ngvla

Next Generation Very Large Array

PROJECT SUMMARY

January 2019

NSF AUI NRAO

Science with a Next-Generation Very Large Array
ASP Conference Series, Monograph 7
Eric J. Murphy, ed.

The ngVLA Science Case and Associated Science Requirements

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Abstract. The science case and associated science requirements for a next-generation Very Large Array (ngVLA) are described, highlighting the five key science goals developed out of a community-driven vision of the highest scientific priorities in the next decade. Building on the superb cm observing conditions and existing infrastructure of the VLA site in the U.S. Southwest, the ngVLA is envisaged to be an interferometric array with more than 10 times the sensitivity and spatial resolution of the current VLA and ALMA, operating at frequencies spanning $\sim 1.2 - 116$ GHz with extended baselines reaching across North America. The ngVLA will be optimized for observations at wavelengths between the exquisite performance of ALMA at submm wavelengths, and the future SKA-1 at decimeter to meter wavelengths, thus lending itself to be highly complementary with these facilities. The ngVLA will be the only facility in the world that can tackle a broad range of outstanding scientific questions in modern astronomy by simultaneously delivering the capability to: (1) unveil the formation of Solar System analogues; (2) probe the initial conditions for planetary systems and life with astrochemistry; (3) characterize the assembly, structure, and evolution of galaxies from the first billion years to the present; (4) use pulsars in the Galactic center as fundamental tests of gravity; and (5) understand the formation and evolution of stellar and supermassive blackholes in the era of multi-messenger astronomy.

1. Introduction

The Very Large Array (VLA) has had a major impact on nearly every branch of astronomy, and the results of its research are abundant in the pages of scientific journals and textbooks. Five years after the completion of the Expanded Very Large Array (EVLA) Project, and more than 40 years since the first VLA antenna was commissioned, the VLA has strengthened its position as the most versatile, widely-used radio telescope in the world. Rededicated as the Karl G. Jansky VLA in March 2012, the array continues to make cutting-edge discoveries across a broad range of disciplines including exoplanet formation, galaxy formation in the nearby and distant Universe, and the rapidly growing field of time-domain astronomy. More than 3,000 researchers from around the world have used the VLA to carry out more than 11,000 observing projects.

Inspired by the VLA's ability to perennially deliver high-impact scientific results, and to prepare for the changing landscape in science priorities and capabilities of facilities at other wavelengths, the National Radio Astronomy Observatory (NRAO) recently started to consider ways to continue the legacy of the VLA as one of the most powerful radio telescopes to be included in the next generation of the world's suite of cutting edge astronomical observatories. By teaming with the greater astronomical community in an exercise to develop a cogent science case requiring observations at cm–mm wavelengths, NRAO is now currently pursuing a large collecting area radio interferometer that will open completely new discovery space by delivering an angular resolution and sensitivity that is each an order of magnitude larger than that of the VLA and the Atacama Large Millimeter Array (ALMA), allowing it to address fundamental questions in all major areas of astrophysics.

This chapter describes the community response following a solicitation from the NRAO to develop key science cases for a future U.S.-led radio telescope, the next generation Very Large Array (ngVLA). The resulting list of more than 80 science use cases received by NRAO represent some of the fundamental astrophysical problems that require observing capabilities at cm–mm wavelengths well beyond those of existing, or already planned, telescopes. The summary of this exercise has resulted in a transformative radio facility having roughly 10 times the sensitivity of the VLA and ALMA, frequency coverage from $\sim 1.2 - 116$ GHz with up to 20 GHz of instantaneous sampled bandwidth, a compact core for good sensitivity to low surface-brightness emission, and extended baselines reaching across North America for extremely high-resolution imaging. The ngVLA is being built on the scientific and technical legacies of the VLA and ALMA, and is being designed to provide the next major leap forward in our understanding of planets, galaxies, black holes, and the dynamic sky. As such, the ngVLA will open a new window on the universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcecond resolution, as well as deliver unprecedented broad band continuum polarimetric imaging of non-thermal processes.

2. Developing the ngVLA Key Science Goals

The ngVLA Science Advisory Committee (SAC)[1], a group of 24 leading scientists with a wide range of interests and expertise appointed by NRAO, in collaboration with the broader international astronomical community, recently developed a series of than 80 compelling science cases requiring ≈200 unique observations between $\sim 1.2 - 116$ GHz with sensitivity, angular resolution, and mapping capabilities far beyond those provided by the VLA, ALMA, and the Square Kilometre Array Phase 1 (SKA-1). The science cases submitted spanned a broad range of topics in the fields of planetary science, Galactic and extragalactic astronomy, as well as fundamental physics, and formed the basis for developing the ngVLA Key Science Goals (KSGs).

Given the overwhelmingly large spread of compelling science cases generated by the community, it is clear that the primary science requirement for the ngVLA is to be flexible enough to support the wide breadth of scientific investigations that will be proposed by its highly creative user base over the full lifetime of the instrument. This mandate is also made obvious given the breadth of scientific endeavors included in this volume, ranging from studies of planet formation and understanding the conditions for habitability in other star systems to rigorous testing of the theory of gravity using pulsars immersed in the space-time potential of the Galaxy's supermassive black hole.

[1] `http://ngvla.nrao.edu/page/sciencecouncil`

This in turn makes the ngVLA a different style of instrument than many other facilities on the horizon (e.g., SKA-1, LSST, etc.), which are heavily focused on carrying out large surveys.

In the next stage of the process, each of the individual science cases were objectively reviewed and thoroughly discussed by the different Science Working Groups within the ngVLA-SAC. The ultimate goal of this exercise was to distill the top scientific goals for a future radio/mm telescope. KSGs were identified as projects which satisfied three criteria: (1) the science case addresses an important and currently unanswered question in astrophysics that has broad implications to communities outside of radio astronomy; (2) progress in this area is uniquely addressed by the capabilities of the ngVLA; and (3) the science case exhibits strong synergies/complementarity with science being pursued by other existing/planned facilities in the $\gtrsim$ 2025 time frame.

The resulting initial KSGs, along with the results from the entire list of over 80 science use cases (Selina, Murphy & Erickson 2017) were then presented and discussed with the broader community at the ngVLA Science and Technology Workshop June 26 − 29, 2017 in Socorro NM in an attempt to build consensus around a single vision for the key science missions of the ngVLA. Here we describe the five KSGs to come out of this community-driven science use case capture process (see Table 1) along with their corresponding requirements that in turn drive the Reference Design described by Selina et al. (this volume, p. 15).

3. The ngVLA Key Science Goals and Associated Requirements

In this section we briefly describe each of the five highest-priority ngVLA KSGs that are expected to be carried out during the lifetime of the ngVLA (see Table 1). We also provide a brief description of their basic requirements that in turn form the foundation used to construct the ngVLA Reference Design described in Selina et al. (this volume, p. 15). A more detailed description of the ngVLA KSGs can be found in (Bolatto et al. 2017), and the corresponding full description of the ngVLA Level 0 Science Requirements can be found in Murphy et al. (2017).

Table 1. The ngVLA Key Science Goals

KSG	**Title**
1	Unveiling the Formation of Solar System Analogs on Terrestrial Scales
2	Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
3	Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present
4	Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity
5	Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

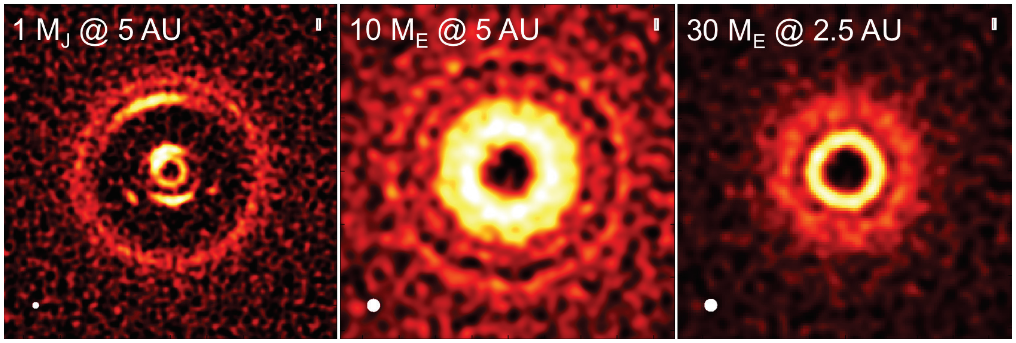

Figure 1. Simulated ngVLA observations of protoplanetary disk continuum emission perturbed by a Jupiter mass planet at 5 au (left), a 10 Earth mass planet at 5 au (center), and a 30 Earth mass planet at 2.5 au (right). The ngVLA observations at 100 GHz were simulated with 5 mas angular resolution and 0.5 μJy/bm rms (Ricci et al. 2018).

3.1. KSG 1: Unveiling the Formation of Solar System Analogs on Terrestrial Scales

Planets are thought to be assembled in disks around pre-main sequence stars, but the physical processes responsible for their formation are poorly understood. Only recently, optical, infrared, and (sub-) millimeter telescopes have achieved the angular resolution required to spatially resolve the innermost regions of nearby protoplanetary disks, unveiling morphological features with characteristic sizes of >20 au suggestive of gravitational perturbations of yet unseen giant planets. This in turn provides a powerful tool to measure planet masses, orbital radii, study the circumplanetary environment, and investigate how forming planets interact with the circumstellar material. The angular resolution, frequency coverage, and sensitivity of current disk imagery is limited to probing for the presence of planets more massive than Neptune at orbital radii larger than 20 − 30 au. The next step forward in the study of planet formation is the ability to image the formation of super-Earths and giant planets across the entire disk, particularly within 10 au from the central star.

To achieve this science goal requires that the ngVLA have the frequency coverage, sensitivity, and angular resolution to be able to measure the planet initial mass function down to a mass of 5 − 10 Earth masses. This capability will unveil the formation of planetary systems similar to our own Solar System by probing the presence of planets on orbital radii as small as 0.5 au at the distance of ≈140 pc. The ngVLA shall also be able to reveal circumplanetary disks and sub-structures in the distribution of mm-size dust particles created by close-in planets and measure the orbital motion of these features on monthly timescales.

This in turn requires continuum observations for center frequencies between 20 − 110 GHz with angular resolution better than 5 mas. This requirement will enable studies on the formation of planets in the innermost 10 au of nearby ($\lesssim$140 pc) proto-planetary disks. Extensive simulations of the disks perturbed by planets (see Figure 1; Ricci et al. 2018), suggest that a sensitivity of 0.2 μJy/bm in the continuum at 100 GHz is required to routinely map structures in the dust distribution created by planets of mass down to 10 Earth-masses and orbital radius of 2.5 au. Matching resolution (i.e., 5 mas) and achieving a continuum sensitivity of order 0.02 μJy/bm at 30 GHz will map the planet-disk interactions where the disk emission is expected to be optically thin.

3.2. KSG 2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

One of the most challenging aspects in understanding the origin and evolution of planets and planetary systems is tracing the influence of chemistry on the physical evolution of a system from a molecular cloud to a solar system, while also trying to determine the potential for habitability. To make significant progress in this area requires that the ngVLA has the frequency coverage and sensitivity to be able to detect predicted, but as yet unobserved, complex prebiotic species that are the basis of our understanding of chemical evolution toward amino acids and other biogenic molecules. In doing so, the ngVLA will also allow us to detect and study chiral molecules, testing ideas on the origins of homochirality in biological systems. The detection of such complex organic molecules will provide the chemical initial conditions of forming solar systems and individual planets.

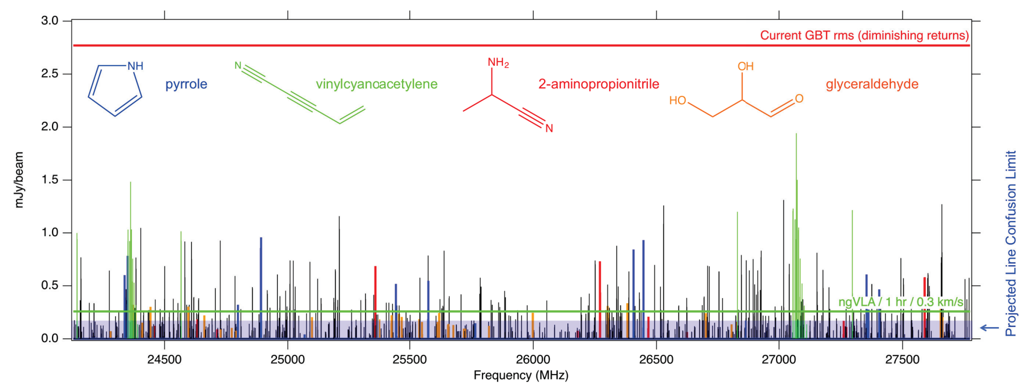

Figure 2. A conservative simulation of 30 as-yet-undetected complex interstellar molecules (black) likely to be observed by the ngVLA above the confusion limit around hot cores with typical sizes of $\sim 1-4''$. Key molecules are highlighted in color. (Credit: B. McGuire)

Presently, existing observations of complex organic (prebiotic) molecules using ALMA and the Great Bank Telescope (GBT) are hitting the limit of what can be accomplished due to a combination of achievable sensitivity and line confusion at higher frequencies. Both problems can be solved by sensitive observations in the cm-wave regime with the ngVLA. State-of-the-art models predict these molecules will display emission lines with intensities that are easily detectable with the ngVLA, but well below the current detectability thresholds of existing telescopes including ALMA, GBT, and IRAM. Figure 2 shows simulations of a representative set of the types of molecules whose discovery will be enabled by the ngVLA: N, O, and S-bearing small aromatic molecules, direct amino acid precursors, biogenic species such as sugars, chiral molecules, and, possibly amino acids themselves. The simulation assumes column densities of $10^{12}-10^{14}$ cm^{-2} (with more complex molecules being assigned lower column densities), a temperature of 200 K, and 3 km/s linewidth.

To achieve this science goal requires an angular resolution on the order of 50 mas at 50 GHz along with an rms sensitivity of 30 μJy/bm/km/s for frequencies between

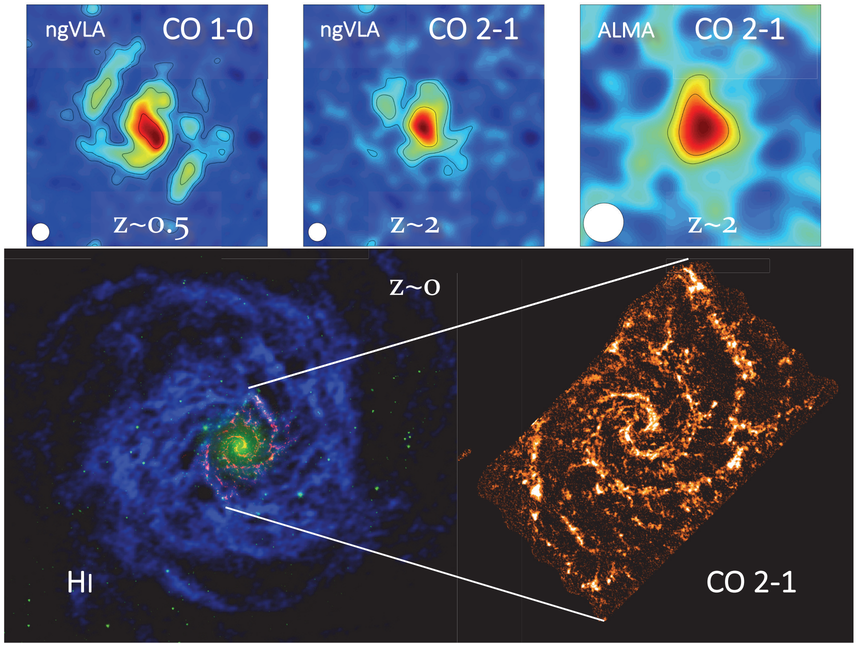

Figure 3. *Top Panels:* Simulations based on M 51 with molecular mass scaled by 1.4× (z = 0.5) and 3.5× (z = 2) to match the lowest molecular mass galaxies observable by ALMA and NOEMA (Carilli & Shao 2017). The synthesized beam shown in the bottom left corner is (left to right) θ_s = 0.″19, 0.″20, and 0.″43 corresponding to linear scales L = 1.2, 1.7, and 3.7 kpc, respectively. Integration times are 30 hr. *Bottom Panels:* The spiral galaxy M 74 illustrating the CO molecular disk imaged by ALMA (red; Schinnerer in prep.), the stellar disk at 4.5 μm imaged by *Spitzer* (green; Kennicutt et al. 2003), and the atomic disk imaged in HI by the VLA (blue; Walter et al. 2008), showing the gas phases to which the ngVLA will be sensitive. *Bottom Right Panel:* A zoom in showing the CO $J = 2 \rightarrow 1$ map at 1″ resolution.

16 – 50 GHz. Further, spectral resolution of 0.1 km/s is required, preferably concurrent with broadband (4+ GHz) observations.

3.3. KSG 3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

To make substantial progress in the field of galaxy formation and evolution requires that the ngVLA have the sensitivity to survey cold gas in thousands of galaxies back to early cosmic epochs, while simultaneously enabling routine sub-kiloparsec scale resolution imaging of their gas reservoirs. In doing so, the ngVLA will afford a unique view into how galaxies accrete, process, and expel their gas through detailed imaging of their extended atomic/molecular reservoirs and circumgalactic regions. To reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the universe requires that the ngVLA also have enough sensitivity to map the physical and chemical properties of molecular gas over the entire local galaxy population.

To carry out detailed studies of CO kinematics of high-z galaxies and blind CO searches of > 1000 galaxies requires a line sensitivity of ∼46 μJy/bm/km/s at 0.″1 and 1″angular resolution between 10 – 50 GHz with a spectral resolution of 5 km/s. This is illustrated by a simulation of M 51 (the Whirlpool galaxy) shown in the top three panels of Figure 3 (see Carilli & Shao 2017). The spatial and kinematic information recovered by the ngVLA allows for the measurement of a precise rotation curve, which would only be possible to obtain from ALMA with an extraordinarily large (~ 1000 hr) time investment. Furthermore, a large instantaneous bandwidth (i.e., a minimum 1.6:1 BW ratio, up to 20 GHz instantaneous bandwidth) is required to conduct wide band observations at 5 km/s resolution to efficiently perform blind surveys of large cosmic volumes in a single observation and provide routine access molecular species in addition to CO (e.g., HCN, HCO^+, or N_2H^+).

Thermal imaging of 0.1 − 0.2 K sensitivity of CO (115 GHz) at 0.″1 angular resolution and 1 km/s spectral resolution is required for detailed studies of molecular gas in the nearby universe (see bottom panels of Figure 3). Thermal imaging of 1 − 5 mK sensitivity between 70 and 116 GHz at 1 − 5″ angular resolution and 1 − 5 km/s spectral resolution is required to support studies of gas density across the local universe.

Full 1.2 − 116 GHz frequency coverage is required to obtain accurate, simultaneous measurements of star formation rates from free-free continuum and radio recombination line (RRL) emission. Angular resolutions of 0.″1 − 1″ for continuum imaging at all available frequencies are required. A continuum sensitivity of 0.15 μJy/bm at 33 GHz for a 1″ synthesized beam is required to robustly study star formation within large samples of nearby galaxies. For studies of galaxies in the local universe, accurate recovery of flux density for extended objects on arcminute scales at all frequencies is required, along with the ability to make large mosaics or conduct on-the-fly line and/or continuum mappings of galaxies that extend beyond the area of a single primary beam.

Finally, a brightness dynamic range of ≈50 and 40 db is required at 10 GHz for deep field continuum studies of MW-like galaxies at Cosmic Noon to not be dynamic range limited in total and polarized intensity, respectively. Such deep field observations will be sensitive to $\gtrsim$90% of all stars formed since $z \lesssim 3$.

3.4. KSG 4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity

Testing theories of gravity requires probing as close as possible to the strong field regime, for which pulsars near the Galactic Center offer a powerful path forward. However, only a handful of pulsars in the central half-degree of the Galaxy are currently known (see Figure 4), which may be the result of enhanced radio-wave scattering toward the inner Galaxy that further decreases the effective sensitivity of searches, by increasing both the dispersion measure smearing and pulse broadening. Observing at higher frequencies than currently planned for the SKA can mitigate radio-wave scattering, but by itself the benefits are limited because of the generally steep radio spectra of pulsars. Thus, to achieve this goal, the ngVLA must deliver a combination of sensitivity and frequency range, enabling it to probe much deeper into the likely Galactic Center pulsar population to address fundamental questions in relativity and stellar evolution. The ability to address these questions is afforded by the fact that pulsars in the Galactic Center represent clocks moving in the space-time potential of a super-massive black hole and allow for qualitatively new tests of theories of gravity. More generally, they offer the opportunity to constrain the history of star formation, stellar dynamics, stellar evolution, and the magneto-ionic medium in the Galactic Center.

To carryout this science requires that the ngVLA be able to support pulsar search and timing observations from ~ 1 − 30 GHz for Galactic Center pulsars. Pulsar search-

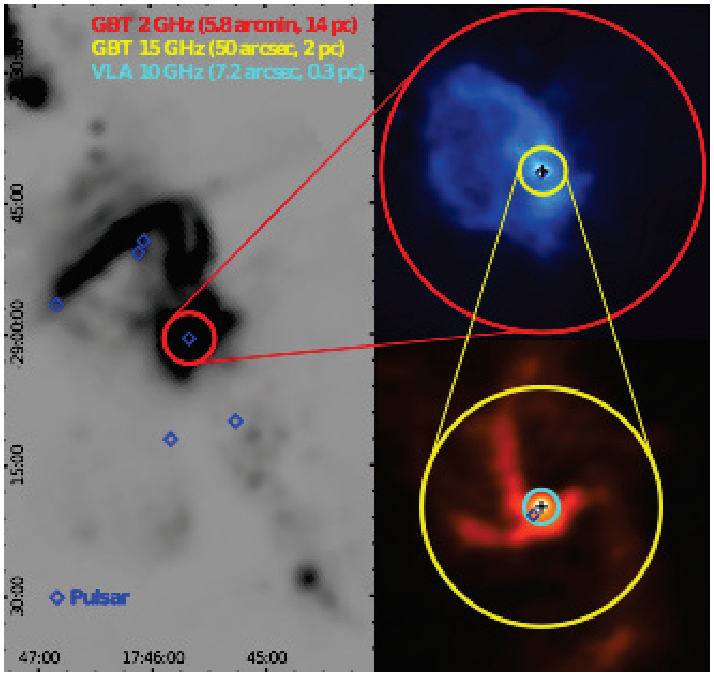

Figure 4. The pulsar distribution near the Galactic Center. Despite being the highest density in the Galaxy and multiple searches at sensitivities comparable to the VLA, only a few pulsars are known though $\sim$ 1000 are predicted. (Credit: R. Wharton)

ing requires the ability to search on 100 μs scales (20 μs scales desired), while timing requires 20 μs resolution. A continuum sensitivity equivalent of order 50 nJy/bm is desired at 20 GHz, which is a significant improvement compared to existing 100 m-class radio telescopes that have found few pulsars, indicating that substantial additional sensitivity is necessary. The system timing accuracy also must be better than 10 ns (1 ns desired) over periods correctable to a known standard from 30 min to 10 yr. To efficiently time time multiple pulsars, the array must have the ability to make multiple (minimum 10) beams (i.e., phase centers within the primary beam) within a single subarray, or distributed amongst multiple subarrays. Timing multiple pulsars within a single primary beam is desirable. Support for 5 or more independent de-dispersion and folding threads is desired.

3.5. KSG 5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

While we now know that black holes exist on practically all mass scales, the astrophysics of how these objects form and grow remains a mystery. The Laser Interferometer Gravitational-wave Observatory (LIGO) is now detecting black holes that are substantially more massive than previously known stellar mass black holes, and observing black hole-black hole mergers, although we do not know how black hole binaries form. While supermassive black holes (SMBHs) are thought to be widespread in galaxy centers, we do not understand how their growth was seeded or how (and how often) these extreme objects merge. To address these questions requires that the ngVLA have the

Figure 5. Two tiny, but very dense neutron stars merge and explode as a kilonova. Such a very rare event produces gravitational waves and electromagnetic radiation, as observed on 17 August 2017. The ngVLA will play a pivotal role in characterizing the physics of such events in the era of multi-messenger astronomy. (Artist's impression, Credit: ESO/L. CalÇada/M. Kornmesser).

combination of sensitivity and angular resolution to be able to survey everything from the remnants of massive stars to the supermassive black holes that lurk in the centers of galaxies, making it the ultimate black hole hunting machine. High-resolution imaging abilities are required to separate low-luminosity black hole systems in our local Universe from background sources, thereby providing critical constraints on the formation and growth of black holes of all sizes and mergers of black hole-black hole binaries.

To become the ultimate black-hole survey instrument requires that the ngVLA have high angular resolution (mas – μas) imaging with relative astrometric accuracy that is $< 1\%$ of the synthesized beam FWHM or equal to the positional uncertainty in the reference frame, for a bright ($SNR \gtrsim 100$) point source. Such high-resolution imaging will enable proper motion separation of local black holes (both Galactic and in nearby galaxies, out to 15 Mpc) from background sources. Long baselines are required to enable the ngVLA to image the SMBH binaries that will be detected in gravitational waves by LISA and pulsar timing arrays. These astrometric science goals benefit from the implementation of very long baselines ($\gtrsim$ 1000 km for mas – μas accuracy). Associated VLBI recording capabilities shall be available for 3 or more beams (for 2 calibrators and the science target).

The field of multi-messenger astronomy continues to mature as we continue to open new astronomical windows through gravitational waves and neutrino observations. However, to progress further in our understanding of the physics associated with these phenomena requires the ability to localize and characterize the sources. Only the detection of the electromagnetic radiation associated with these energetic, and often cataclysmic events, can provide precise localization, establish energetics and allow us to understand how such events interact with their surrounding environments. Thus, to have a transformational impact in the growing era of multi-messenger astronomy, the ngVLA must also be able to identify the radio counterparts to transient sources discovered by gravitational wave, neutrino, and optical observatories (see Figure 5). This requires high-resolution, fast-mapping capabilities to make it the preferred instrument to pinpoint transients associated with violent phenomena such as supermassive black hole mergers and blast waves.

Specifically, mapping a ~10 square degree region (i.e., the localization uncertainty expected by gravitational wave detectors when ngVLA is operational) to a depth of $\sim 1\,\mu$Jy/bm at 2.5 GHz for detection of NS-NS and NS-BH mergers is required. Completing the on-the-fly mapping of each epoch within $\sim$ 10 hr is desirable. Similarly, mapping a $\sim$ 10 square degree region at 28 GHz to a depth of $\sim 10\,\mu$Jy/bm with on-the-fly mapping is required for localization of LISA-detected SMBH mergers. Again, completing the on-the-fly mapping of each epoch within $\sim$ 10 hr is desirable. Furthermore, an rms sensitivity of $\approx 0.23\,\mu$Jy/bm at 10 GHz for a 0.6 mas beam (i.e., on continental-scale baselines) is required to detect a source like GW170817 with a $SNR \approx 10$ at the Adv. LIGO horizon distance of 200 Mpc, which will in turn allow for measurements (movies) of its expansion at the 5σ level.

The ability to receive and respond to external triggers rapidly is also an essential requirement to enable multi-messenger science. Triggered response times not to exceed 10 minutes is required, while response times of better than 3 minutes is desired. The ability to perform time-domain transient searchers (e.g., for Fast Radio Bursts) requires a search capability on $100\,\mu$s scales, with $20\,\mu$s scales desired.

4. Summary

The ngVLA is being designed to tap into the astronomical community's intellectual curiosity by providing them with a world-class instrument that will enable a broad range of scientific discoveries (e.g., planet formation, signatures of pre-biotic molecules, cosmic cycling of cool gas in galaxies, tests of gravity, characterizing the energetics of gravitational wave counterparts, etc.). Based on community input to date, the ngVLA is the obvious next step to build on the VLA's legacy and continue the U.S.'s place as a world leader in radio astronomy. The ultimate goal of the ngVLA is to give the U.S. and international communities a highly capable and flexible instrument to pursue their science in critical, yet complementary ways, with the large range of multi-wavelength facilities that are on a similar horizon. Presently, there have been no major technological risks identified. However, the project is continually looking to take advantage of major engineering innovations, seeking to optimize the performance and operational efficiency of the facility. As the project continues to move forward and mature, the project will continue to work with the community to refine the ngVLA science mission and instrument specifications/performance. This science book acts as a major milestones in this effort.

Acknowledgments. The authors thank the 100's of community members that have contributed to the definition of the ngVLA science mission and corresponding science requirements. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Science with a Next-Generation Very Large Array
ASP Conference Series, Monograph 7
Eric J. Murphy, ed.

The ngVLA Reference Design

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Abstract. The next-generation Very Large Array (ngVLA) is an astronomical observatory planned to operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode. We provide a technical overview of the Reference Design of the ngVLA. This Reference Design forms a baseline for a technical readiness assessment and the construction and operations cost estimate of the ngVLA. The concepts for major system elements such as the antenna, receiving electronics, and central signal processing are presented.

1. Introduction

As part of its mandate as a national observatory, the National Science Foundation's (NSF) National Radio Astronomy Observatory (NRAO) is looking toward the long-range future of radio astronomy and fostering the long-term growth of the U.S. and global astronomical community. With NSF support, NRAO has sponsored a series of science and technical community meetings to define the science mission and concept for a next-generation Very Large Array (ngVLA; McKinnon 2016) that builds on the legacies of the Atacama Large Millimeter/submillimeter Array (ALMA) and the Jansky Very Large Array (VLA).

Based on input solicited from the astronomical community, the ngVLA is planned as an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 to 116 GHz). The observatory will be a synthesis radio telescope consisting of:

- A main array of 214 reflector antennas each of 18 meters diameter, operating in a phased or interferometric mode. The main array is distributed to sample a wide range of scales from 10s of meters to 1000 km. A dense core and spiral arms provide high surface brightness sensitivity, with mid-baseline stations enhancing angular resolution.
- A short baseline array (SBA) of 19 reflector antennas of 6 m aperture will be sensitive to a portion of the larger angular scales undetected by the main array.

The SBA may be combined with 4 18 m (main-array) antennas used in a total power mode to completely fill in the central hole in the (u, v)-plane left by the 6 m dishes.

- A long baseline array (LBA) will add an additional 30 reflector antennas each of 18 m diameter in 10 clusters providing continental scale baselines ($B_{MAX} \sim$ 8860 km). The LBA is designed to sample a broad range of scales for stand-alone sub-array use, as well as for integrated operation with the main array.

It total, the ngVLA will have approximately ten times the sensitivity of the VLA and ALMA, continental-scale baselines providing sub-milliarcsecond-resolution, and a dense core on km-scales for high surface brightness sensitivity. Such an array bridges the gap between ALMA, a superb sub-mm array, and the future SKA1, optimized for longer wavelengths.

The dense core and the signal processing center of the array will be located at the Very Large Array site, on the plains of San Agustin, New Mexico. The high desert plains of the Southwest U.S., at over 2000 m elevation, provide excellent observing conditions for the frequencies under consideration, including reasonable phase stability and opacity at 3 mm wavelength over a substantial fraction of the year.

The array will also include stations in other locations throughout the state of New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US. Virgin Islands, and Canada.

Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will be collocated in a large metropolitan area and will be the base for science operations and support staff, software operations and related administration. Research and development activities will be split amongst these centers as appropriate.

The facility will be operated as a proposal-driven instrument. The fundamental data products delivered to ngVLA users will be science-ready data products (i.e., images and cubes) generated using calibration and imaging pipelines created and maintained by the project. Both the pipeline products and the "raw" visibilities and calibration tables will be archived, retaining the option of future re-processing and archival science projects.

The ngVLA project is developing a Reference Design for the array as a baseline for construction and operation costing, and future design trade-off decisions. This Reference Design is intended to be low technical risk in order to provide a degree of conservativism in the estimates. However, leading-edge concepts and techniques that may improve the performance and/or reduce cost are being developed in parallel, and will be evaluated in the conceptual design phase of the facility. This paper provides an overview of the Reference Design as the project approaches the Astro2020 Decadal Survey.

2. Key Science & Technical Requirements

The Key Science Goals and all other science use cases were parameterized and analyzed (Selina, Murphy & Erickson 2017) to determine the science requirements for the ngVLA (Murphy 2017). While this aspect of the requirements definition is top-down and mission-driven, some judicious adjustment of the requirements is still appropriate.

A primary science requirement for the ngVLA is to be flexible enough to support the breadth of scientific investigations that will be proposed by its creative scientist-users over the decades-long lifetime of the instrument. The requirements have therefore been adjusted to provide a balanced, flexible, and coherent complement of capabilities. The primary requirements that drive the design are described below:

- **Frequency Coverage:** The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits are bracketed by spectral line emission from HI and CO respectively.
- **Continuum Sensitivity:** A continuum sensitivity of better than 0.02 μJy/bm at 30 GHz and 0.2 μJy/bm 100 GHz is required for studying protoplanetary disks. This requires a combination of large collecting area and wide system bandwidth.
- **Line Sensitivity:** A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is simultaneously required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of $1-100$ mK at $0\farcs1-5''$ angular resolution and $1-5$ km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe. The spectral line cases push the system design towards quantum-limited noise performance at the expense of bandwidth above 10 GHz.
- **Angular Resolution:** A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz, while meeting the continuum sensitivity targets.
- **Largest Recoverable Scale:** Angular scales of $> 20'' \times (100\,\mathrm{GHz}/\nu)$ must be recovered at frequencies $\nu < 100$ GHz. A more stringent desire is accurate flux recovery on arcminute scales at all frequencies. These scales approach the size of the primary beam of an 18 m dish, so both shorter baselines and a total power capability are necessary to completely fill in the central hole in the (u, v)-plane.
- **Surface Brightness Sensitivity:** The array must provide high-surface brightness sensitivity over the full range of angular scales recoverable with the instrument. This leads to a centrally condensed distribution of antennas.
- **Brightness Dynamic Range:** The system brightness dynamic range shall be better than 50 dB for deep field studies. This requirement pushes a number of systematic requirements including pointing, gain, and phase stability.
- **Survey Speed:** The array shall be able to map a ~10 square degree region to a depth of $\sim 1\,\mu$Jy/bm at 2.5 GHz and a depth of $\sim 10\,\mu$Jy/bm at 28 GHz within a 10 hr epoch for localization of transient phenomena identified with other instruments. Holding collecting area and receiver noise constant, this favors smaller apertures.
- **Beamforming for Pulsar Search, Pulsar Timing and VLBI:** The array shall support no less than 10 beams spread over 1 to 10 subarrays that are transmitted, over the full available bandwidth, to a VLBI recorder/correlator, pulsar search engine or pulsar timing engine. The pulsar search and timing engine must be integral to the baseline design.

- **Science Ready Data Products:** The primary data product delivered to users shall be calibrated images and cubes. Uncalibrated, “raw" visibilities shall be archived to permit reprocessing. Producing these higher-level data products requires some standardization of the initial modes/configurations that the system is used in (e.g., limited tuning options), and repeatability/predictability from the analog system to reduce the calibration overheads.

3. Site Selection & Performance

The VLA site on the plains of San Agustin was originally chosen as the location for the array because of its desirable properties: large, relatively flat, undeveloped (to minimize RFI) yet not too remote (for accessibility), at low latitude (for sky coverage), and at high elevation (to minimize atmospheric effects) (Thompson et al. 1980). These properties still hold true, and motivate examination of the VLA site as the center of the ngVLA. Furthermore, with extensive existing infrastructure, the VLA site leverages an already-existing system of power, fiber, and buildings, which will reduce cost. The three main environmental or atmospheric quantities that may affect data, and what is known about them at the VLA site, are discussed in the following sections.

3.1. RFI

The VLA site is remote enough that Radio Frequency Interference (RFI) is not a debilitating problem, so it will be possible to observe at the lower frequencies of ngVLA (Stewart 2005). Furthermore, the ngVLA will benefit by advanced studies of RFI detection and excision that are currently ongoing (Burnett et al. 2018). The degree of RFI characterization of the site reduces the risk in site selection, and leveraging existing infrastructure could create significant cost savings for both the construction and operation of the array. Given the large extent of ngVLA ($B_{MAX} \sim 8860$ km), it is clear that the antennas which are outside the plains will experience different RFI environments than that at the site. However, there are locations which are relatively free of locally generated RFI (downward RFI from orbiting satellites is ubiqitous and nearly site-independent), and the U.S. southwest has many such locations (Li et al. 2004).

3.2. Atmospheric Phase Stability

Analysis of data from the VLA site atmospheric phase monitor shows that fast switching phase calibration at 3 mm should be viable for most of the year with a 30 s total calibration cycle time (Carilli 2015). This analysis was based on one year of atmospheric phase monitoring at the VLA site (Butler & Desai 1999). A much longer time base of these values is now available. Figure 1 shows median values of the rms phase on the 300 m E-W baseline of the atmospheric phase monitor from 1995 through 2017, plotted as a function of UTC hour, and month. It is easy to see that these fluctuations are small for much of the time, and only become greater than 10° (rms @ 11.7 GHz, over 10 minutes) in the summer during daytime. Little information is available on phase fluctuations at locations outside the plains; this is a topic to be studied to determine the ability to use the remote sites at the highest frequencies of ngVLA. Note that there should also be a 25 mJy calibrator source within 2° in 98% of observed fields, ensuring short slews. Such a calibrator is adequate to ensure that the residual rms phase noise due to the signal-to-noise ratio on the phase calibrator is much less than that due to the

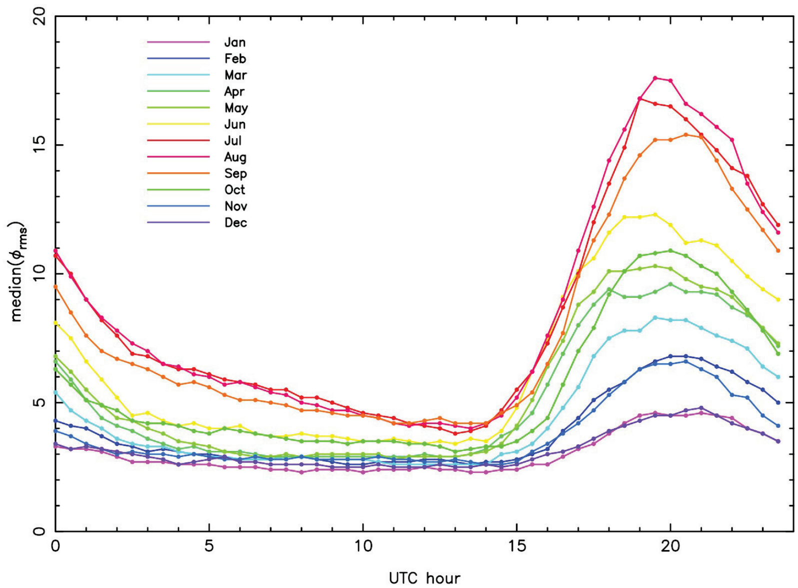

Figure 1. The median rms phase measured with the atmospheric phase monitor at the VLA (300 m E-W baseline, 11.7 GHz beacon), from 1995 to 2017. Measurements are calculated over a 10 minute period after subtracting any linear trend. Different months are plotted as different colors, as shown in the legend.

troposphere, even for a 30 s cycle time with only 3 s on the calibrator each visit (Carilli 2015; Clark 2015). The project is also investigating radiometric phase correction techniques as part of the ngVLA project to increase the total phase calibration cycle time.

3.3. Atmospheric Opacity

While at centimeter wavelengths atmospheric opacity is a relatively minor issue compared to phase stability, it becomes a much bigger issue at millimeter wavelengths. Similar to the atmospheric phase stability data, there is a long-time baseline of surface weather data at the VLA site. This can be used to estimate the atmospheric Precipitable Water Vapor (PWV), which is the main contributor to the fluctuating part of atmospheric opacity (Butler 1998). Figure 2 shows this value for the years 2010 through 2017. In winter months, the median over all hours is around 3 mm, and over the entire year the median over all hours is 5.4 mm. Vertical opacity for 5.4 mm PWV at 90 GHz is less than 7%, so opacity should not be a major problem for ngVLA. As with RFI and phase stability, there is little information on atmospheric opacity at other locations, though it is almost always clear that higher sites have less opacity. The project does have access to surface weather data, and to radiosonde launch data (twice per day) from NOAA for some tens of sites across the southwest US, which will be the subject of a future study to determine opacity properties across the extent of the ngVLA.

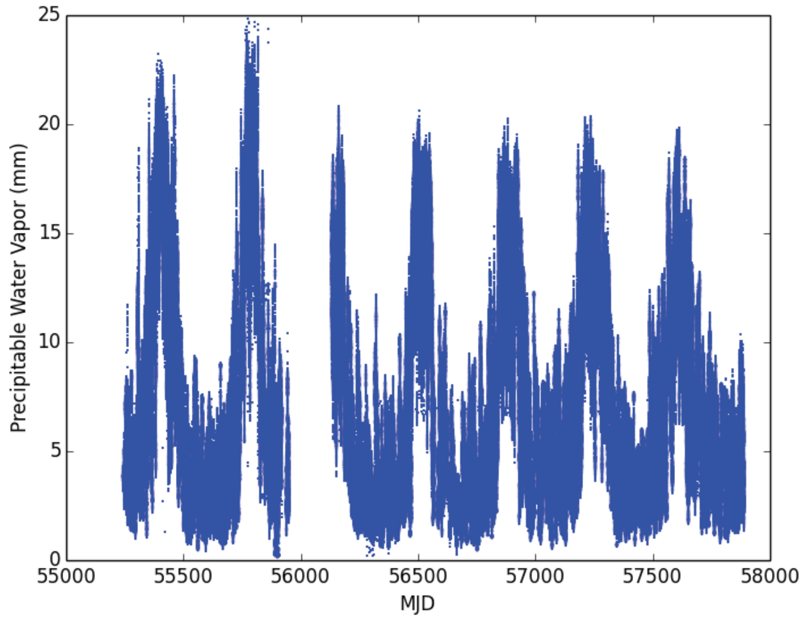

Figure 2. PWV at the VLA site, estimated using surface weather measurements, from 2010 to 2017. Note that a PWV of 6 mm produces an opacity of less than 7% at 90 GHz.

3.4. Final Site Selection

Because of the quality of the site for both low- and high-frequency observing, and the existing infrastructure, the ngVLA is centered near the current VLA. The southwest U.S. and northern Mexico are sparsely populated and the antennas within 1000 km of the VLA are sited to select remote, radio quiet, and dry sites, while still considering the logistics of site access, electrical infrastructure and fiber optic network topology. The long baseline array sites were selected to minimize site impact and leverage shared infrastructure of other existing observatories, so sites operated by the VLBA or other observatories are preferred. Note that the VLA site was used for acceptance testing of the original ALMA antennas, including observations up to 230 GHz, and the experience was that the VLA site, at 2124 m elevation is a high-quality 90 GHz site - comparable to the Plateau de Bure site in overall performance (Thompson, Moran & Swenson 2004).

4. Array Configuration

The ngVLA array design includes three fundamental subarrays providing a wide range of angular scales: a main interferometric array, a short baseline array, and a long-baseline array.

The main array configuration will consist of 214 18 m antennas at the approximate locations shown in Figure 3. The array collecting area (see Table 1) is distributed to provide high surface brightness sensitivity over a range of angular scales spanning from approximately 1000 to 100 mas while providing high point source sensitivity on scales

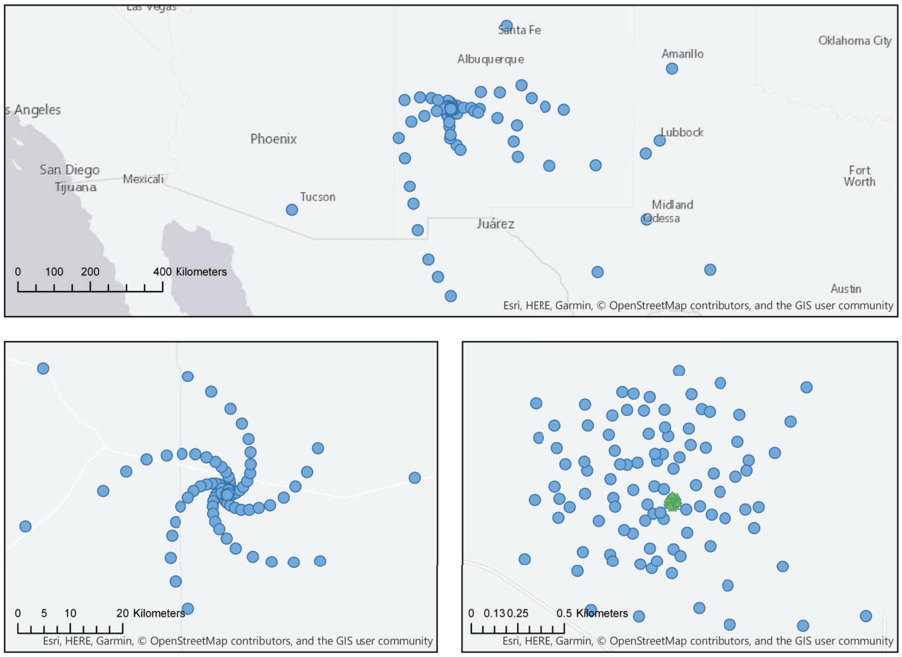

Figure 3. (*Top:*) ngVLA Main Array Configuration Rev. B (Spiral-214). The antenna positions are still notional, but are representative for performance quantification and cost estimation. (*Bottom Left*): Zoom view of the plains of San Agustin. (*Bottom Right:*) Zoom view of the compact core. SBA antennas are shown in green.

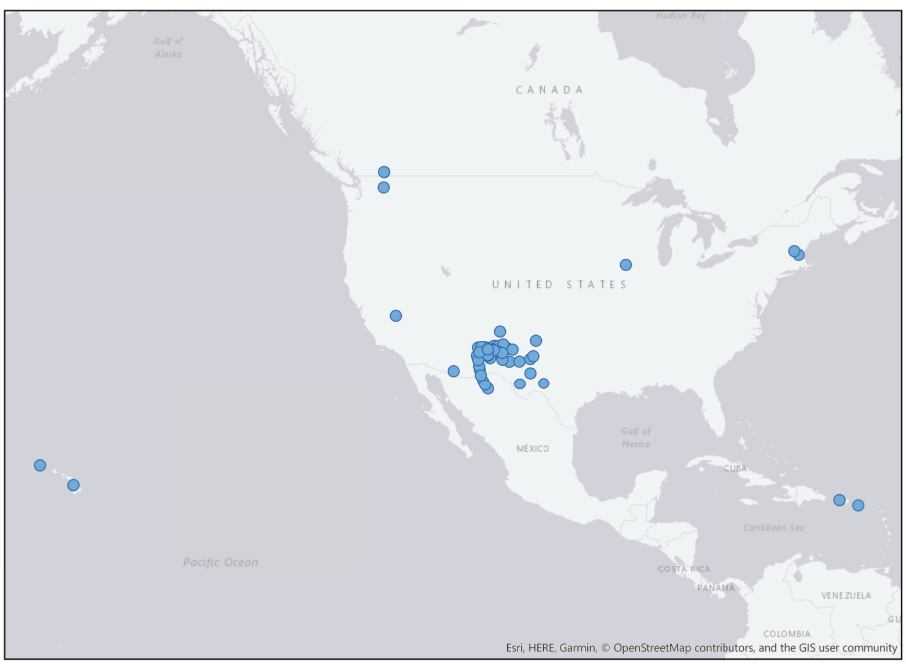

Figure 4. View of the Main Array and Long Baseline Array stations. Multiple antennas are located at each LBA site.

Radius	Collecting Area Fraction	Quantity
$0\,\mathrm{km} < R < 1.3\,\mathrm{km}$	$\approx 44\%$	94
$1.3\,\mathrm{km} < R < 36\,\mathrm{km}$	$\approx 35\%$	74
$36\,\mathrm{km} < R < 1000\,\mathrm{km}$	$\approx 21\%$	46

Table 1. Radial distribution of collecting area for the main array (214 antennas).

up to 10 mas. A large fraction of the collecting area is in a randomly distributed core to provide high snapshot imaging fidelity and there are arms extending asymmetrically out to ~1000 km baselines to fill the (u, v)-plane via Earth rotation and frequency synthesis.

The design has been extended from the main interferometric array to include both a short spacing array and total power dishes (Mason 2018b). This was necessary after a review of the key science cases, as these are dependent on the recovery of large scale structure that approaches the size of the antenna primary beam.

The auxiliary short baseline array (SBA) of 19 reflector antennas of 6 m aperture will be sensitive to a portion of the larger angular scales undetected by the main array. The SBA will provide spacings from $\sim$ 11 m to 56 m, providing comparable surface brightness sensitivity to the main array, in equal observing time, when the main array is (u, v)-tapered to the natural resolution of the SBA. This allows for commensal observing, and more importantly, full cross-correlation and cross-calibration of the SBA and main array. The array distribution is semi-randomized to improve the point spread function (Mason et al. 2018a).

The SBA will be combined with four 18 m (main array) antennas used in total power (TP) mode to completely fill in the central hole in the (u, v)-plane left by the 6 m dishes. It is a design goal to share the mount design of the 18 m interferometric array antennas and the TP antennas, but this will require further study.

In response to community feedback, a long baseline array (LBA) has also been added to the configuration (see Figure 4). The long baseline array adds 30 antennas of 18 m diameter at 10 additional sites. The LBA provides continental scale ($B_{MAX} \sim$ 8860 km) baselines while also providing scales from $\sim$ 30 m to 1000 km within the subarray. This will enable the LBA to function effectively as a stand-alone array or as an integrated part of the main array.

The ngVLA array configuration elements are summarized in Table 2. The design of the array configuration is practical, accounting for logistical limitations such as topography, utility access, local RFI sources and land management/availability. An analysis of different weighting schemes (i.e., Briggs, (u, v)-taper) for specific science applications (Carilli 2017) found that the current configuration provides a reasonable

Array Element	Aperture Diameter [m]	Quantity	B_{MIN} [m]	B_{MAX} [km]
Long Baseline Array	18	30	32.6	8856
Main Interferometric Array	18	214	30.6	1005
Short Baseline Array	6	19	11.0	0.06
Total Power / Single Dish	18	$4^{\dagger}$	-	-

†These 4 dishes are included as part of the 214 main array.

Table 2. Summary of elements within the ngVLA array configuration.

compromise and baseline for further iteration. The configuration will be a primary area of study in the coming years, e.g., investigations are underway to improve the imaging fidelity and quality of the synthesized beam.

5. Array Calibration

The calibration strategy for ngVLA is being developed early in the design so that it may guide the design of the hardware elements. The size and complexity of the calibration and imaging pipeline requires that the system design be responsive to its needs, and it should inform the design where possible.

A secondary concern is the efficiency of the calibration process. Algorithms used must be suitable for parallel processing, antennas must not require much individual attention, and minimal human intervention should be generally required for routine operation. The calibration overheads applied will vary with the science requirements of a given observation, and less computationally or time intensive calibration approaches will be applied when possible.

The operations plan calls for guaranteed time on source to each observer, with calibration overheads being the responsibility of the facility (Ford et al. 2018). This enables the reuse of calibration observations for adjacent observations when their requirements are sufficiently similar, further improving observation efficiency.

The general calibration strategies under consideration for the reference design are summarized below.

- **Fast Atmospheric Phase Calibration:** Rapid atmospheric phase fluctuations will be mitigated by a combination of relative water vapor radiometry (WVR) and antenna switching cycles to astronomical phase calibrators. The switching cycle time will depend on empirical validation of the strategy, but is expected to be necessary on one to ten minute scales. The antenna will be designed to both house the WVR and move 4° on sky and settle to within the pointing specification with 10 seconds for elevation angles < 70° (Selina 2017).

- **Slow Atmospheric & Electronic Phase Calibration:** Slow atmospheric and electronic phase calibration will be achieved by traditional approaches, with astronomical phase calibrator observations bracketing all observations. Several astronomical calibrators may be used to map the slow varying terms, including ionospheric fluctuations.

- **Amplitude Calibration:** A list of known astronomical amplitude calibrators will be used to correct for system gain fluctuations within an observation and between observations taken over an extended period of time. The calibration pipeline will maintain a history of recent solutions to enable look-up of prior values.

- **Bandpass Calibration:** At a minimum, the system will correct for digital effects, given the predictable bandpass ripple from finite impulse response filters. The number of setups in the analog portions of the system will be limited, so typical calibration can also correct for analog bandpass effects based on historical look-up tables that are updated as the configuration of the system changes (i.e., when an antenna is serviced).

- **Polarization Calibration:** The use of linear feeds will require polarization calibration for most observations. Feeds may be placed at different (but known) position angles in the various antennas, so a single observation of a point source can solve simultaneously for the polarization leakage terms and the source polarization. Calibration for polarization as a function of position within the antenna beam will be assumed to be time invariant and corrected based on look-up tables for most observations.
- **Relative Flux Density Calibration:** This calibration is used to tie together observations of a source taken over an extended period. The system will model atmospheric opacity based on barometric pressure and temperature monitored at the array core and each outlying station. A temperature stabilized noise diode will provide a flux reference, and when combined with corrections for modeled atmospheric opacity, we can assume a constant ratio in power from the switched noise calibrator and the source.
- **Absolute Flux Density Calibration:** Absolute flux scale calibration will employ similar methods to relative calibration, with two notable changes. First, atmospheric tipping scans will be used to empirically determine atmospheric opacity, with improved fidelity. Second, observations of astronomical flux density calibrators will be used, along with the switched power system, to determine the absolute flux density of the source.

The ngVLA will need to maintain multiple lists of calibrators by calibration intent. The flux density calibrator list can be relatively small and based on the one built and maintained by the VLA. An extensive grid of sources will be required for phase and amplitude calibration. The large range of baselines present on the ngVLA means that it cannot be assumed that the source is unresolved at all scales, and the calibrators themselves will have to be imaged before use in the calibration process.

6. Antenna

The antenna concept strikes a balance between competing science requirements and the programmatic targets for life cycle cost. Sensitivity goals will be met, in part, by the total effective collecting area of the array. The reference design includes 244 antennas of 18 m aperture (main array and long baseline array) and 19 antennas of 6 m aperture (short baseline array) using an offset Gregorian optical design.

The inclusion of frequencies down to 1.2 GHz, when combined with the operational cost targets, significantly constrain the optical configuration. The use of feeds with wide illumination angles decreases their size such that they can be mounted within shared cryostats. This choice constrains the secondary angle of illumination to a degree that only Gregorian optical designs are practical. However, with a science priority of high imaging dynamic range in the 10 – 50 GHz frequency range, an offset Gregorian is near optimal. The unblocked aperture will minimize scattering, spillover and sidelobe pickup. Maintenance requirements favor antenna optical configurations where the feed support arm is on the “low side” of the reflector.

The optimization for operations and construction cost suggests that a smaller number of larger apertures is preferable to larger numbers of small apertures. Survey speed requirements push the opposite direction, and a compromise value of 18 m diameter is

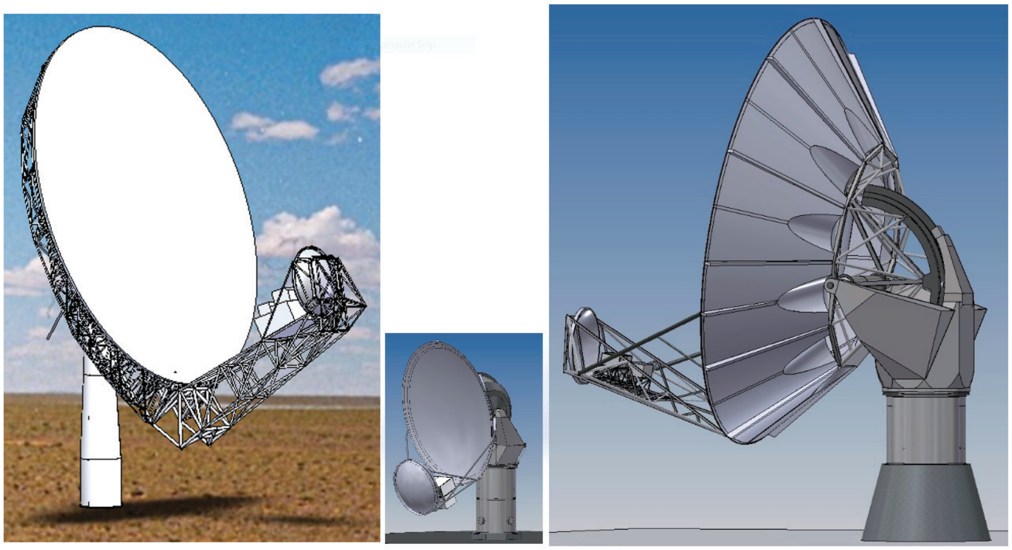

Figure 5. (*Left:*) ngVLA 18 m antenna reference design concept prepared by GDMS. Center: 6 m short spacing array antenna concept prepared by NRCC. (*Right:*) ngVLA 18 m antenna composite design concept prepared by NRCC.

adopted for the reference design. The design aims for Ruze performance to 116 GHz, with a surface accuracy of 160 μm rms ($\lambda/16$ @ 116 GHz) for the primary and subreflector combined under precision environmental conditions. The antenna optics are optimized for performance above 5 GHz with some degradation in performance accepted at the lowest frequencies due to diffraction, in exchange for more stiffness in the feed arm to improve pointing performance.

Since the ngVLA is envisioned as a general purpose, proposal-driven, pointed instrument (rather than a dedicated survey telescope), the optics will be shaped to optimize the illumination pattern of single pixel feeds, increasing antenna gain while minimizing spillover. High pointing accuracy will also be necessary to provide the required system imaging dynamic range. With an unblocked aperture, variations in the antenna gain pattern are expected to be dominated by pointing errors. Preliminary requirements are for absolute pointing accuracy of 18 arc-seconds rms, with referenced pointing of 3 arc-seconds rms, during the most favorable environmental conditions (Mason 2018b).

The mechanical and servo design is a typical altitude-azimuth design, Figure 5. Initial studies suggest pedestal designs are expected to have lower life-cycle cost while meeting pointing specifications. The antenna mechanical and servo design will be optimized for rapid acceleration and a fast settling time, in order to manage the switching overhead associated with short slews.

The project is pursuing a reference design to specifications for the 18 m antenna with General Dynamics Mission Systems (GDMS). A parallel study into a composite design concept with the National Research Council of Canada (NRCC) is also underway, and NRCC are also preparing a reference design for the 6 m short baseline array antenna.

The 6 m aperture for the SBA antenna was chosen to provide overlapping (u, v)-plane coverage with the 18 m dishes when the later are used in both interferometric and total power mode. The optical design is inherently more offset than the 18m design in order to maintain a suitable minimum subreflector aperture (2.7 m) for 1.2 GHz operation, but shares the same feed illumination angle. Maintaining common interfaces ensures that the 6 m design can share the majority of the antenna electronics, including feeds and receivers.

The 6 m design employs a composite singe-piece reflector, and composite segmented backup structure on a steel pedestal mount. The mount includes space to house the digital electronics, power supplies and servo system, Figure 5.

7. Receiver Configuration

The ngVLA will provide continuous frequency coverage from 1.2 - 50.5 GHz and 70 - 116 GHz in multiple bands. Receivers will be cryogenically-cooled, with the receiver cryostats designed to integrate multiple receiver bands to the extent possible. Limiting the number of cryostats will reduce both maintenance and electrical power costs. The total number of bands required strongly depends on their fractional bandwidths: maximizing bandwidths will reduce the number of cryostats, with a possible penalty in sensitivity. Feeds for all receiver bands are cooled, and fully contained within the cryostat(s).

Band #	f_L (GHz)	f_M (GHz)	f_H (GHz)	BW (GHz)	Aptr. Eff., ηA @ f_L	@ f_M	@ f_H
1	1.2	2.0	3.5	2.3	0.80	0.79	0.74
2	3.5	6.6	12.3	8.8	0.80	0.78	0.76
3	12.3	15.9	20.5	8.2	0.84	0.87	0.86
4	20.5	26.4	34	13.5	0.83	0.86	0.83
5	30.5	39.2	50.5	20	0.81	0.82	0.78
6	70	90.1	116	46	0.68	0.61	0.48

Table 3. Band definitions and aperture efficiency of the baseline receiver concept.

The baseline ngVLA receiver configuration consists of the low-frequency receiver (1.2 - 3.5 GHz) in one cryostat, and five receivers spanning from 3.5 to 116 GHz in a second cryostat. Bands 1 and 2 employ wideband feed horns and LNAs, each covering L+S bands, and C+X bands. Quad-ridged feed horns (QRFHs) are used, having dual coaxial outputs. Due to improved optical performance (improving illumination efficiency and reducing T_{spill}), cooled feeds, and the simplified RF design sensing linear polarization, the T_{sys} is lower than current VLA L, S bands and comparable for C and X bands. Overall aperture efficiency and T_{sys} are slightly degraded from optimal due to the wider bandwidths spanned, but this permits a compact package that can be affordably constructed and operated.

The four high-frequency bands (12.3 - 116 GHz) employ waveguide-bandwidth (~1.67:1) feeds & LNAs, for optimum aperture efficiency and noise performance. Axially corrugated feed horns with circular waveguide output ensure uniform illumination over frequency, with minimum spillover and resistive loss.

Band #	T_{spill} (K)			T_{RX} (K)			T_{sys} (K)		
	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	12.8	10.1	4.0	9.9	10.3	13.8	27.1	24.9	22.4
2	12.8	7.0	3.9	13.4	15.4	14.4	30.8	27.1	23.6
3	4.1	4.1	4.1	13.9	16.9	18.6	23.3	27.3	36.3
4	4.1	4.1	4.1	15.4	16.2	18.6	33.1	32.4	36.0
5	4.1	4.1	4.1	19.1	20.4	26.5	34.0	41.0	101
6	4.1	4.1	4.1	50.6	49.0	72.6	123	68	189

Table 4. Noise performance of the baseline receiver concept. Assumes 1 mm PWV for band 6, and 6 mm PWV for others; 45° elev. on sky for all.

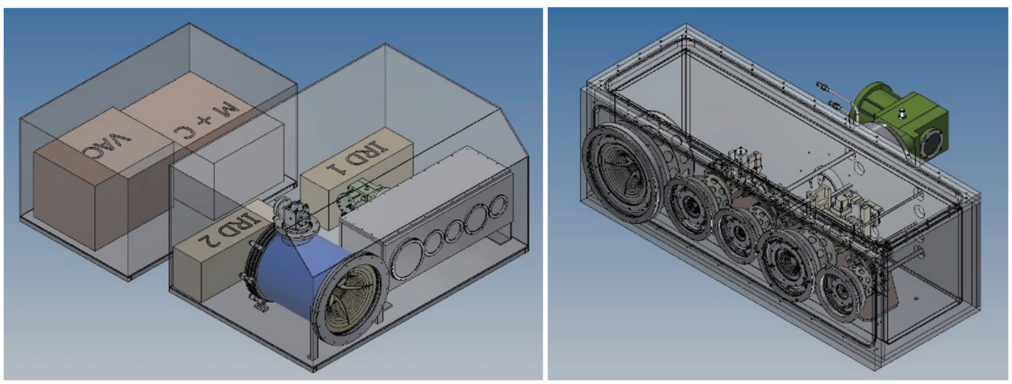

Figure 6. Front end component packaging at the secondary focus of the antenna. Band selection and focus are achieved with a dual-axis translation stage.The integrated receiver packages (labeled IRD 1 and IRD 2) are located in close proximity to the cryostats. Bands 2 – 6 are housed within in single cryostat.

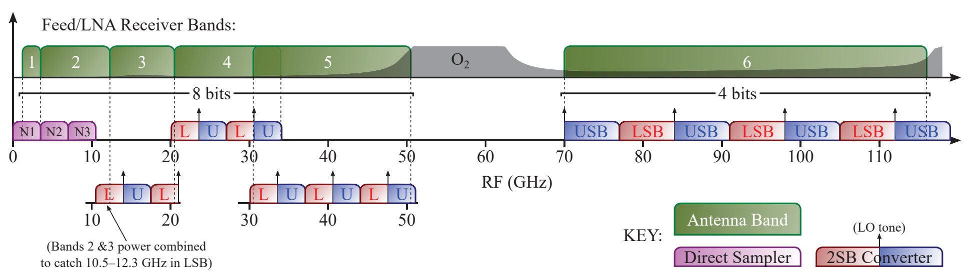

Figure 7. Sampling concept employing integrated receiver technology for both direct and dual sideband converter/samplers. Direct single side-band 8-bit sampling is used for the first three Nyquist zones. Dual sideband 8-bit samplers are then used up to 50 GHz. The 70-116GHz band is spanned by 4-bit samplers, due to the reduced risk of persistent RFI at these frequencies.

The electronics concept relies on integrated receiver packages (Morgan & Wunduke 2017) to further amplify the signals provided by the cryogenic stage, down convert them if necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point (typically the antenna pedestal) where they can be launched onto a conventional network for transmission back to the array central processing facility. Interfaces are provided for synchronization of local oscillators (LO's) and sampler clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

The integrated receiver concept is central to the antenna electronics concept for the ngVLA. Compact, fully-integrated, field-replaceable, warm electronic modules support single-stage, direct-to-baseband downconversion (when needed), followed by a very low-power, low-overhead digitization scheme and an industry-standard fiber optic interface carrying unformatted serial data. The frequency plan is shown in Figure 7.

8. Reference Distribution & Data Transmission

Given the large extent of the array, multiple time and frequency reference distribution concepts will be required to optimize for cost and performance. The array will be built as a combination of two different design methodologies.

A large number of antennas are located on the Plains of San Agustin, and each of these will be connected directly to the central processing facility by dedicated, buried fiber optics. Roughly 70% of the ngVLA antennas will be within this region. Clocks and local oscillator signals will be generated locally at the antenna and locked to a central reference with round trip phase correction.

The remainder of the antennas, the mid and long baseline antennas, will fall into a VLBI[1] station model with a number of local oscillator (LO) and data transmission stations located beyond the central core. These stations will be linked to the central timing system, correlator, and monitor and control system via long haul fiber optics. The most remote of these sites will have independent precision timing and frequency references, such as GPS-disciplined active hydrogen masers. Intermediate sites will used a mixed model dependent on the site logistics.

9. Central Signal Processor

The Central Signal Processor (CSP) ingests the voltage streams recorded and packetized by the antennas and transmitted via the data transmission system, and produces a number of low-level data products to be ingested by the archive. Among its many functionalities, the CSP is responsible for compensating for the large transmission delays from the remote stations, correcting the I/Q channel imbalance of the receiver and improve the separation of the upper and lower sidebands, tracking the delay and phase differences between antennas, flagging the spectral channels corrupted with RFI at a pre-correlation stage, selecting the spectral window of interest within the digitized bandwidth, offsetting the different frequency standards used by the remote stations, and achieving the desired spectral resolution.

In addition to synthesis imaging, the CSP will support other capabilities required of modern telescopes to enable VLBI and time-domain science. The functional capabilities of the CSP include full-polarization auto- and cross-correlation computation, as

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[1] Very Long Baseline Interferometry.

well as beamforming capabilities for pulsar timing, pulsar/transient search, and VLBI recording. The CSP data products will vary by operation mode. The most common will be raw/uncalibrated visibilities, recorded in a common data model. The CSP will include all necessary "back end" infrastructure to average visibilities and package them for the archive, where they will be recorded to disk in a standard format. Calibration of these data products will be carried out through asynchronous data post-processing pipelines.

The CSP will support multiple sub-arrays operating simultaneously and fully independent from each other. Two key requirements for the system are the degree of commensality supported within a sub-array and the desired capabilities for sub-arrays operating simultaneously. At a minimum, the CSP will be able to compute auto- and cross-correlation products within a sub-array, as well as simultaneous cross-correlation and either pulsar timing, pulsar search or VLBI capabilities for different sub-arrays. Enabling correlation and beamforming products simultaneously within a sub-array is also under evaluation. Such a mode would reduce calibration overheads of the beamformer, and provide for localization/imaging concurrent with time-domain observations. The degree of commensality is expected to be a cost/complexity driver in the system and will be optimized on a best value basis.

The ngVLA correlator will employ an FX architecture, and will process an instantaneous bandwidth of up to 20 GHz per polarization. The correlator-beamformer Frequency Slice Architecture (Rupen 2017) developed by NRC Canada for the SKA Phase 1 mid-frequency telescope in South Africa (Dewdney et al. 2015) is well suited to ngVLA demands and is adopted for the reference design. This architecture will scale to the additional ngVLA apertures, bandwidth, and commensal mode requirements. Adopting this architecture could significantly reduce the non-recurring engineering costs during the design phase, while additional improvements in electrical efficiency can be expected from one additional FPGA manufacturing process improvement cycle due to ngVLA's later construction start date as compared to SKA Phase 1. Key performance requirements for the correlator are summarized in Table 5.

Requirement Description	**Specification**
Number of Connected Antennas	263 total
Maximum Baseline Length	10,000 km
Maximum Instantaneous Bandwidth	20 GHz per polarization
Maximum Number of Channels	$\geq 750,000$ channels
Highest Frequency Resolution	400 Hz, corresponding to 0.1 km/s resolution at 1.2 GHz.
Pulsar Search Beamforming	≥ 10 beams, $\geq 1''$ coverage, 60 km diameter sub-array
Pulsar Timing Beamforming	≥ 5 independent sub-arrays ≥ 1 beam per sub-array

Table 5. Central signal processor key specifications.

10. Post Processing System

The software architecture for ngVLA will leverage NRAO's existing algorithm development in reducing VLA and ALMA data and the CASA software infrastructure. The array will have a progressive series of data products suitable to different users groups. The data products may also change based on how well supported a mode is - common modes will have higher level data products that add value to the user, while clearly not all permutations can benefit from such a degree of automation. As with the VLA and ALMA, the fundamental data product that will be archived are uncalibrated visibilities, enabling future reprocessing. The online software system will also produce flags to be applied to the visibilities that would identify known system problems such as antennas being late on source, or the presence of RFI.

Automated post-processing pipelines will calibrate the raw data and create higher-level data products (typically image cubes) that will be delivered to users via the central archive. Calibration tables that compensate for large-scale instrumental and atmospheric effects in phase, gain, bandpass shapes, polarization and flux scale will be provided. Data analysis tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The VLA and ALMA "Science Ready Data Products" project will be an ngVLA pathfinder to identify common high-level data products that will be delivered to the Principal Investigator and to the data archive to facilitate data reuse. This model will also enable the facility to support a broader user base, possibly catering to astronomers who are not intimately aware of the nuances of radio interferometry, thereby facilitating multi-wavelength science.

11. Overall System Performance

The predicted performance of the array is summarized in Table 6. This is an update to the performance estimates originally documented in Selina & Murphy (2017)[2].

The continuum and line rms values in Table 6 are for point source sensitivity with a naturally weighted beam. Imaging sensitivity is estimated based on a similar procedure as shown in Carilli (2017) and provided as a function of angular resolution in Table 7. The table is by necessity a simplification and the imaging sensitivity will vary from these reported values depending on the quality of the (sculpted) synthesized beam required to support the science use case. Herein, quality is defined as the ratio of the power in the main lobe of the sculpted beam attenuation pattern to the power in the entire beam attenuation pattern as a function of the FWHM of the synthesized beam (Murphy 2017).

The brightness sensitivity of an array is critically dependent on the array configuration. The ngVLA has the competing aims of both good point source sensitivity at full resolution and good surface brightness sensitivity on a range of larger scales. Different array configurations that might provide a reasonable compromise through judicious weighting of the visibilities for a given application have been explored (Clark & Brisken 2015) – see Lal (2011) for similar studies for the SKA. It is important to recognize that for any given observation, from full resolution imaging of small fields,

[2] `http://ngvla.nrao.edu/page/refdesign`

to imaging structure on scales approaching that of the primary beam, some compromise will have to be accepted to enable a practical and flexible general purpose facility.

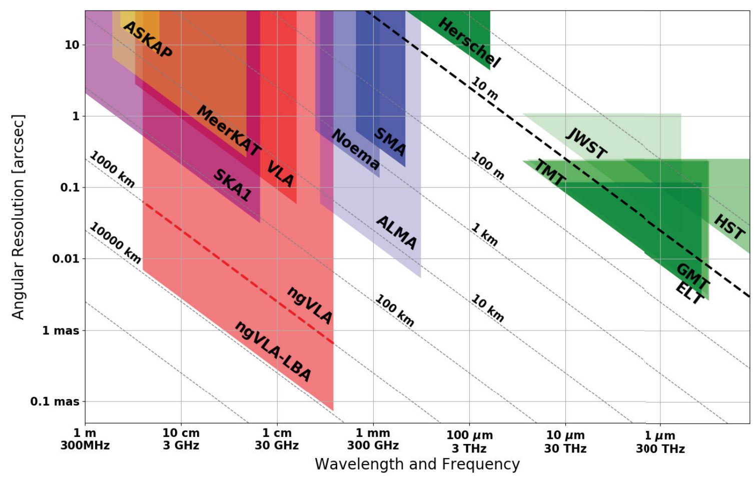

Figure 8. Spatial resolution versus frequency set by the maximum baselines of the ngVLA as compared to that of other existing and planned facilities.

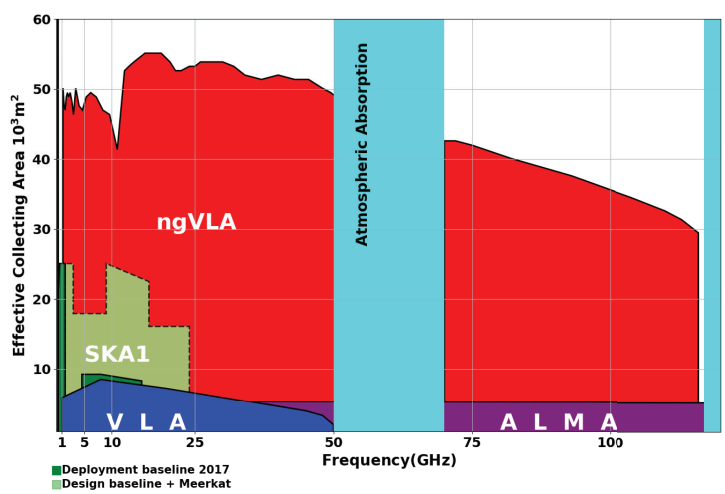

Figure 9. Effective collecting area versus frequency for the ngVLA as compared to that for other existing or planned facilities. Both the SKA1 'deployment baseline' (dark green) and 'design baseline' (light green) are shown, inclusive of the MeerKAT array (Dewdney 2013).

Figure 8 shows a slice through the parameter space, resolution versus frequency, covered by the ngVLA along with other existing and planned facilities that are expected in the 2030s at radio to optical wavelengths. The maximum baselines of the ngVLA support a resolution of better than 0.5 mas at 1 cm. Coupled with the high sensitivity of the array, this resolution provides a unique window into the formation of planets in disks on scales of our own Solar system at the distance of the nearest active star forming regions.

Figure 9 shows a second slice through parameter space: effective collecting area versus frequency. A linear-linear plot highlights the parameter space opened by the ngVLA. Note that the SKA-1 will extend to below 100 MHz while ALMA extends up to almost a THz. We note that there are other aspects of telescope phase space that are relevant, including field of view, mapping speed, surface brightness sensitivity, bandwidth, system temperature, dynamic range, etc. We have presented the two principle and simplest design goals, namely, maximum spatial resolution and total effective collecting area (as a gross measure of system sensitivity).

Imaging sensitivity will be dependent on the required resolution and imaging fidelity. Figures 10 and 11 show the effects of adjusting imaging weights to vary the resolution and PSF quality. These figures are based on a 4 hour simulation at 30 GHz using the 244 antenna array configuration, for a source at +24° Declination observed during transit. The reported beam size is the geometric mean of the major and minor axes full width at half maximum (FWHM) of the synthesized beam as parameterized by Gaussian fitting in the CASA `tclean` task. The highly centrally condensed antenna distribution leads to a naturally weighted beam that is not well characterized by a Gaussian function. Specific science applications may need to adjust the (u, v)-weighting and image parameters to 'sculpt' a synthesized beam that is adequate for the particular science goal being considered (Carilli 2017). The results in Figures 10 and 11 should be considered representative of the possibilities, and optimizing sensitivity vs. resolution will be a major area of investigation during telescope development.

In order to account for the change in sensitivity due to use of imaging weights (relative to the naturally weighted rms σ_{NA}), we have adopted an efficiency factor η_{weight} such that the expected image rms after weighting is $\eta_{weight}\,\sigma_{NA}$. The sensitivity calculations in Table 7 include η_{weight}, estimated using the blue and red data series in Figure 10 and by scaling $\theta_{1/2}$ with frequency ($\theta_{1/2} \times \nu/30\,\mathrm{GHz}$).

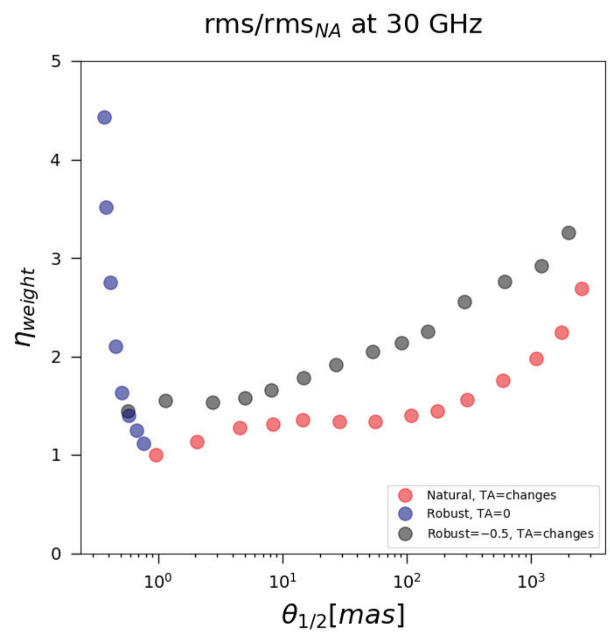

Figure 10. Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (rms$_{NA}$). The red symbols correspond to use of a (u, v)-taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = -0.5 and a varying (u, v)-taper, which has a large effect on beam quality (see Figure 11).

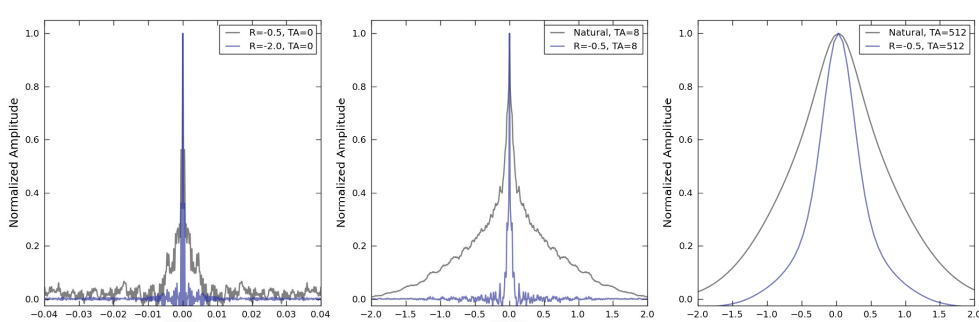

Figure 11. Simulated 30 GHz PSFs over a range of resolutions, showing the effect of different imaging weights (TA: (u, v)-taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 10: left panel (blue circles), central and right panels (gray and red circles). These examples illustrate how combinations of robustness and tapering allow for a beam of much higher quality at the expense of sensitivity.

Center Frequency [GHz]	2.4	8	16	27	41	93	Notes
Band Lower Frequency [GHz]	1.2	3.5	12.3	20.5	30.5	70.0	a
Band Upper Frequency [GHz]	3.5	12.3	20.5	34.0	50.5	116.0	a
Field of View FWHM [arcmin]	24.3	7.3	3.6	2.2	1.4	0.6	b
Aperture Efficiency	0.77	0.76	0.87	0.85	0.81	0.58	b
Effective Area, A_{eff}, x 10^3 [m^2]	47.8	47.1	53.8	52.6	50.4	36.0	b
System Temp, T_{sys} [K]	25	27	28	35	56	103	a, e
Max Inst. Bandwidth [GHz]	2.3	8.8	8.2	13.5	20.0	20.0	a
Sampler Resolution [Bits]	8	8	8	8	8	4	
Antenna SEFD [Jy]	372.3	419.1	372.1	485.1	809.0	2080.5	a, b
Resolution of Max. Baseline [mas]	2.91	0.87	0.44	0.26	0.17	0.07	c
Continuum rms, 1 hr [μJy/beam]	0.38	0.22	0.20	0.21	0.28	0.73	d
Line Width, 10 km/s [kHz]	80.1	266.9	533.7	900.6	1367.6	3102.1	
Line rms, 1 hr, 10 km/s [μJy/beam]	65.0	40.1	25.2	25.2	34.2	58.3	d

Table 6. ngVLA Key Performance Metrics. Notes: (a) 6-band ‘baseline’ receiver configuration. (b) Reference design concept of 244 18 m aperture antennas. Unblocked aperture with 160 μm surface. (c) Current reference design configuration, including LBA. Resolution in E-W axis. (d) Point source sensitivity using natural imaging weights, dual polarization and all baselines (main array + LBA). (e) Averaged over the band. Assumes 1 mm PWV at 93 GHz, 6 mm PWV for other bands, 45° elevation on sky.

Center Frequency [GHz]	2.4	8	16	27	41	93
Resolution [mas] : 1000						
Continuum rms, 1 hr, Robust [μJy/beam]	0.52	0.34	0.35	0.39	0.59	2.24
Line rms 1 hr, 10 km/s Robust [μJy/beam]	88.9	61.1	43.3	47.9	70.9	179.6
Brightness Temp. (T_B) rms continuum, 1 hr, Robust [K]	0.110	6.4E-3	1.7E-3	0.7E-3	0.4E-3	0.3E-3
T_B rms line, 1 hr, 10 km/s, Robust [K]	18.76	1.16	0.21	0.08	0.05	0.03
Resolution [mas] : 100						
Continuum rms, 1 hr, Robust [μJy/beam]	0.50	0.30	0.27	0.28	0.40	1.14
Line rms 1 hr, 10 km/s Robust [μJy/beam]	85.0	53.6	33.6	34.8	48.4	91.3
Brightness Temp. (T_B) rms continuum, 1 hr, Robust [K]	10.58	0.56	0.13	0.05	0.03	0.02
T_B rms line, 1 hr, 10 km/s, Robust [K]	1794.1	101.9	15.9	5.8	3.5	1.3
Resolution [mas] : 10						
Continuum rms, 1 hr, Robust [μJy/beam]	0.41	0.27	0.26	0.27	0.38	0.97
Line rms 1 hr, 10 km/s Robust [μJy/beam]	69.9	48.3	32.4	33.2	46.3	77.7
Brightness Temp. (T_B) rms continuum, 1 hr, Robust [K]	870.58	50.51	12.42	4.53	2.77	1.36
T_B rms line, 1 hr, 10 km/s, Robust [K]	1.5E5	9173	1540	555	335	109
Resolution [mas] : 1						
Continuum rms, 1 hr, Robust [μJy/beam]	-	20.87	0.31	0.21	0.29	0.90
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	3789.8	38.2	25.7	34.7	72.0
Brightness Temp. (T_B) rms continuum, 1 hr, Robust [K]	-	4.0E5	1466	350	207	126
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	7.2E7	1.8E5	4.3E4	2.5E4	1.0E4
Resolution [mas] : 0.1						
Continuum rms, 1 hr, Robust [μJy/beam]	-	-	-	-	-	20.96
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	-	-	-	-	1683.2
Brightness Temp. (T_B) rms continuum, 1 hr, Robust [K]	-	-	-	-	-	2.9E5
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	-	-	-	-	2E7

Table 7. Projected image sensitivity as a function of angular resolution. These calculations include η_{weight} and are scaled by frequency, as described in the text.

Acknowledgments. The ngVLA is a project of the National Science Foundation's National Radio Astronomy Observatory which is operated under cooperative agreement by Associated Universities, Inc.

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Reaching Communities and Creating New Opportunities with the ngVLA

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Abstract. The Office of Diversity and Inclusion (ODI) and the Education and Public Outreach (EPO) Department serve the strategic goal of the National Radio Astronomy Observatory (NRAO) to broaden public awareness of, support for, and participation in Science, Technology, Engineering, and Mathematics (STEM). ODI operates a suite of programs designed to support underrepresented minority undergraduate, graduate students in pursuit of careers in STEM. EPO highlights the discoveries, technologies, and careers pioneered and exemplified by the NRAO via multipurpose engagement strategies that include face-to-face and standalone learning programs, products, and public services for the general public and K-12 students, with attention to reaching diverse audiences. These established and diverse programs are described, along with proposals for new, unique opportunities enabled by the development and realization of a next-generation Very Large Array (ngVLA).

1. Broadening Participation

As a facility under the management of the National Radio Astronomy Observatory (NRAO), the next-generation Very Large Array (ngVLA) has full access to NRAO's suite of widely well-regarded Broadening Participation programs. NRAO's programs address the key priorities identified by the National Science Foundation (NSF) that include:

- Preparing a diverse, globally engaged science, technology, engineering, and mathematics (STEM) workforce;
- Integrating research with education, and building capacity;
- Expanding efforts to broaden participation from underrepresented groups and diverse institutions across all geographical regions in all NSF activities; and
- Improving processes to recruit and select highly qualified reviewers and panelists.

The NRAO has adopted a comprehensive, observatory-wide, "pipeline" approach to the development of STEM capacity, with particular emphasis on broadening participation of underrepresented groups and diverse institutions. This approach begins with engaging K-12 students in a seamless flow of STEM activities that relate to the full spectrum of fields associated with radio astronomy, and continues through providing undergraduate, graduate, and post-doctoral research, training, education, and mentoring programs (described below). The ngVLA will vastly increase the opportunities

Figure 1. The NRAO's Broadening Participation "Pipeline".

that the NRAO can offer to the U.S. and international public, student, and scientific communities.

In addition to its "outward-facing" broadening participation efforts, the NRAO has developed a set of policies and practices that are designed to recruit and select highly qualified, and diverse, reviewers, panelists, and search committees, with the goal of ensuring that selections are fair and equitable across all populations.

Examples of the NRAO's existing, significant investment in broadening participation efforts appear in this section (see Figure 1). Discussions about new opportunities generated by the ngVLA appear in Section 4 (Emerging Opportunities for Broader Impact and Broader Participation through the VLA).

K-12 Education Programs: The NRAO's education programs are designed to introduce the hidden universe revealed by radio astronomy by engaging program participants in age appropriate inquiry based activities and research. Examples of K-12 education programs aimed at broadening participation include:

- **Radio Astronomy and Physics in New Mexico (RAP-NM):** A one-week residential summer camp experience on the NM Tech campus for rising 9th graders from around the state of New Mexico. Student mentors are first recruited from the National Astronomy Consortium (NAC) program (see below).

- **Sister Cities and Observatories:** A 10-day international exchange recruiting from high school youth in areas near the Atacama Large Millimeter/submillimeter Array (ALMA) and VLA introducing them to the world class observatories and the diverse range of careers possible at each. This program will continue under ngVLA.

National Astronomy Consortium (NAC) Program: Opportunities for undergraduate research will be coordinated through the NRAO's NAC program, which is designed to provide research opportunities to underrepresented minority (URM) students. Students are recruited for participation in this program from an established network of Historically Black Colleges and Universities (HBCUs) and Hispanic-serving Institutions (HSIs). The ngVLA will open more opportunities for traditionally underrepresented students to participate in cutting-edge research which, in turn, increases opportunities for the students to attend graduate school and/or begin careers in radio astronomy.

National and International Non-Traditional Exchange (NINE) Program: Collaborative opportunities also exist with the NRAO NINE, which trains the next generation of scientists and engineers from countries in which radio astronomy expertise is limited, but needed. The NINE program focuses on training traditionally underrepresented populations in skills that result in meaningful contributions to the astronomical science body of knowledge. The NINE program includes a network of ever-growing national and international "Hubs" where regional populations learn state-of-the art science and technology relevant to astronomy. The ngVLA will provide cutting edge research opportunities to the NINE program, while benefiting from access to skilled scientists and technicians from the broad network of NINE Hub communities.

2. Public Engagement

Public Website: In addition to programs designed with face-to-face interactions, the ngVLA will have a strong presence on the NRAO website that will serve as a portal for the public to explore the engineering advances and astronomical discoveries made possible by ngVLA. Clear information for visitors wishing to visit the site will be on the website, as well as opportunities to explore the site virtually. An ngVLA Explorer[1], combining video and augmented reality, will be created to give those who cannot visit the facility a virtual tour. The Role Model[2] series will be expanded to include ngVLA staff. It currently reflects the diversity of jobs and experiences that are needed to run a national observatory.

Visitor Center: The planned upgrade of the VLA Visitor Center (VC) reflects modern interpretive methods to explore the intersection of three realms: The stories arising from the resource, visitors' intrinsic interests, and the mission and goals of NRAO. The goals for the ngVLA VC will echo those for the VLA VC, with a substantial update to be inclusive of the international collaborations that will help make the ngVLA possible. These interpretive goals will be expressed through an overarching theme that the ngVLA serves humanity's deep curiosity and drive to explore the universe and our relationship to it:

- Interpretation will make information understandable and relevant for scientists and non-scientists alike.

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[1] e.g., `https://public.nrao.edu/special-features/vla-explorer/`

[2] `https://public.nrao.edu/special-features/role-models/`

  - Non-scientist visitors will understand in general terms the basics of radio astronomy and the ngVLA - and feel happily surprised that they can.
  - Scientists will appreciate the message clarity, without over-simplification to the point of introducing inaccuracies.

- People of diverse backgrounds will feel welcome and actively included as the VC will actively:
  - Provide a venue for diverse cultural voices.
  - Include women, persons of color.
  - Encourage Navajo and Puebloans to share their stories.

- Educators will value and use the ngVLA as a resource.

- Visitors and residents will understand how natural conditions here support the VLA, and will feel inspired to help maintain those conditions.

- Visitors will understand why the ngVLA exists, and feel the program is useful, relevant and worth supporting.
  - People will understand how the ngVLA fits into the bigger picture of astronomy and human discovery.
  - Users will feel they are an integral part of the universe, not separate from it.
  - Local residents and visitors will feel pride and ownership in the ngVLA's role in unlocking the secretes of the universe.

- Visitors will share their positive experiences with others back home.

Media Relations NRAO's EPO department includes a full media relations team with public information officers, artists and graphic designers to best represent the discoveries made possible by ngVLA observations in the popular science media. News and information about ngVLA will be featured in such national outreach venues as the U.S.A. Science and Engineering Festival and National Astronomy Night on the Mall.

3. Broader Impacts: Training the Next Generation

In addition to the NAC and NINE programs that focus on providing research, engineering, and other "full spectrum" astronomy fields, to underrepresented students, the NRAO has provided substantial internship opportunities for undergraduate and graduate students through its REU, graduate research, and NM Ops undergraduate internship programs. The NM Ops internship program, for example, has provided engineering students experience by working in the Observatory's electronics lab. The ngVLA will provide an opportunity to significantly increase the number of students with access to state-of-the-art research and engineering projects.

For the last 2 years EPO has funded a media intern at NRAO headquarters each summer, with the inauguration of ngVLA a media intern will also be stationed at the ngVLA to supplement the efforts of the Public Information Officer and assist with major media efforts.

4. Emerging Opportunities for Broader Impact and Broader Participation through the ngVLA

The NRAO recognizes that the ngVLA project will span more than 10 years; this longevity offers a unique opportunity for the Observatory to build a pipeline for future employees from the regions in which the ngVLA will be present. Our BI and BP plans, then, include a proactive, intentional plan to include workforce development as an integral part of the entire ngVLA project, from beginning construction through and beyond first science. We expect to continue to ask the community for input into this important component of the ngVLA project; we have, however, identified the following opportunities for new, substantial, outcome-oriented Broader Impact (BI) and Broadening Participation (BP) activities (see Table 1).

These ideas represent our commitment to building an ngVLA that is responsible to all members of the scientific and broader communities. We recognize and acknowledge that the ngVLA is indebted to and responsible to taxpayers, local and regional communities, members of underrepresented communities in STEM, K-12 and high education students, postdocs, faculty, scientists, engineers, technical experts, Education and Public Outreach professionals, and all other professions that support the ability to deliver cutting-edge science and technology to the scientific and broader communities.

5. Summary

The ngVLA will build on NRAO's existing, well-designed, and implemented, suite of EPO programs, including the creation of new opportunities to educate the general public about the exciting science resulting from ngVLA observations. The ngVLA will make use of, and significantly enhance, the Observatory's flagship National Astronomy Consortium (NAC) and National and International Non-traditional Exchange (NINE) programs, by providing cutting-edge research and engineering opportunities for a new generation of astronomers, engineers, and technicians. In addition to these existing programs, ngVLA will create innovative new BI and BP opportunities that enhance the value of the ngVLA well beyond the scientific community. Importantly, the ngVLA will embrace the NRAO's commitment to providing these opportunities to populations that are unrepresented in STEM fields, and in the field of astronomy in particular.

Table 1. Potential Broader Impact/Participation Opportunities Enabled by the ngVLA

Emerging Opportunities through ngVLA	**BI/BP**	**Communities Impacted**
Enhancement of broadband Internet access infrastructure, including fiber optics, as an intentional by-product of ngVLA internet needs.	BI	small, rural communities along antenna paths
Enhancement of emergency services (e.g., fire response units) through collaboration with local communities.	BI	small, rural communities along antenna paths
Educational opportunities to engage and inform local stakeholders about radio astronomy and the importance of 'their backyard' to important national/international science. • Educational sessions will be presented by a diverse group of students and post-doc to raise visibility of both radio astronomy and diversity in STEM. • Role model videos for grade school girls and URM students in all fields that support an Observatory.	BI & BP	small, rural communities along antenna paths
Opportunity for partnership with URM college or university to develop educational and historical films: • Filming of the ngVLA build for EPO and historical reference. • Filming at each site to document community stories and engagement with the ngVLA. • K-12 lesson plans developed to accompany films and film segments.	BI & BP	K-12, Undergraduate and graduate students; faculty; and members of underrepresented STEM groups (e.g., African-American, Hispanic, and Native American students and faculty); the general public

Table 1. Continued

Opportunities for collaborative, cross-discipline research during archaeological site excavations during the pre-construction period: • Research opportunities with multiple departments (e.g., archeology/environmental sciences, water quality) at community colleges and universities (e.g., Dry Lake Bed). • Efforts will be made to identify URM students for participation in the research opportunities. • Development of lesson plans centered around the archeology and environment of ngVLA sites. • Educational material produced for local communities and the general public, with a focus on connection to the land on which ngVLA antennas are located.	BI & BP	K-12, Undergraduate and graduate students; faculty; and members of underrepresented STEM groups (e.g., African-American, Hispanic, and Native American students and faculty); the general public; the scientific community
Opportunities to incorporate non-Western cosmologies into the education about the ngVLA: • Invite indigenous community members (expert and local) to organized talks about indigenous cosmology. • STEAM projects (e.g., murals, stories, videos) to capture non-Western cosmologies in local schools and community centers. • Collaborate with the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS) to engage experts and students in these projects, with a plan to publish comparisons of western and indigenous cosmologies in the context of the ngVLA locations. • Development and delivery of Star Parties that incorporate different cosmologies.	BI & BP	Local community members; the general public; K-12, undergrad and graduate students; post-docs and faculty; the scientific community
Investigate additional benefits/applications of radio frequency interference (RFI) mitigation: • Providing research opportunities to URM students. • Publications. • Inventions.	BI & BP	General public; industry; local communities; K-12, undergrad and grad students; faculty; scientific community

Table 1. Continued

Develop “road shows" to provide information – along the project timeline – about the ngVLA, its progress, scientific outcomes, careers, and its incorporation into the landscape: • Use of URM students as guides and speakers to provide opportunities for the students to gain experience speaking about their work, raise their visibility, and allow them to serve as role models for members of the audiences. • Material developed for the road show can also be distributed more broadly through social media, and traditional EPO routes. • Lesson plans for delivery to local/state schools and after school groups that incorporate radio astronomy and the ngVLA into state standards.	BI & BP	General public; local communities, major towns along the array; K-12, undergrad and grad students; faculty
Opportunities for connections to international colleges and universities to offer post-doctoral exchanges.	BI & BP	Graduate students
Opportunities for developing materials and resources that are tri-lingual (partners: Mexico and Canada): • Engage URM students and faculty in the creation of materials.	BI & BP	General public; local communities, K-12, undergrad and grad students; faculty; scientific community
Exploration of opportunities to explore uses and sharable benefits of renewable energy (e.g., solar): • Partnerships with energy collection and storage industries that may include co-op experiences for URM students and community members.	BI & BP	General public; local communities, K-12, undergrad and grad students; faculty; scientific community
Infrastructure improvement in Magdalena, NM: • Opportunities for employment and training of local community members.	BI & BP	Local community; workforce
Vocational training for regional students and community members: • Beta team to conduct remote diagnostics (quick telescope fixes and data back to A-team at HQ). • Partnerships with regional community colleges.	BI & BP	Undergrad and graduate students at Minority Serving Institutions (MSIs) and other URM-serving institutions

Table 1. Continued

Expanded National Astronomy Consortium (NAC) program: • Opportunity to develop new cohorts of colleges and universities in ngVLA regions.	BP	Undergrad and graduate students at MSIs and other URM-serving institutions
Identification of new outlets for dissemination of technical, engineering, and scientific information: • National Astronomy Day. • Engineers Week. • DragonCon and other similar conferences.	BI	General public, scientific community
Greater presence at SACNAS meetings: • Student and professional recruitment. • Opportunity to share information about radio astronomy and the ngVLA to a large population of URM students and professionals.	BP	undergrad and grad students; faculty; scientific community
Co-op opportunities for students from URM schools to work with the world-class NRAO Central Development and Electronics labs.	BP	undergrad and grad students; faculty; scientific community