

The National Radio Astronomy Observatory through the 2030s: Strategic Goals and Initiatives

State of the Profession White Paper

Astro2020

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The mission of the National Radio Astronomy Observatory (NRAO) is to enable forefront research into the Universe at radio wavelengths. In partnership with the science community, the NRAO:

- provides world-leading telescopes, instrumentation, and expertise,
- helps train the next generation of scientists and engineers, and
- promotes astronomy to foster a more scientifically literate society.

In the coming decade, the NRAO will operate three state-of-the-art telescope systems funded primarily by the National Science Foundation (NSF): (a) the international Atacama Large Millimeter / submillimeter Array (ALMA), (b) the Karl G. Jansky Very Large Array (VLA), and (c) the Very Long Baseline Array (VLBA). The NRAO also proposes to build and bring into early science operations a much more capable next generation Very Large Array (ngVLA) designed to open a vast new discovery space and address high priority Key Science Goals defined by the astronomy community. These forefront NRAO telescope systems will enable the community to address the highest priority astrophysics questions of our time from meter to submillimeter wavelengths, and with an order of magnitude or more improvement in resolution, sensitivity, frequency coverage, spectral line capabilities, and field-of-view.

This white paper summarizes the key NRAO strategic goals and initiatives through the 2030s:

- Advancing 21st century science
- Building a next generation Very Large Array
- Enhancing and expanding ALMA
- Delivering a new VLA Sky Survey
- Developing radio astronomy technologies
- Broadening education & public outreach
- Supporting diverse & inclusive environments and
- Protecting astronomy from radio interference.

Advancing 21st Century Science

Transformational science transforms not just the profession, but society itself. Radio astronomy and the NRAO have made truly transformational advances over the last decade, with the NRAO facilities and scientists playing a leading role in some of the most profound discoveries of modern science.

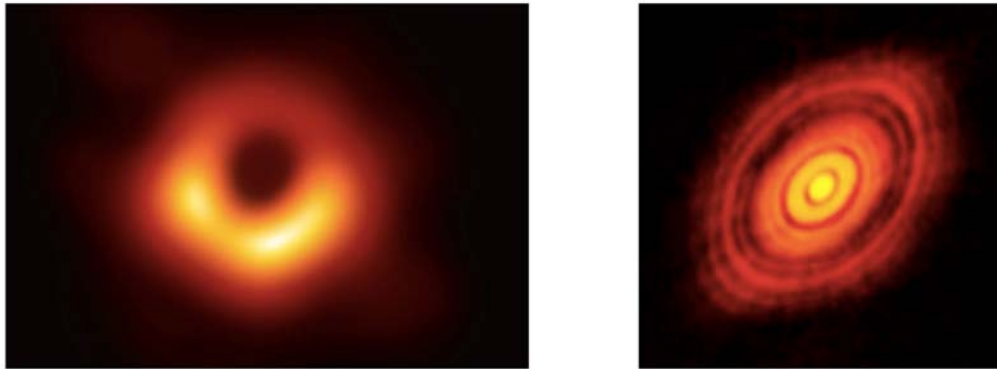
Using the Event Horizon Telescope (EHT), with ALMA as the foundational element, radio astronomers achieved the first direct imaging of a supermassive black hole event horizon (The EHT Collaboration et al. 2019). Once considered the realm of science fiction, imaging the supermassive black hole event horizon in the active galaxy, M87, at

the unprecedented resolution of 20 micro-arcseconds, provides perhaps the ultimate test of strong-field general relativity. The EHT program provides a blueprint for a successful collaborative effort between the U.S. university community, a large NSF facility, and the international research community. The result excited the interest of the public and the media around the globe, with the press estimating that the black hole image was viewed by almost four billion people. This image is just the first glimpse into a whole new field in physics, with great promise for the coming decade through continued improvements planned for ALMA and other EHT elements.

Equally dramatic, the Laser Interferometer Gravitational-wave Observatory (LIGO) direct observations of gravitational waves has inaugurated the era of multi-messenger astronomy (The LIGO Scientific Collaboration 2019). The VLA and the Very Long Baseline Array played crucial roles in these initial LIGO studies, through identification of the radio-emitting counterpart, then direct imaging on milli-arcsecond scales to confirm the smothered relativistic jet model for the merging neutron star system (Hallinan et al. 2017). As the event rates from LIGO and counterparts increase by an order of magnitude in the coming years, the VLA and VLBA will remain vital instruments in finding and characterizing merging neutron star systems, and informing the design of the ngVLA.

Nothing captures the imagination of scientists and the general public more than the possibility of life beyond the Earth. Over the last decade, the study of exoplanets and planet formation, and the search for prebiotic signatures, biosignatures, and technosignatures has evolved from a notional endeavor to a mature field. The extraordinary progress of the past two decades in the astronomical discovery and characterization of planets orbiting stars other than the Sun (exoplanets) is motivating renewed investment in the search for extraterrestrial intelligence at NASA, in the private sector, and among philanthropic organizations. To address the exciting possibility that extraterrestrial life may exist, scientists are developing capabilities to search for evidence of biological processes and technology activities that would indicate not only the existence of life but advanced intelligence (NASA Technosignatures Workshop 2018). The VLA and ALMA are in the vanguard of this renaissance, providing the unique capability to image the rings and gaps in dusty protoplanetary disks caused by forming planets. The now iconic image of the protoplanetary disk in HL Tauri, a 1 Mega-year analog to a forming planetary system similar to our Solar System, was a landmark event in the study of planet formation (ALMA Partnership, C.L. Brogan et al., 2015). ALMA and the VLA are now imaging large samples of protoplanetary systems, and the ngVLA promises to make the next step to imaging in the terrestrial zone of planet formation. Combined with the Extremely Large Telescope and space-based imaging of

terrestrial planets, the coming decade will see the emergence of a complete picture of the formation through maturity of extrasolar planetary systems.



[Left] Image of the event horizon of the supermassive black hole in Messier 87 made with the Event Horizon Telescope at 230 GHz and 20 micro-arcsecond resolution. **[Right]** ALMA 230 GHz image of the dusty protoplanetary disk around the 1Myr old, solar mass protostar, HL Tau.

Time domain science is becoming a dominant branch of astronomy, in particular, with the imminent operation of the NSF Large Synoptic Survey Telescope (LSST). For radio astronomy, entirely new physical phenomena continue to emerge in the explosive Universe. The recent discovery of Fast Radio Bursts as micro-second radio bursts from distant galaxies, opens a new window on the intergalactic medium (Chatterjee et al. 2017). Radio imaging, spectra, and temporal behavior provide unique diagnostics into the physics of the most extreme explosions in the Universe, from tidal disruption events, corresponding to stellar in-fall onto supermassive black holes, to gamma ray bursts associated with jets in extreme luminosity supernovae. The VLA, VLBA, and ALMA remain the premier tools for localizing and characterizing the exploding Universe.

The NRAO instruments offer broad versatility, making contributions from the Solar System to the first objects in the Universe. ALMA and the VLA are providing unprecedented insights into the origins of space weather, through micro-second, spectroscopic imaging of the sites of solar flares, as well as into the composition of minor planet regoliths in the Kuiper Belt, as probes of the early solar neighborhood. VLBA astrometry has traced out the spiral structure of the Milky Way over unprecedented scales. ALMA and the VLA have made the first unbiased measurements of the evolution of the dense gas content of galaxies across cosmic time – the fuel driving the star formation history – while the sensitivity of ALMA at high frequency has allowed for direct imaging of atomic fine structure line emission from galaxies into the Dark Ages, at $z > 9$. The VLBA is playing an important practical role in space exploration, through continued work on the International Celestial Reference System, spacecraft tracking, and space situational awareness.

Demand for the NRAO telescopes is strong, with ALMA receiving 1800+ proposals per annual observing Cycle – more than any other telescope in history. The publication rates from the NRAO facilities are at all-time highs and competitive with the ground- and space-based great observatories.

These programs represent but a fraction of the breadth of science being undertaken with NRAO facilities. All of these fields are growing rapidly, with tremendous future potential. The NRAO Strategic Plan for the coming decade is designed to advance the field through continued development of capabilities, in particular, geared toward realizing the ngVLA in the 2020s and a more powerful ALMA in the 2030s, as well as enhanced user support, such as science ready data products (SRDPs), for optimal science return from the community investment in the large NSF facilities. Further description of our computing and software plans can be found in the APC white paper by Kern et al.

Building a next generation VLA (ngVLA)

Inspired by dramatic discoveries with the Jansky VLA, ALMA, and the VLBA, and in cooperation with the science community, NRAO is developing a detailed plan to build and operate a large collecting area radio interferometer that will open a vast swath of new discovery space from protoplanetary disks to distant galaxies (Murphy et al., 2018). Building on the superb centimeter observing conditions and existing VLA infrastructure, the ngVLA vision is an interferometric array with more than 10x the sensitivity and spatial resolution of the Jansky VLA and ALMA, operating at 1.2 – 116 GHz.

This ngVLA will be optimized for observations between the exquisite performance of ALMA in the submillimeter regime and the future Square Kilometre Array Phase-1 performance at decimeter to meter wavelengths, and will be highly complementary with these facilities. The ngVLA will open new windows on the Universe via ultra-sensitive imaging of thermal line and continuum emission to milli-arcsecond resolution, delivering unprecedented broadband continuum polarimetric imaging of non-thermal processes.

The ngVLA will simultaneously deliver the capability to:

- unveil the formation of Solar System analogues
- probe the initial conditions for planetary systems and life with astrochemistry
- characterize the assembly, structure, and evolution of galaxies from the first billion years to the present
- employ pulsars in the Galactic Center as fundamental tests of gravity and
- understand the formation and evolution of stellar and supermassive black holes in the era of multi-messenger astronomy.

The ngVLA is envisioned as a homogeneous array of 244 antennas, each 18m in diameter. Each fixed antenna is outfitted with front ends spanning 1.2 – 50 and 70 – 116 GHz. The array achieves high surface brightness sensitivity and high-fidelity imaging on angular scales from ~ 1000 to 1 milli-arcseconds by having a large collecting area fraction randomly distributed in the array core, arms extending asymmetrically to ~ 1000 km baselines, and continental-scale (~ 9000 km) baselines reaching across North America and beyond. With a construction start in mid-2024, Early Science would be initiated in mid-2028, and the ngVLA would achieve Full Science Operations in mid-2034. Further description of ngVLA can be found in the APC white paper by McKinnon et al. In a companion APC white paper by Beasley et al., we discuss coordination with other projects in the community, and the changes needed in the NSF Major Research Equipment and Facilities Construction (MREFC) system, to enable large projects such as ngVLA and ALMA enhancement to proceed in the coming decade. Further description of our VLBA plans can be found in the APC white paper by Brisken et al.

Enhancing & Expanding ALMA

Over the past decade, ALMA has transitioned from a construction project to the premier ground-based observatory in the world. The 66 ALMA antennas on the 5000m elevation Chajnantor Plateau observe a broad frequency range – 8 bands covering 84-950 GHz, or 3.6-0.3 mm – with each band individually upgradeable. Owing to its large collecting area (>6600 m²) and instantaneous spectral bandwidth (8 GHz in dual polarization), ALMA provides astronomers with vastly improved spectroscopic sensitivity over past (sub)millimeter telescopes.

ALMA has defined key new scientific goals for the 2030s:

- tracing the cosmic evolution of key elements from the first galaxies ($z > 10$) through the peak of star formation ($z = 2-4$) by imaging their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour;
- examining the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (10-100 AU) by performing full scans of a frequency band at a rate of 2-4 protostars per day; and
- imaging of protoplanetary disks in nearby (150 parsec) star formation regions to resolve the Earth-forming zone (1 AU) in the dust continuum at wavelengths shorter than 1 mm, enabling detection of the tidal gaps and inner holes created by forming planets.

To achieve these ambitious goals, the ALMA partners have launched programs to develop the technologies and observing capabilities to produce these scientific outcomes. Near-term initiatives are expected to increase system bandwidths by 2x, and

mid-term studies are exploring improved angular resolution, increased imaging speed, and the inclusion of a complementary large single dish in the array. For the 2030s, studies are investigating a more ambitious ALMA capabilities expansion, including a 10x continuum sensitivity increase and a 6x spectral line sensitivity increase. A more complete description of ALMA development plans is given in the ALMA Development Roadmap (Carpenter et al. 2019) and an APC white paper by Brogan et al.

Delivering a New VLA Sky Survey

Radio interferometry remains a relatively specialized astronomy technique, making science-ready survey data products particularly valuable. Historically this has been illustrated by the high community usage of data products from the NRAO VLA Sky Survey (NVSS) and Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) surveys undertaken in the late 1990s, which continue to garner ~ 400 citations per year. With the completion of the wide bandwidth receivers and backends as part of the Expanded VLA project in 2012, undertaking a new VLA survey was proposed by the community. In collaboration with the community, NRAO designed a survey – the VLA Sky Survey (VLASS) – that takes imaging of the radio sky to a new level.

The VLASS is the first all-sky, high angular resolution synoptic radio survey. The main VLASS science goals are transient searches, the study of the radio source polarization properties, imaging highly obscured Milky Way sources, and the demographics of different classes of extragalactic radio sources and their effects on galaxy evolution. The VLASS provides a reference radio sky image at an angular resolution of 2.5 arcsec, comparable to new large area optical-infrared surveys such as LSST, Pan-STARRS and the Wide-field Infrared Survey Explorer. The VLASS is being observed at 2–4 GHz in the VLA B and BnA configurations, and will detect ~ 5 million radio sources. The VLASS goals and design were initiated by and developed in concert with the community, represented by the ongoing Survey Science Group.

NRAO initiated VLASS observing in September 2017 and will complete observations for the first epoch in July 2019. Results from the VLASS1.1 data have been reported in several papers; see Lacy et al. (2019) for further details. By September 2019, Quick Look images covering the whole sky visible to the VLA will be available to the community, and processing of higher quality images will begin. An innovative aspect of the VLASS is the concept of NRAO delivering Basic Data Products, and the community taking these products to create Enhanced Data Products that are also widely available. The Canadian Initiative for Radio Astronomy Data Analysis project will deliver multi-wavelength, cross-matched catalogs, transient alerts, and cubes of rotation measure for the VLASS.

NRAO will continue to work with the community to deliver science-ready images of the radio sky over the next decade, drive detection of obscured transient sources, and innovate to optimize science opportunities at radio wavelengths. The VLA Sky Survey is a pathfinder and precursor for delivery of science-ready quality assured data products to the astronomy community that is a cornerstone of the NRAO vision for a ngVLA.

Developing Radio Astronomy Technologies

To fulfill its mission, NRAO must commit to strategic investments in key emerging technologies in the coming decade. The technologies selected for investment by the NRAO Central Development Laboratory (CDL) will be determined by future science requirements for ALMA, VLA, VLBA, and ngVLA, by the feasibility and maturity of the technologies, and by CDL expertise in providing robust, state-of-the-art instrumentation to the community.

The frontiers of radio astronomy instrumentation involve increasing the radio frequency (RF) and intermediate frequency (IF) bandwidth, improved receiver image rejection, and gain flatness. NRAO strategic investments will focus on crucial receiver technologies.

Millimeter and Submillimeter Detectors: Investments are merited to improve the Superconductor-Insulator-Superconductor (SIS) architecture of the current millimeter wave and submillimeter wave receivers as new materials and techniques can deliver significant performance improvements. Developing SIS mixers with high quality tunnel barriers from new compounds that offer more bandwidth and flatter noise temperature and gain versus frequency is an NRAO-CDL priority. With university collaborators, CDL is developing multiple new device junctions, such as Nb/Al-AlN/NbN.

These devices will feature high critical current density and are sufficiently reproducible to permit receiver production on the scale necessary for a synthesis array such as ALMA, and can operate up to 1 THz. Other technologies under exploration for SIS-based receivers include wideband balanced IF amplifiers, wideband cryogenic field-displacement isolators, and improved orthomode transducers (OMTs).

CDL is pursuing a new technology – Traveling-wave Kinetic Inductance Parametric (TKIP) amplifiers – that is theoretically capable of near quantum-limited performance over more than an octave of instantaneous bandwidth for all ALMA bands. On-going research on these devices, which nominally operate at milli-Kelvin temperatures, is focused on developing devices that operate at higher temperatures and have flat gain at IF and RF frequencies. Adding instrumentation for RF amplifier measurements and continuing the refinement of TKIP design should continue to determine if this technology will be suitable for millimeter and submillimeter receivers.

Additive Manufacturing (3-D) Printing: Significant improvements have been made in 3-D printing technology to produce passive electromagnetic devices. Printable waveguides, antennas, RF lenses, horns, OMTs, and circuit interconnects are a focus of research. There are particular advantages for millimeter-wave applications, but challenges remain to build such devices suitable for radio astronomy, including feature size resolution, surface smoothness, and tolerances on complex internal RF pathways. An emerging capability to print three-dimensional structures with arbitrary dielectric gradients is promising. This technology could revolutionize the design of antennas and other passive devices used in radio astronomy.

NRAO partnerships with university-based research and commercial organizations are working on 3-D printing of electromagnetic devices, focusing on high frequency operation. There is potential dual-use application of this technology, especially in aerospace and defense.

Integrated Receiver Development: The NRAO Research & Development program aims to develop compact, mass-producible, and field-replaceable front-end hardware for the next generation of radio telescope facilities. Goals include early digitization as near to the telescope focal point as possible, and relatively seamless integration of analog, digital, and photonic technologies into lightweight, low-overhead front-end modules. The architecture is optimized to exploit the complementarity of integrated construction techniques and digital signal processing, achieving a level of precision and stability that is unmatched by state-of-the-art radio astronomy receivers.

The current suite of integrated receiver prototypes uses commercial off-the-shelf Analog-to-Digital Converters and serialization hardware. This functionality has been implemented in a tiny Application-Specific Integrated Circuit which performs the same function with an order of magnitude less power and footprint.

Broadening Education & Public Outreach

Education and Public Outreach (EPO) is a mission critical NRAO department, bringing the discoveries made possible by our observatories to a broad, science-attentive audience with a goal of broadening that audience and expanding interest and engagement in our facilities and discoveries. EPO's divisions collaborate to achieve these goals: (a) News; (b) Science, Technology, Engineering, the Arts, and Mathematics (STEAM) Education; (c) the VLA Visitor Center; and (d) Multimedia.

The NRAO EPO team will pursue new opportunities to grow STEAM programs that serve communities local to our facilities and then disseminate content nationally through professional development; and redesign the VLA Visitor Center to be an exemplary

interpretive center, facilitating opportunities for visitors to gain a deeper understanding and appreciation of NRAO facilities and the extraordinary discoveries they enable.

The new STEAM Education team is leveraging its tools to become the go-to resource of radio astronomy education providing K-12 lesson plans and activities aligned to national standards. These resources will be distributed online and through professional development for teachers at appropriate local and national venues. The definition of “local” expands beyond New Mexico and Virginia to include states and territories where most VLBA dishes reside.

NRAO is committed to seek private funding to renovate the VLA Visitor Center and create an innovative interpretive center modeled after those at National Parks. This is an opportunity to create exhibits that reflect our increased understanding of neurodiversity, diverse cultures and abilities/disabilities that create a more inclusive environment for all visitors. The STEAM Education team is committed to creating programming that reflects the local culture that will also expand visitorship to local school children throughout central New Mexico.

Supporting Diverse & Inclusive Environments

The NRAO strongly believes that a diverse staff is critical to our mission. NRAO is committed to creating and maintaining a diverse and inclusive environment, and to serving as a leader in efforts that build and support opportunities for members of underrepresented groups to participate fully in the fields that support radio astronomy, including science, software and hardware engineering, data science, and more. Through its Office of Diversity & Inclusion, NRAO programs work across Observatory departments to accomplish these goals.

The **National Astronomy Consortium (NAC)**, led by the NRAO in partnership with the National Society of Black Physicists, Historically Black Colleges and Universities (HBCUs), community colleges, and research institutions, has demonstrated the effectiveness of long-term research and mentoring investment in individual students toward maintaining academic career momentum and success. The NAC program’s extended, multiple-point support system includes summer research experiences, long-term mentoring, personal and professional development, fellowships, internships, speaking and presentation training, as well as opportunities to present at national professional meetings, and assistance in removing barriers to graduate school. Long-term commitment to individual students is vital to successful “pipeline” development.

The **National and International Non-traditional Exchange (NINE)** program innovatively approaches building sustainable skills via the use of Raspberry Pi units and

radio astronomy data to combine and analyze astronomical images. A key NINE program component is the development of “hubs” in domestic and international regions where there is growing interest in the scientific and technical opportunities within disciplines supporting radio astronomy. Following intensive training at NRAO, NINE hub representatives return to their home institution to train others, supported by continuing engagement with NRAO staff.

The **Radio Astronomy Data Imaging and Analysis Labs (RADIAL)** project addresses current and future radio astronomy data challenges by working with Minority-Serving Institutions with an interest in data management, delivery, and analysis to develop data centers, science centers, and/or related partnerships in activities at multiple scales, such as curriculum development and summer student research. RADIAL acknowledges the important roles that HBCUs and Hispanic-Serving Institutions have in developing the next generation of data scientists and astronomers.

Diversity & Inclusion Education and Training creates and sustains a diverse and inclusive workplace culture. Training and education are accomplished via online training, workshops, and a robust speaker series. NRAO provides intensive training to its Diversity Advocates and Employee Diversity Group members, and expects managers and supervisors to support these efforts across the Observatory.

Protecting Astronomy from Radio Interference

Over the past decade, the growth of key commercial sectors using parts of the radio spectrum has been rapid and problematic for astronomy. Developments in WiFi, navigation, mobile phones (4G/5G), and satellite-based internet providers (e.g. SpaceX) are continuing, and in most cases negative impacts to radio astronomical observing can be found. In the coming decade, new technologies and agreements between spectrum users will be required to continue our respective missions, with enhanced site or regional protection for key radio astronomy facilities perhaps the most important goal. NRAO will expand its monitoring and research interests in this area. Further discussion of these issues can be found in the APC white papers by Hall et al. and van Zee et al.

Summary

Through its instruments and data, NRAO enables scientific excellence and supports the community across a broad spectrum of activities, including astronomy, engineering, education, and outreach. In the coming decade, with the guidance and support of the research community, the exciting initiatives NRAO is pursuing promise to greatly increase our understanding of the Universe, support human technological development, and benefit and inspire individuals and society. NRAO proudly serves as a key resource for the U.S. and global research communities.

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