ensure that planned network connectivity will be adequate to support future operations, and is committed to increase bandwidth from the current ~ tens of Megabits/second to the Gigabit/second speeds that will enable access to the 100+ Gigabyte data sets from new instruments. The core network at each site must also be moved to 10 Gigabit/second between routers and key servers to enable support for Gigabit to the desktop. A 10+Gigabit/sec backbone network in West Virginia in 2012-13 will dramatically improve the access to the Green Bank site for data acquisition and analysis. The EVLA link will likewise be increased from 1 to 10 Gigabit/sec to keep pace with the full science operations data rates.

During the 2012-14 timeframe, the archive synchronization from the ALMA Santiago Central Office to the multiple regional centers will be initiated. Observed data will be replicated to the NAASC from Santiago in real time over a Gigabit data connection shared with the National Optical Astronomy Observatory.

The 20 videoconference systems supported by CIS provide critical communication links between the major sites, leveraging the intranet infrastructure. This equipment will be upgraded to enhance collaborations with HD video and high-resolution remote data presentation, and to enhance the options for training as well as desktop video access.

Computing Security

A solid computer-security policy is a prerequisite in securing any enterprise from on-line threats. NRAO policy balances the conflicting requirements of accessibility with the need for security in an increasingly hostile yet access-enabled environment. NRAO policy was augmented recently by well-defined data sensitivity ratings and annual all-employee training sessions that ensure awareness is sustained. This will be periodically updated with regard to mobile data access for financial, health and sensitive data.

NRAO security is achieved via implementation of the security policy crafted by the Computing Security Committee (CSC), which includes representatives from each major NRAO activity, plus Management Information Services (MIS) due to their responsibility for our 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 CSC is addressing the growing risk from mobile and wireless equipment.

NRAO will continue to improve and periodically refresh security education and documentation for all its computer users. It will maintain and enhance the security measures already in place, and move to a Risk Management framework to better prioritize the mitigation of service disruption. NRAO will also maintain Virtual Private Networking, which allows travelers and telecommuters to securely access internal services, and enable secure communications channels to remote institutions.

Observatory-wide Computing Infrastructure Coordination

Digital Infrastructure: Observatory wide Digital Infrastructure (DI) covers larger enhancements to computing infrastructure, as well as enhancements for individual science requirements. Large-ticket items are in this category: servers, wide-bed printers, central disk arrays, etc. The on-going expense of growing the EVLA-VLBA-GBT and ALMA-NAASC archive track to OSO for cost accountability and operational efficiency. With the commitment to preserve validated observation data, our planning must include the imminent 2-3 orders of magnitude growth in data rate over the next 2 years. This is an identified risk for storage, and for the space, power, cooling and staff needed to service these data indefinitely. A unified strategy of leveraging commodity disk in high availability arrays, with diverse site redundancy, is in place and will support our predicted needs through FY 2017. A concomitant increase in computing resources and network bandwidth is likewise predicted. It is expected that highly parallel—Multi-core nodes, Clusters and GP-GPUs—resources will be employed for data manipulation and analysis communicated over 40 Gbps interconnect fabrics. In addition, each of the three main sites Internet connections will be uplifted to 10Gbps bandwidth to ensure adequate access to archived data and VAO resources.

Recurring Costs: The Recurring Cost items ensure that our computer systems are refreshed on a regular cycle: a maximum of ~ 5 years for desktops and laptops with the upgrade of mission critical servers migrating to virtual hosts as appropriate. The total NRAO computer system count is 1,500+ and continues to present a challenge, especially the popularity of more expensive laptops. Net-books, Smartphones and Tablets will be embraced insofar as they align to the Observatory mission and reduce overall cost while improving access and communications.

Contracts: Maintenance of 100+ contracts and support for widely used software (Office productivity suites etc.), hardware (computers, video systems, etc.), and our intranet service is a major CIS activity. By consolidating licenses or equipment from multiple sites, CIS negotiates better discounts with vendors. The contracts volume will increase in FY 2013-2017.

Business Services

The Observatory Business Services (OBS) division provides management and support for budget development and analysis, facilities planning, and general business administration for Charlottesville operations and Observatory-wide requirements. OBS has three main functions that will continue in FY 2013-2017: Budgets & Business Analysis, General Business & Administration, and Charlottesville Facilities.

Budget & Business Analysis: Budget & Business Analysis is responsible for developing, monitoring, and reporting on the Observatory budgets including multi-year forecasts, monthly budget reports, and ad hoc requests.

General Business and Administration: The business and administration duties include preparation of the Observatory Commitment Authority and Blanket Travel lists, non-medical insurance, Charlottesville invoice processing, sales summary, material receiver processing, petty cash, charge card reconciliation, visitor coordination, NSF submittals, employee relocation (Charlottesville, Green Bank, and Chile) and general clerical support.

Charlottesville Facilities: The Charlottesville facilities activities include managing all aspects of maintaining the facilities, assigning office assignments, lease management, and ensuring the safety, security, and usability of the site.

As ALMA approaches full science operations, OBS will have more routine involvement with the OCA especially with budget development, budget tracking, and business processes. No increase in personnel is projected, but more travel to Chile is anticipated to oversee and coordinate activities with the OCA and JAO staff.

During the FY 2013–2017 period, several facilities projects will be necessary to enable ongoing communications, preserve Charlottesville facility security, and enhance inventory reporting. The Charlottesville-Edgemont Road facility will require physical security enhancements including surveillance cameras on all external accesses and parking lots. To achieve and maintain an accurate and timely inventory, the Charlottesville facility will implement a bar code inventory system that parallels systems used at other NRAO North America facilities.

Fiscal

The Fiscal Division provides strategic financial support for business and operational planning, supports the NRAO in major financial functions, and meets external and internal audit and reporting requirements.

External and Internal Audit Support: Fiscal is primarily responsible for the planning, preparation, and interface with the external auditors pertaining to the annual OMB-A-133 and financial audits. NRAO/AUI received exceptional reports for the FY 2007 through FY 2010 OMB A-133 and Financial Statement Audits. The "Auditor's Report" cited an "Unqualified Opinion" and the "OMB A-133 Report" cited no findings or questioned costs. Fiscal will participate in all future planned internal audits pertaining to financial reporting.

Observatory Support for Major Accounting Functions: The Fiscal Division is primarily responsible for the administration and oversight of all major accounting functions, including the following.

- Payroll processing: Fiscal processes payroll for ~ 650 employees for multi-state and international employees. Labor reporting is completed via an Electronic Time-Keeping (ETK) system.
- Accounts Payable: Fiscal administers accounts payable at three sites for invoices associated with purchase orders and standard invoices.
- Cash Management: Fiscal monitors cash flow at the three primary sites and administers the drawdowns of federal funding to ensure adequate cash availability to meet all disbursements.
- Program Revenue: Fiscal administers the recording of all program revenue pertaining to guest housing, cafeteria, and gift shop income.
- Financial Reporting: Fiscal is responsible for monthly and year-end closing of the general ledger and issuance of the monthly and annual financial statements.

Fiscal will execute the following initiatives in FY 2013-2017.

- Automated Clearing House (ACH) Payments: Fiscal will complete the implementation of ACH payments to vendors for all categories of payments in FY 2013.

- Business Services Cost Pool: Fiscal will work with Management Information Systems to manage the "Business Services Cost Pool" to allocate NRAO shared administrative and overhead costs to all funding sources, and will administer the system allocation as part of the monthly closing.
- Personnel/Training: Maintain the current staff of competent and qualified personnel by providing challenges, training opportunities and encouraging professional growth through continued education and certification processes. Additionally, Fiscal will monitor the current Succession Plan to ensure continuity of service.

Management Information Systems

The Management Information Systems (MIS) Division provides Observatory-wide business systems support to all aspects of Observatory operations including electronic timekeeping, payroll, human resources, general ledger, accounts payable, business computer (Windows Based and SQL), and support hardware computers. 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 EnterpriseOne 8.10 product as the NRAO Enterprise Resource Planning business software.

MIS has the following projects scheduled for FY 2013-2017.

- Business Services Cost Pool: MIS will work with Fiscal to manage the Business Services Cost Pool that will allocate administrative and overhead costs to funding sources using proration calculation methods.
- Business Software Upgrade: MIS will perform a major upgrade to the Oracle J. D. Edwards EnterpriseOne software and its associated hardware.
- Audits, Enhancing Reporting, and Employee Information Central Repository: MIS will support all enhance the reporting capabilities for new and existing work breakdown structures, electronic timekeeping, and Business Services Cost Pool. MIS will also develop a central repository for employee information housed within the J. D. Edwards software, which will include information currently not in the Human Resources module.

Contracts and Procurement

Contracts and Procurement (C&P) commits AUI funds through the procurement of goods and services to meet corporate and customer needs in a timely, cost effective manner, in accordance with our policies, the NSF Cooperative Agreement and the Federal Regulations. C&P ensures that asset tags are placed on capital equipment and reviews invoices to ensure they are in accordance with Purchase Order Terms & Conditions. An internal client approves for payment, which is then submitted to Fiscal.
C&P supports the numerous internal/external audits. C&P ensures contracts administration is performed in accordance with contract terms and conditions and pricing, and ensures compliance with change order procedures. It interfaces and acquires approval from AUI/NSF for all procurements exceeding $250K or major change orders, and non-AST NSF funding opportunities exceeding $25K.

In addition, C&P provides these services:

- Authorizations/Approvals: Responsible for NRAO's commitment list and approval routes, ensuring they are current and complied with based on levels and authorizes. Ensure the updates are published and communicated to NRAO.
- Proposals: Provide contractual support to AUI and NRAO for all new funding sources.

- Manage grants and ensure they are submitted through Fastlane.
- Website: Update the Peer-to-Peer information and online training. Update the Procurement Website.
- Manuals: Update Import/Export and the recently republished C&P Manual, as needed. Create a P-Card program, issue a P-Card Manual, provide training and add to the website.
- Training: Create or update training modules for internal users. Ensure contracts and procurement personnel continue with their individual training and/or certification programs.
- Import/Export: Perform import/export transactions in an economic and expedient manner. Ensure Import/Export actions are in compliance U.S. and International Governmental regulations. Monitor the regulations for impacts and/or required changes performed by Contracts and Procurement. Ensure that all procurements, contracts and grants follow requirements of Contracts and Procurement Manual, the Cooperative Agreement and other regulations.

During the period of this plan, C&P will experience some scope change. Procurements and contracts will decline somewhat as ALMA Construction ends, although NRAO expects to assume a role in NWNH projects and alternative funding opportunities that will involve contracts and procurements. ALMA Operations will increase, including development activity. Non-programmatically funded projects with new institutions will increase which will involve additional contracting complexity.

Export compliance. By early FY 2013 C&P will implement an export compliance program across the Observatory. The program will include a technology transfer plan, export procedures manual, and awareness training.

Office of Chile Affairs

The small Office of Chile Affairs (OCA) in Santiago, part of the NRAO Administrative Services, carries out primarily the NA share of the procurement and business activities and budget tracking for the JAO during ALMA construction and operations, and on matters of policy, relations with the Chilean government, and legal issues in Chile acts for and reports directly to AUI. It makes sure on a daily basis that business and legal activities in Chile follow the required local and U.S. norms and that these are applied in ways that optimize performance and accountability. Specifically, it supports the business and legal affairs of NRAO/AUI in Chile including NA legal representation of ALMA to the Republic of Chile and the local scientific community for NRAO and AUI and maintains daily interactions with and support for JAO staff. Very importantly, the OCA takes care of all legal aspects for the hiring of all local ALMA Chilean staff, as AUI/NRAO is the sole employer of such staff.

The OCA will continue to provide support for ALMA Human Resources activities in the JAO as directed by the NRAO head of Human Resources, including contracts, payroll, labor negotiations and local travel support. The OCA directly interacts with the labor union of local ALMA staff, all AUI employees, and also monitors and interfaces with the Peer Health & Safety Committees NRAO/AUI has created both in Santiago and the ALMA site. The OCA is therefore directly involved in the critical area of labor relations and health and safety supervision in support of the JAO.

The OCA Fiscal Department manages payment of purchases made in Chile via the NRAO for ALMA construction and operations and monitors compliance with standard norms and strict adherence to the established ALMA budget. This office is also responsible for local property management and NRAO import/export activities for ALMA.

Continuing site protection activities will include supervision of ALMA mining claims, external claims monitoring (e.g., water and geothermal claims), monitoring of RFI-related activities, and functioning as the channel for formal government and community contacts, including the aboriginal community in the ALMA site area, and the monitoring and maintenance of ALMA's environmental commitments. The OCA also supports the relocation and cultural immersion of NA expatriates and their families to Chile.

Reductions to Meet the Budget

The Administration functional managers for Business Services, Fiscal, Contracts & Procurement, and Management Information Systems have reviewed their respective budgets and identified a variety of areas that will be cut or significantly reduced within this budget guidance level unless supplemental funding sources are available and the need to retain staffing levels is in balance. The primary areas of reduction include travel and professional training, reduction in copier leases, and reduction in the availability of general office supplies and vehicles. Mailing and courier services will also be reduced in scope and frequency. These options will be reviewed on a continuing basis as actual costs are applied and the extent of necessary reductions are better understood.

The Charlottesville leases are one of the single largest budget elements within Administration. If the scope of the ALMA Operations Maintenance & Repair program and the ALMA Operations Development program are relatively small it will present the opportunity to reduce the NRAO Technology Center (NTC) footprint when the lease expires at the end of FY 2013. A renegotiation of the lease for a smaller NTC footprint can achieve savings that will reduce leasehold and utilities costs and be a significant portion of the Administration contribution towards keeping the budget balanced.

Appendix A: Budget Projections

Omitted for external distribution

Appendix B: Resource Projections

Omitted for external distribution

Appendix C: Major Milestones and Functional Tasks

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
OSO	User Portal	Provide NRAO users with integrated access to ALMA & EVLA/VLBA/GBT portals.		X			
	Helpdesk	Develop an integrated helpdesk interface for both users and NRAO support staff including combined access to the Knowledgebase.			X		
	Proposal Handling	Ensure that users will be able to apply for joint observations between facilities (ALMA, EVLA, VLBA, GBT).		X			
	User Support	Host Single Dish Summer School and NRAO Synthesis Imaging School.	X	X	X	X	X
		North American ALMA Science Center Community Day training model will be extended Observatory-wide.	X	X	X	X	X
		Design and repackage the face-to-face tutorials and training to also be available as customizable on-line, on-demand programs.		X			
		Develop user training materials for instrument and technique-specific workshops, observation preparation, data reduction/analysis, online and live demos, and online courses and teaching materials.	X	X			
		Track quantitative metrics of program effectiveness, user community size, and diversity.	X	X	X	X	X

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		Conduct periodic surveys of the user community (in consultation with the NRAO Users Committee and other advisory committees) to assess the effectiveness of the training program.	X	X	X	X	X
	Science Community Outreach	Semi-annual American Astronomical Society (AAS)	X	X	X	X	X
		Organize one or more science symposia at various venues	X	X	X	X	X
		Implement technologies into our Internet environment that improve two-way communication between and among our users and staff	X	X	X	X	X
		Create more flexible forums for on-line communication between and among our staff and the broad community of users	X	X	X	X	X
		Evolve science Internet content management system to offer more flexible, adaptable workflows with improved security and extensibility.	X	X	X	X	X
		Create and manage documentation appropriate to the science web, including observer "cookbooks," user manuals, and expert documents.	X	X	X	X	X
	Archival Access and Storage	Community access to a validated set of historical GBT data products will be completed.				X	
		Deliver an ALMA archive interface that is common across the international project			X		

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		Provide an integrated interface to archives across to all four instruments – GBT, VLBA, ELVA, ALMA that leverages technology developed for the Virtual Observatory.			X		
		Provide storage capacities for each facility in the petabyte range.	X				
		Leverage commodity storage with the Next Generation Archive System (NGAS) developed by ALMA	X				
		Provide scientific and technical support for comprehensive NRAO participation in, and data availability through, the VAO.	X	X	X	X	X
	Metrics and Statistics	Generate Observatory-wide metrics and statistics, routine reports, on-demand special reports, for GBT, VLBA, EVLA, and ALMA, covering proposals, observations, visiting users, remote users, community support programs, and bibliometrics.	X	X	X	X	X
	Pipeline Processing	Individual pipeline heuristics (rules for processing of data) will be in place by FY 2013 for each of GBT, VLBA, EVLA, and ALMA.	X				
		Completion of data reduction pipeline for 90% of GBT observations		X	X		
	Data Processing	Continue to incorporate new calibration and imaging algorithms into (CASA) data reduction package for ALMA and EVLA.	X	X	X	X	X
		VLBI-related functionality and a single-dish data reduction path for the GBT developed.				X	X

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		Splatalogue will be expanded to support observers of all NRAO telescopes, and new spectral line data will be incorporated as they become available.			X	X	X
	High Performance Computing	Provide access to high performance computing platforms sufficient to process ALMA, EVLA, and GBT data.		X			
		Provide advice and guidance to assist the user community in defining and implementing computing resources at their home institutions.		X	X	X	
		Define methodologies for managing, analyzing and visualizing multi-Terabyte datasets.			X		
		Adopt and evolve existing software tools from other data-intensive disciplines and make them available to the user community via the NRAO science web.	X	X	X	X	X
		Capabilities and tools developed for interdisciplinary discovery across the electromagnetic spectrum and observing platforms; and for users to access, interact with, and analyze observed and archived data.	X	X	X	X	X
OTO							
	NA ALMA Ops	ALMA Full Science Operations	X	X	X	X	X
		Start providing ALMA Offsite Hardware Maintenance Support	X				
		Start providing ALMA Offsite Software Maintenance Support	X				
		Execute development projects	X	X	X	X	X
	EVLA	EVLA Construction Closure	X				
		EVLA Full Science Operations	X				

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		Provide end-to-end data products comprising raw and pipeline-calibrated visibilities, and reference images for each spectral window, for data acquired in standard observing modes.					X
		Data reduction and analysis software, and a post-processing computer cluster, will be available for users for the re-processing of data at the beginning of full EVLA operations.	X				
		Provide advanced WIDAR observing modes that lie beyond the capabilities delivered under the EVLA construction project.	X	X	X	X	X
		Flagging of RFI-affected data automated and incorporated into the EVLA's online system.	X	X	X	X	X
		Conduct periodic inspection and overhaul cycles on EVLA and VLBA antennas.	X	X	X	X	X
		Replace approximately 5000 ties per year at the EVLA site.	X	X	X	X	X
	GBT	GBT Structural painting performed.	X	X	X	X	X
		GBT structural inspection performed.	X			X	
		Replacement of software libraries for GBT.	X				
		Replacement of the servos on the GBT's secondary mirror.	X				
		Monitor and Control Software upgrade complete.	X				
		Installation of multi-frequency Tipping Radiometer complete.	X				
		GBT Receiver Room Upgrades study complete.	X				

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		New backend for the GBT to replace the existing GBT spectrometer completed (collaboration)		X			
		200 MHz bandwidth cooled phased array feed in the 1-2 GHz range for GBT available (CDL plus collaboration)				X	
		8-pixel 82-116GHz prototype integrated feed horn system for GBT available (CDL plus collaboration)				X	
		100-pixel bolometer array using Microwave Kinetic Inductance Detectors (MKID) technology (CDL plus collaboration)				X	
		4mm two-pixel receiver for molecular line and VLBA studies for GBT available (CDL plus collaboration)	X				
		Wide-bandwidth receiver optimized for the NANOGrav Gravitational Wave detection pulsar experiment at 15cm for GBT available (CDL plus collaboration)	X				
		Broadband receiver covering 12-18 GHz for the detection and study of pulsars in the Galactic Center	X				
		GBT will be readily able to store, visualize, and analyzed datasets of 50-100 TB in size.					X
	VLBA	Monitor and control system and the aging computers on which it runs will be completely replaced with EVLA system		X			

Section	Subcategory	Specifics	FY2013	FY2014	FY2015	FY2016	FY2017
		Extension to 512 MHz/pol (4 Gbps) or better through improvements in data recorder technology.					X
		Design of a new pulse calibration (PCAL) generator complete.	X				
ODP							
	CDL	Develop a 37-element cryogenic array on the GBT with system temperature less than 25 K.			X		
		Develop an end-to-end integrated receiver that incorporates a state-of-the-art digital orthomode transducer	X	X	X		X
		Develop the technology for a nearly quantum-limited receiver at 350 microns (~850 GHz).	X				
		Develop reproducible, reliable, inexpensive, quantum-limited SIS receivers based on NbTiN technology	X	X	X	X	X
		Develop fully reconfigurable computing; using FPGAs, Graphics Processing Units (GPUs) and multi-core, clustered Central Processing Units (CPUs) to provide signal processing capability in the most flexible and cost-effective way	X	X	X		X
		Designs and build passive electromagnetic components.	X	X	X	X	X
	Computing Development	Develop and implement data processing, storage, and communications architectures	X	X	X	X	X
		Automate and standardize key activities such as data flagging and editing, calibration, and the excision of radio frequency interference in real time for streaming data.					X

Appendix D: Above Guidance

NRAO operates under a SPO for ALMA Construction and two separate Cooperative Service Agreements for North America ALMA Operations and NRAO Operations. In addition, NRAO obtains supplemental funding through Memoranda of Agreement, grants, or other contracts. To correctly identify projects that that would benefit the Observatory as a whole, projects are solicited across all funding sources and then prioritized in a uniform manner, according to science impact and importance to mission. Projects approved by this process that are specific to ALMA Operations, or other specific contracts are then charged to those accounts. In this way, projects are chosen that have the greatest potential within all NRAO. If additional supplemental funding is obtained, these projects will be reviewed to determine which projects fit within the priority and level of additional funding.

Not all projects can be funded at the present allocation levels. NRAO maintains a list of development and infrastructure initiatives in case funds become available and as a reminder of issues and opportunities pending. The lists are organized below as Instrumentation & Development Projects and Infrastructure Upgrades. Details for these projects are maintained outside this document.

- Instrumentation & Development Projects
    - EVLA E-configuration upgrade
    - EVLA Pie-Town Link
    - EVLA Water Vapor Radiometers
    - EVLA long-wavelength receiver system
    - EVLA Tipping Radiometer
    - GBT W-Band Focal Plane Array Development
    - GBT Camera Development Infrastructure
    - CDL Waveguide Thermal Gap for Cryo Rx
    - CDL High Temperature Superconducting Circuits
    - CDL Four-Probe Square Coax Coupler OMT
    - CDL Wideband Low Freq Rx Development
    - RFI Excision R&D
    - VLBA 4Gbps Upgrade
    - VLBA Advanced LO/IF Development
    - Software Development Lab
- Infrastructure Upgrades
    - EVLA / VLBA: Telescope Control and Drive System Replacement
    - EVLA: Computing Infrastructure and Networking Upgrades
    - EVLA: Atmospheric Phase Monitoring System
    - EVLA: Standby Diesel Generator and Switchgear
    - EVLA: Drive Cabinet Replacement SCR Logic Card
    - EVLA New Atmospheric Phase Interferometer for the EVLA
    - EVLA: Upgrade bar coding property control tooling
    - EVLA / VLBA: Domenici Science Operations Center Upgrade key card entry system
    - GBT: Digital Lab Test Equipment
    - GBT: W-Band Test Equipment
    - GBT: Lab Spectrometer
    - GB: Site Emergency Generator
    - GB: All-site Public Address System
    - GB: RFI shielding for computers

- GB: Telephone Line Connection to the central switching office
- GB: Gigabit to the desktop
- GB: Bridge replacement
- GB: Energy-efficient Window Replacement
- GB: Fuel-efficient off-site vehicle replacement
- GB: JLG Manlift, 1200SJP
- GB: Wellness Center
- GB: Dormitory Addition
- GB: Humidification system for laboratory addition
- GB: Outdoor Telescope Range Control Upgrade
- GBT: Vibration Monitoring System
- GBT: Warehouse heating and insulation – Offices
- GBT: Warehouse shielded electronics areas
- VLBA: PT Diesel Generator
- VLBA: Media to Support 2Gps Recording
- Central Instrument Lab: 16 inch CNC Conversational Lathe
- Central Instrument Lab: 10 inch Conversational Lathe
- Central Instrument Lab: Swiss Machining Center
- Central Instrument Lab: Lab expansion
- CV: 1st floor reconfiguration
- CV: Cell phone booster installation
- CV: Wireless internet improvements
- CV: Exterior video surveillance cameras
- CV: HD video upgrade to CV auditorium
- CV: Renovate Freight Elevator
- CV: Mobile video conference units x3
- CDL: Very high precision Kern Evo milling machine
- EPO / EVLA: Outdoor Tour Signage
- EPO / GBT: Tour Video
- EPO / GB: Lift settled outdoor star party patio slab that has settled below sidewalk level
- EPO / GB: Science Center - Emergency Generator
- EPO / GB: Science Center - Finish basement
- EPO / GB: Well & Septic for 40' Telescope (GB)
- EPO / GB: Expand Science Center for Science institute
- Other: Electronic Document Management System
- Other: NRAO Quality System
- Other: Digital Library of Telescope Construction Documentation
- Other: Commerce Class Web Site

Appendix E: Acronyms

Acronym	Definition
AAS	American Astronomical Society
ACH	Automated Clearing House
ADASS	Astronomical Data Analysis Software and Systems (ADASS)
AGN	Active Galactic Nucleus, or Active Galactic Nuclei
ALMA	Atacama Large Millimeter Array
ARC	ALMA Regional Center
ARRA	American Recovery and Reinvestment Act
ASC	Array Science Center
ASIC	Application-specific integrated circuits
ASKAP	Australian Square Kilometre Array Pathfinder
ASIAA	Academia Sinica Institute of Astronomy and Astrophysics
AST	NSF Division of Astronomical Sciences
ATI	NSF Division of Advanced Technologies and Instrumentation
AU	Astronomical Unit
AUI	Associated Universities, Incorporated
BAO	Baryon Acoustic Oscillations
BeSSeL	Bar and Spiral Structure Legacy Survey
BYU	Brigham Young University
CALTECH	California Institute of Technology
CASA	Common Astronomy Software Applications
CASPER	Center for Astronomy Signal Processing and Electronics (UC Berkeley)
CCE	Common Computing Environments
CDL	Coordinated Development Laboratory (renamed from Central)
CH	Carbon Hydrogen
CICADA	Configurable Instrument Collaboration for Agile Data Acquisition
CIS	Computing and Information Services
cm	centimeter
CMB	Cosmic Microwave Background
CO	Carbon Monoxide molecule
COSPAR	Committee on Space Research
COTS	Commercial Off-the-Shelf Software
CPU	Central Processing Unit
CSA	Cooperative Support Agreement
CSC	Computing Security Committee
CV	Charlottesville, Virginia
C&P	Contracts and Procurement
DARE	Dark Ages Radio Explorer
DARPA	Defense Advanced Research Projects Agency
DI	Digital Infrastructure
DiFX	Distributed FX Correlator
DSP	Digital Signal Processing
DVA-1	Dish Verification Antenna
EELT	European Extremely Large Telescope
EoR	Epoch of Reionization
EPO	Education and Public Outreach
ESA	European Space Agency
ETK	Employee Timekeeping
EVLA	Expanded Very Large Array

Acronym	Definition
FASR	Frequency-Agile Solar Radiotelescope
FAQ	Frequently Asked Questions
FCC	Federal Communications Commission
FITS	Flexible Image Transport System
FPGA	Field-programmable Gate Array
FTE	Full-Time Equivalent
FY	Fiscal Year (October 1 through September 30)
GB	Green Bank, WV
Gbps	Giga-bits per second
GBSO	Green Bank Science Operations
GBT	Green Bank Telescope
GHz	Gigahertz
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSA	General Services Administration
GUPPI	Green Bank Ultimate Pulsar Processing Instrument
HBCU	Historically Black Colleges and Universities
HBT	Hetero-structure Bipolar Transistors
HCN	Hydrogen cyanide (HCN)
HCO+	Formylium
HD	High Definition
HDF	Hierarchical Data Format
HERA	Hydrogen Epic of Reionization Array
HFET	Heterojunction Field-Effect Transistor
HI	Neutral Hydrogen
H_0	Hubble Constant
HR	Human Resources
HVAC	Heating, Ventilating, and Air Conditioning
H_20	Properties of Water
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IDC	Infrared Dark Clouds
IF	Intermediate Frequency
IGM	Inter-Galactic Medium
IR	InfraRed
ISM	Interstellar Medium
ITU-R	International Telecommunications Union - Radiocommunications
IUCAF	Inter-Union Commission on Frequency Allocation (IAU)
JAO	Joint ALMA Observatory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
K	Kelvin
Kpc	Kiloparsec
LIGO	Laser Interferometer Gravitational Wave Observatory
LISA	Laser Interferometer Space Antenna
LNA	Low Noise Amplifier
LO	Local Oscillator
LOFAR	Netherlands astronomical foundation ASTRON's Low Frequency Array
LRP	Long Range Plan
LSM	Local Staff Member
LSST	Large Synoptic Survey Telescope
LUNAR	Lunar University Node for Astrophysics Research

Acronym	Definition
LWA	Long-Wavelength Array
MAS	milliarcseconds
M&C	Monitor and Control
MeerKAT	Karoo Array Telescope
MHz	Megahertz
MIS	Management Information Services
MIT	Massachusetts Institute of Technology
MKID	Microwave Kinetic Inductance Detectors
m	meter
mm	millimeter
MMIC	Monolithic Millimeter-wave Integrated Circuit
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
Mpc	megaparsec
MPIfR	Max Planck Institut für Radioastronomie
MPLS	Multi-Protocol Label Switching
MRI	Major Research Instrumentation
MSI	Minority Serving Institutions
μJy	microjansky
NA	North American / Not Applicable / Not Available
NAA	North American Array
NAASC	North American ALMA Science Center
NAIC	National Astronomy and Ionosphere Center (NAIC)
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NGAS	Next Generation Archive System
NGST	Northrop Grumman Space Technology
NIO	New Initiatives Office
NRAO	National Radio Astronomy Observatory
NRQZ	National Radio Quiet Zone
NS	Nanosecond
NSF	National Science Foundation
NTC	NRAO Technology Center (Charlottesville, VA)
NWNH	New Worlds – New Horizons
OAS	Observatory Administrative Services
OBS	Observatory Business Services
OCA	Office of Chile Affairs
ODP	Observatory Development & Programs
OMB	Office of Management and Budget
OSAA	Office of Science and Academic Affairs
OSO	Observatory Science Operations
OSRO	Open Shared Risk Observing
PAF	Phased Array Feed
PAPER	Precision Array to Probe the Epoch of Reionization
pc	parsec
PCAL	Pulse Calibration Generator
PI	Principal Investigator
PMS	Pre-main-sequence stars
PST	Proposal Submission Tool
PTCS	Precision Telescope Control System
R&D	Research and Development

Acronym	Definition
REU	Research Experiences for Undergraduates
RFI	Radio-Frequency Interference
RMS	Astro2010 Radio, Millimeter, and Submillimeter Astronomy Panel
RSRO	Resident Shared Risk Observing
SASPO	South African SKA Project Office
SED	Spectral Energy Distributions
SI-Ge	Silicon-germanium
SIS	Superconductor–Insulator–Superconductor
SKA	Square Kilometre Array
SMBH	Super-Massive Black Hole
SN	Supernova
SOPHIA	Stratospheric Observatory for Infrared Astronomy
SPO	Scientific Program Order
SRP	Science Review Panels
STEM	Science, Technology, Engineering, and Mathematics
submm	submillimeter
SZE	Sunyaev-Zel'dovich Effect
TAC	Time Allocation Committee
TB	Terabyte
TDP	Technology Development Program (SKA)
TES	Transition Edge Sensor
THz	Terahertz
TRS	Total Rewards Strategy
ULIRG	Ultra-luminous Infrared Galaxies
μm	micrometer
UNM	University of New Mexico
URSI	International Union of Radio Science
U.S.	United States
USNO	United States Naval Observatory
UVML	University of Virginia Microfabrication Laboratory
VAO	Virtual Astronomical Observatory
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
WIDAR	Wideband Interferometric Digital Architecture
WMAP	Wilkinson Microwave Anisotropy Probe
WSRT	Westerbrork Synthesis Radio Telescope
WVRAZ	West Virginia Radio Astronomy Zone
z	Redshift