ngVLA: The Next Generation Very Large Array (Astro2020 APC White Paper)

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CONTACT INFORMATION:	Mark McKinnon mmckinno@nrao.edu 1-575-835-7300 1003 Lopezville Rd Socorro, NM 87801

AUTHORS	ORGANIZATION	DATE
M. McKinnon, T. Beasley, E. Murphy, R. Selina, R. Farnsworth, A. Walter, C. Carilli	ngVLA Project Office, NRAO	07/10/2019

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E. Murphy, Project Scientist	ngVLA Project Office, NRAO	Digitally signed by Eric Murphy Date: 2019.07.10 12:19:38 -04'00'

PROJECT SUMMARY

Building on nearly half a century of cutting-edge science from the Very Large Array (VLA), over a quarter-century of ultra-sharp imaging with the Very Long Baseline Array (VLBA), and the ground-breaking research areas that have been opened up by the Atacama Large Millimeter/submillimeter Array (ALMA), the National Radio Astronomy Observatory (NRAO) and the broad U.S. and international science and technical communities have engaged in the design of a next-generation radio/mm telescope, the next generation VLA (ngVLA). The ngVLA is a research infrastructure project under consideration for the National Science Foundation Astronomical Sciences Division (NSF-AST) that will replace the VLA as the U.S. flagship radio observatory. When completed, it will provide the scientific community with the requisite sensitivity and resolution at radio wavelengths needed for the emerging astrophysical frontiers in the 2020s and beyond.

The ngVLA will be a transformative, multi-disciplinary general-use scientific facility that will advance our knowledge of the Universe and our place within it. By delivering an order of magnitude improvement in both sensitivity and angular resolution compared to existing and planned radio facilities at frequencies spanning 1.2 – 116 GHz, the ngVLA will uniquely tackle a broad range of high-priority scientific questions in modern astronomy, physics, chemistry, and biology. The ngVLA will simultaneously provide the capability to unveil the formation of Solar System analogues on terrestrial scales; probe the initial conditions for planetary systems and life; characterize the assembly, structure, and evolution of galaxies from the first billion years to the present; perform fundamental tests of gravity using pulsars in the Galactic Center; and understand the formation and evolution of stellar and supermassive black holes in the era of multi-messenger and time domain astronomy. In delivering transformational new science over a remarkably broad range of topical areas, the ngVLA will continue the VLA's powerful legacy of versatility, while providing the order of magnitude advancement in radio capabilities needed to complement up-coming major ground and space-based research facilities, thereby maximizing scientific returns on additional investments made by NSF and NASA.

1 KEY SCIENCE GOALS AND OBJECTIVES

The ngVLA Science Advisory Council (SAC) carried out a global, community-driven program to identify the most compelling science use cases requiring observations between ~1 – 120 GHz with sensitivity, angular resolution, and mapping capabilities far beyond those provided by extant or planned facilities (e.g., VLA, ALMA, VLBA, a SKA1[(1)]). Over 80 science use cases (requiring ~200 unique observations) were submitted by the astronomical community at large, spanning a broad range of topics in the fields of planetary science, Galactic and extragalactic astronomy, as well as fundamental physics. Emerging from this process, the primary requirements for the ngVLA are to deliver order-of-magnitude improvements in sensitivity and angular resolution over the wavelength range from 25 to 0.26 cm (frequencies 1.2 – 116 GHz), bridging the gap between the superb performance of ALMA at 1 mm and shorter wavelengths and the future SKA1 at several decimeter to meter wavelengths. Like ALMA, the ngVLA will be a general-use facility designed from the ground up to be used by a diverse community not necessarily expert in radio techniques.

While there is strong consensus in the community that the ngVLA should be a proposal-driven facility, a finite list of key science goals (KSGs; ngVLA Memorandum #19[(2)]) were distilled from the collected science use cases after being peer reviewed and thoroughly discussed by the various Science Working Groups (SWGs) within the ngVLA SAC. The ngVLA Level 0 Science Requirements[(3)] have been defined to support these KSGs and a Reference Observing Program[(4)] has been constructed to demonstrate that they can be achieved during the lifetime of the facility, while still leaving the majority of time for other PI-led science. While the KSGs guide the design of the instrument, the ngVLA's wide reach is exemplified by the range of science presented in the ngVLA Science Book[(5)], Astro2020 Science White Papers (Table 1), Memo Series, and associated conferences. *Over the decades-long life of this instrument, its capabilities will be leveraged by a diverse scientific community to answer fundamental questions about the origin of life, the birth of planets, the formation of stars and galaxies, and the nature of compact objects and gravity*.

Astro2020 Science White Papers Mentioning ngVLA (Lead Author Given)
KSG1: Airapetian, Butler, de Kleer, de Pater, Green, Holland, Isella, Matra, Monnier, Moullet, Osten, Su, van der Marel, Weinberger, White; KSG2: McGuire[1], McGuire[2], McGuire[3], Oberg; KSG3: Aalto, Appleton, Bolatto, Carilli, Cicone, Darling, Emonts, Fan, Ginsburg, Harrington, Kohno, Kovetz, Lopez-Rodriguez, Leroy, Minchin, Mroczkowski, Murphy[1], Murphy[2], Murphy[3], Nyland, Oppenheimer, Peeples, Pisano, Pope, Smith, Thilker, Walter; KSG4: Bower, Lorimer; KSG5: Blecha, Braatz, Civano, Corsi, Foley, Ford, Gelfand, Johnson, Kelley, Kierans, Law, Lynch, Maccarone, Perlman[1], Perlman[2], Plotkin, Reid, Santander, Sathyaprakash, Siemens, Taylor, Wrobel; Other: Chomiuk, Hunter, Anderson, Darling, Roettenbacher, Fissel, Carilli, Sahai, Margot, Bastian, Friesen, Gutermuth, Chen

Table 1: A listing of (83) ngVLA-related Astro2020 Science White Papers with hyperlinks. See the ngVLA Science Book[(5)] for an additional 88 peer-reviewed science chapters led by 285 unique authors.

KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales: In its first ten years of operation, the ngVLA will map hundreds of protoplanetary disks within 500 pc, probing the distribution of circumstellar dust on angular scales as small as 1 mas (0.1 au at d = 100 pc). The ngVLA will resolve protoplanetary disks on scales more than 20 times smaller than ALMA, unveiling the formation of planetary systems similar to our own Solar System in regions that are opaque at shorter (λ<3 mm) wavelengths (see Figure 1). In 5 hr of integration, ngVLA observations will detect gaps and rings formed by planets as small as 5 Earth masses, as well as circumplanetary disks and dust crescents that probe the presence of gas giants. These observations will measure the initial planet mass function down to 5 – 10 Earth masses and the planet birth radius distribution from the inner edge of the dusty disk to tens of au.

The ngVLA will also measure the time scale for planet formation by revealing substructures in very young (<1 Myr) and heavily embedded protostellar systems across the entire spectrum of protostellar core masses. The unprecedented angular resolution and sensitivity of the ngVLA will probe deep into the inner regions of protoplanetary disks that evolve on dynamical time scales of a few years or less. Consequently, multi-epoch ngVLA observations of forming planetary systems will yield "movies" that reveal the orbital motion of dust structures and circumplanetary disks in regions that are inaccessible to ALMA and other instruments due to optical depth effects. *ngVLA observations will constrain the orbital motion of the planets and the evolution of solids in gaseous disks, providing the framework to understand the demographics of exoplanetary systems around mature stars and thus our place in the Solar system.*

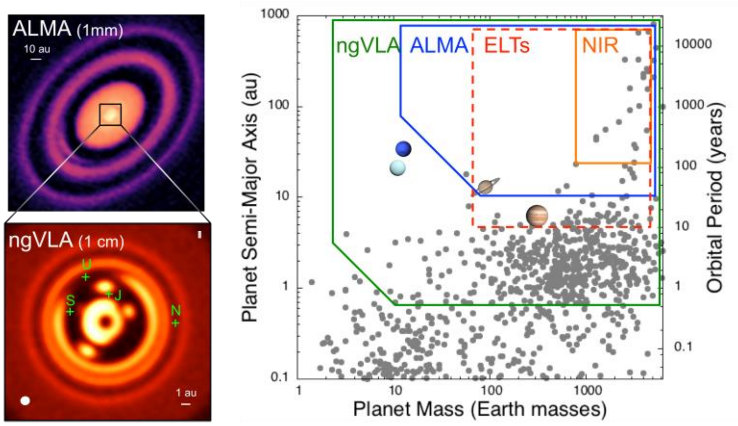

Figure 1: Top-left – ALMA observations of the nearby circumstellar disk HD163296 at 1 mm with a resolution of 0.04" (4 au at d=101 pc) revealing gaps and rings indicative of the presence of Saturn-like planets [6,7]. Bottom-left – Simulated 1 cm ngVLA observations of the innermost 24 au region at 0.01" (1 au) resolution, assuming the presence of a Jupiter-like planet at 3.5 au (J), a Saturn-like planet at 4.5 au (S), a Uranus-like planet at 6 au (U), and a Neptune-like planet at 8 au (N) from the central star. Right – The distribution of exoplanets around mature stars and young planets embedded in circumstellar disks probed by current NIR telescopes (orange box), future ELTs (red box), ALMA (blue box), and the ngVLA (green box). The ngVLA will discover many hundreds of planets with orbital periods < 10 yr, allowing for temporal monitoring and characterization of their orbital motions.

KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry: The ngVLA will deliver the ability to characterize the chemical composition of solar system-forming environments. In its first decade, it will measure the spatial and temporal evolution of the complex organic chemistry in the mid-planes of hundreds of protoplanetary disks, by studying compositions and measuring critical snow-lines, such as that for ammonia[8]. *ngVLA observations will inform, expand, and constrain chemical models for the formation of these compounds. ngVLA observations will also provide the first major view into the initial conditions for the formation of exoplanets, their atmospheres, and trace the prevalence and distribution of prebiotic molecules, identified as the precursors of life on Earth.*

The chemical building blocks of life as we know it on Earth are present in meteoritic and cometary samples, implying that they are part of the original composition of the proto-solar nebula, and may have played a key role in seeding the conditions for life in the early Earth. Glycine (NH_2-CH_2-COOH), the simplest amino acid, was detected by the Rosetta mission in comet 67P/Churyomov-Gerasimenko. The ngVLA is the only planned telescope with the sensitivity and frequency coverage required to detect amino acids, such as glycine and alanine, in cold proto-planetary clouds in less than a day of integration[9], as well as map their formation pathways and those of many other life-related molecules. This will result in a transformational step forward in the field of prebiotic astrochemistry.

KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present: By the end of its life, *JWST* will have characterized the star-formation and stellar mass histories of galaxies back to the Epoch of Reionization (EoR) and beyond. Critically expanding upon this key science, the ngVLA will be the first facility to routinely measure the molecular gas content of "main-sequence" galaxies in the EoR ($6<z<8$) by detecting their fundamental low-J CO ($2\rightarrow1$, $1\rightarrow0$) emission lines (see Figure 2). Higher CO transitions accessible to ALMA require increasingly stringent excitation conditions, which makes them progressively less useful as mass tracers. Only these low-J lines can account for the total molecular gas reservoirs fueling star formation. In its first decade of operations, the ngVLA will measure cold molecular gas in many thousands of galaxies out to z=8, identifying them directly in its large cosmic volume surveys to an order of magnitude lower gas masses than currently possible. This will enable precision measurements of the evolution of molecular gas in galaxies over all of cosmic time. *Combined with cosmic star formation history measurements from JWST and ELTs, this census will measure how gas accretion from the intergalactic medium and star formation efficiencies change throughout cosmic time, starting when the Universe emerged from the EoR, and provide direct answers to some of the most fundamental questions in galaxy evolution.*

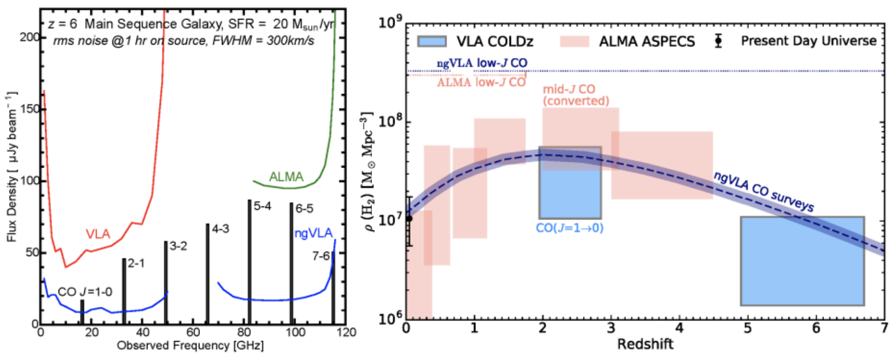

Figure 2: Left – With its unparalleled sensitivity, the ngVLA will routinely detect molecular gas in "normal" star-forming galaxies at z=6, including the critical low-J transitions that remain inaccessible to ALMA. Right – The ngVLA will provide more than an order of magnitude improvement in our knowledge of the cold molecular gas density throughout cosmic time, compared to the best efforts possible with the VLA[10] and ALMA[11]. The ngVLA provides the only means to access low-J CO emission around the EoR to characterize the co-moving molecular gas density.

Meanwhile, resolved imaging of gas in galaxies – from the earliest epochs to the present day – will address major open questions regarding the physical mechanisms driving galaxy growth and evolution. The ngVLA will be capable of arcsec-resolution imaging of HI, and have the sensitivity to image a wide array of diagnostic molecular transitions at high angular resolution. This makes it the only facility capable of directly measuring the conversion from diffuse atomic gas to molecular stellar nurseries, as well as the build-up of dense, star-forming gas in galaxies across the local universe. It will also have the sensitivity to reveal atomic gas accretion, the gas flow through galaxies, and cold outflows at low and high redshift. *By the end of its first decade of operations, the ngVLA will have imaged in atomic and molecular gas all local galaxies, measuring physical, chemical, and star formation properties of millions of clouds across the full range of galactic environments, providing the information needed to accurately model key galaxy evolutionary processes.*

KSG4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity: Neutron stars and black holes represent the most extreme environments in which to test the limits of our understanding of physical laws. Radio pulsars have produced a wide variety of high precision tests for theories of gravity, most often in compact binary systems with white dwarfs or neutron stars. A pulsar orbiting within the spacetime potential of a black hole would present new opportunities to test theories of gravity to a previously impossible precision[12]. These tests include evaluating fundamental predictions of the properties of black holes such as their description by only three quantities—mass, spin, and charge (the "no hair" theorem).

While a neutron star – black hole system may have been detected in gravitational waves, no such systems are known electromagnetically. The ngVLA would offer unparalleled opportunities to discover and study pulsar-black hole systems. The prime target is the Galactic Center, where there could be potentially many hundreds of pulsars in orbit about the supermassive black hole Sgr A*, yet only a handful of radio pulsars are known. This deficit has been attributed to extreme radio wave scattering, though the discovery of a radio magnetar that is only modestly scattered has called this into question. With its unparalleled sensitivity at high frequencies (i.e., >10 GHz), the ngVLA will definitively test whether the apparent deficit is due simply to radio wave scattering — thereby finding many radio pulsars in orbit about Sgr A* with which to probe its spacetime potential — or whether this deficit is real and represents some poorly-understood aspect of star formation and stellar evolution in the Galactic Center. *For all models of radio-wave scattering, the ngVLA will be the instrument most capable of studying Galactic Center millisecond pulsars, which provide the greatest accuracy in testing general relativity.*

KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes and Compact Objects in the Era of Multi-Messenger Astronomy: The detection of gravitational waves, along with their direct link to neutron star mergers, marks one of the major breakthroughs in astrophysics over the past 10 years. The ngVLA will play a critical role in multi-messenger astronomy for both gravitational wave and neutrino events. As upgraded gravitational wave facilities (e.g., Adv. LIGO & Virgo) reveal neutron star mergers out to anticipated horizon distances of 200 Mpc, *the ngVLA will detect nearly all electromagnetic counterparts over this volume, enabling time-series imaging of the evolution of jet structures regardless of orientation.* The continental-scale baselines of the ngVLA will provide one of the best means to determine the physical conditions originating high energy neutrinos from AGN jets, thus probing the sites of acceleration for the highest energy particles in the Universe.

In the Milky Way, the ngVLA will probe the physics of supernova explosions and black hole formation by increasing the current sample size of black hole X-ray binaries (i.e., ~20) by an order of magnitude, and measuring their natal kick velocities, distances, and masses by delivering proper motion accuracies equivalent to 20 km/s at 5 kpc for the faintest sources detected in a wide area survey(13). The ngVLA's sensitivity and astrometric capabilities will enable the measurement of the occupation fraction of intermediate-mass black holes in dwarf galaxies and globular clusters out to 20 Mpc. In the era of LISA, the ngVLA will be pivotal for understanding all phases of supermassive black hole (SMBH) mergers. Out to distances of 200 Mpc, the ngVLA will resolve SMBH binaries with sub-pc separations and measure their orbital motions. The electromagnetic counterparts of LISA mergers, expected to mostly occur in highly-obscured galaxy centers, will be best found with the ngVLA's high-frequency, high-angular resolution capabilities. The ngVLA will also reveal recoiling and wandering SMBHs kicked by the gravitational radiation rocket effect. *The ngVLA's high frequency continuum sensitivity and angular resolution will be vital for all of these aspects for understanding black holes and multi-messenger astronomy.*

2 TECHNICAL OVERVIEW

The science requirements, compiled through the SWGs, led to the ngVLA technical concept, i.e., a synthesis radio telescope constituted of 244 reflectors of 18 m diameter and 19 reflectors of 6 m diameter all connected by optical fiber to a single signal processing center, allowing for real-time correlation of all antennas simultaneously. While a single telescope, the implementation and logistics naturally divide the array into three subsets:

- A **main array** (MA) of 214 reflector antennas each of 18 m 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 (arcmin to mas scales at 30 GHz). A dense core and spiral arms provide high surface brightness sensitivity, while outer stations increase resolution.
- A **short baseline array**[14] (SBA) of 19 reflector antennas of 6 m aperture will be sensitive to a portion of the larger angular scales poorly-sampled by the MA.
- A **long baseline array** (LBA) of 30 reflector antennas each of 18 m diameter located in 10 clusters will provide continental-scale baselines (B_{MAX} = 8860 km) and sub-mas resolution.

In total, the ngVLA will have approximately ten times the sensitivity of the VLA, VLBA, and ALMA, continental-scale baselines providing sub-milliarcsecond-resolution, and a dense core on km-scales for high surface brightness sensitivity.

The dense core and the signal processing center of the array will be located at the VLA site, on the plains of San Agustin, New Mexico. A combination of leased and owned optical fiber will connect all antennas to the signal processing center. The MA extends throughout New Mexico, west Texas, eastern Arizona, and northern Mexico (Figure 3). Long baseline stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the U.S. 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 likely be co-located in a medium/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.

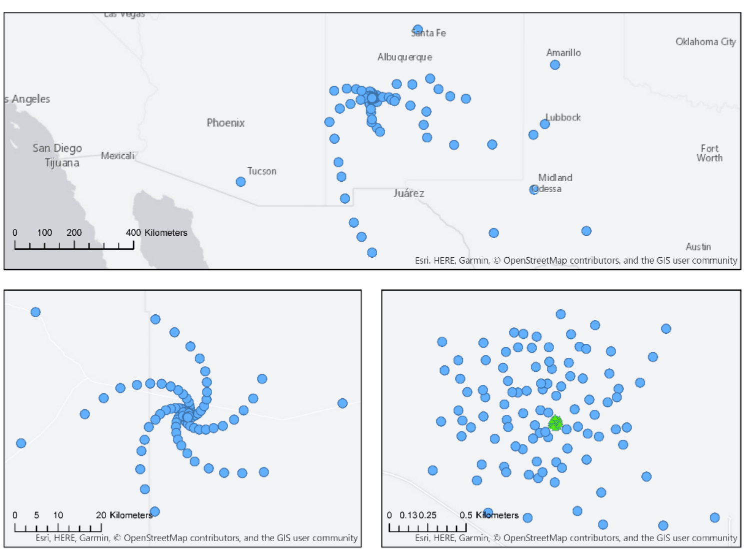

Figure 3 - Top: ngVLA Main Array Configuration Rev. C (Spiral-214). The antenna positions are still notional, but are representative for performance quantification and cost estimation. Bottom left: Zoom view of the Plains of San Agustin. Bottom right: Zoom view of the compact core with the short baseline array shown in green.

Building on the successful operation models of the VLA and ALMA, the facility will be operated as a proposal-driven instrument. The fundamental deliverable for ngVLA users will be images and image cubes (i.e., “science ready data products” following the ALMA philosophy) 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 reprocessing and archival science projects.

2.1 Key Performance Requirements

The KSGs detailed above and associated science use cases were parameterized and analyzed[15] to determine the ngVLA Science Requirements[3]. The flow down of requirements from KSGs to system requirements is captured in the system *Requirements Verification Traceability Matrix* (RVTM), and the key performance requirements that drive the design are summarized below.

Frequency Coverage: The ngVLA shall be able to observe between 1.2 and 116 GHz (except for 50 to 70 GHz where the atmosphere is nearly opaque), enabling observations from the HI (~1.4 GHz) to the CO (~115 GHz) key spectral lines.

Continuum Sensitivity: A continuum sensitivity of better than 0.07 μJy/beam at 30 GHz and 0.5 μJy/beam 100 GHz is required for studying protoplanetary disks (KSG1), and shall be achievable over the range of angular scales recovered by the MA. Continuum sensitivity of better than 0.23 μJy/beam at 10 GHz is required at LBA resolutions to localize the electromagnetic counterparts of gravitational wave events at a distance of 200 Mpc (KSG5).

Spectral Sensitivity: A spectral sensitivity of 30 μJy/beam/km/s for frequencies between 10 and 50 GHz is required to support both astrochemistry studies (KSG2) and deep/blind spectral line surveys of gas in high redshift galaxies (KSG3). A sensitivity of 1–750 mK at 5"-0.1" angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz is required to support detailed studies of CO and dense gas tracers across the local universe (KSG3).

Angular Resolution: A synthesized beam width smaller than 5 mas with uniform weights is required at both 30 and 100 GHz, while meeting the continuum sensitivity targets (KSG1). LBA angular resolution of 0.6 mas at 10 GHz is required to measure the proper motions of gravitational wave events at a distance of 200 Mpc (KSG5).

Largest Recoverable Scale: Angular scales of >20" x (100 GHz/ ν) must be recovered at at all frequencies to study nearby galaxies (KSG3) as well as the Milky Way. These scales approach the physical limits of the 18 m dish primary beam, leading to the need of the SBA and total power measurement capabilities.

Beamforming, Pulsar Search, and Pulsar Timing: The array shall support a minimum of ten beams spread over one to ten subarrays that are transmitted, over the full available bandwidth, to a pulsar search engine or pulsar timing engine within the central signal processor (KSG4).

2.2 Architecture

The ngVLA System Architecture[16] is documented in the Systems Modeling Language (SysML) and provides a logical decomposition of the system, leading to a physical structure that supports the system requirements. The high-level system architecture can be seen in Figure 4, emphasizing the interfaces to the users and operators of the facility. A proposal management and data archive system form the interfaces to scientific users, accepting user proposals for evaluation and delivering data products respectively. A near-real-time control and monitoring system supervises the array and the components of the signal processing chain, leading to the storage of raw visibilities on disk for asynchronous post processing.

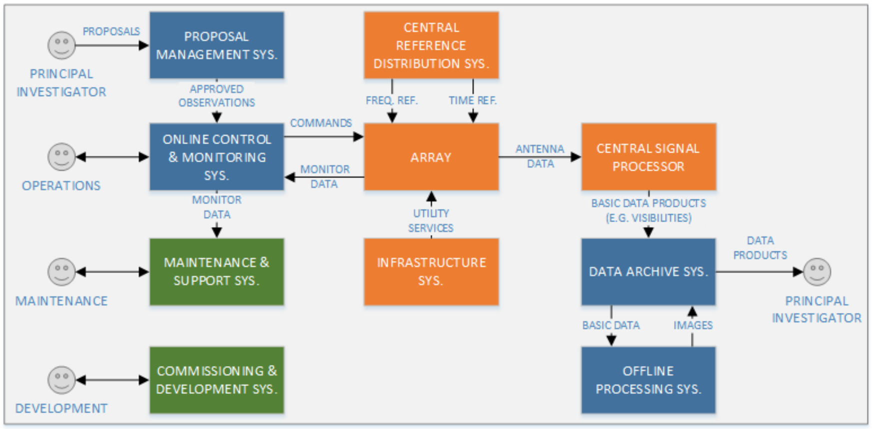

Figure 4: The high-level ngVLA system architecture. All deliverables within the facility are sub-components of the identified 10 sub-systems, with major interfaces to PIs, operations, and engineering shown.

3 TECHNOLOGY DRIVERS

The project has prepared a Reference Design[17,18] as a technical baseline and basis for assessing the technical readiness of the facility concept, and to support the detailed cost estimate. The reference design generally employs technology with a high degree of technical readiness, as further discussed below. The project can be implemented with technologies presently available – no new technologies are required to implement the ngVLA technical concept.

Reduction of system and operation costs through the exploration of leading-edge technologies is a fundamental aspect of the ngVLA development. Technical development sub-projects for key technologies that could simplify subsystem architectures and reduce the cost of reaching the key performance requirements have been identified and initiated. These sub-projects will continue until the respective sub-system conceptual design down-selects, which will be conducted in late 2020 and early 2021. Technologies with inadequate maturation will not be accepted in the updated technical baseline presented at the system conceptual design review (2021).

In limited cases, leading-edge technologies have been incorporated into the system reference design where they offered compelling benefits. In particular, a single-piece composite reflector is included in the antenna (enabling a novel structural concept with reduced mass and cost), and a custom ASIC digitizer-serializer[19] is included in the antenna electronics architecture (enabling a shorter signal chain at reduced cost). Alternative designs are readily available in these cases, and the associated cost and schedule risk are captured in the project risk register[20].

The computing and data post-processing systems are an evolution of designs developed for the VLA and ALMA, and the software systems can benefit from a substantial degree of code reuse (currently projected at ~50%). Benchmark tests of the existing post-processing algorithms inform the compute cluster size, and enable updated estimates of size and cost as the project leverages advancements in commercial computing systems.

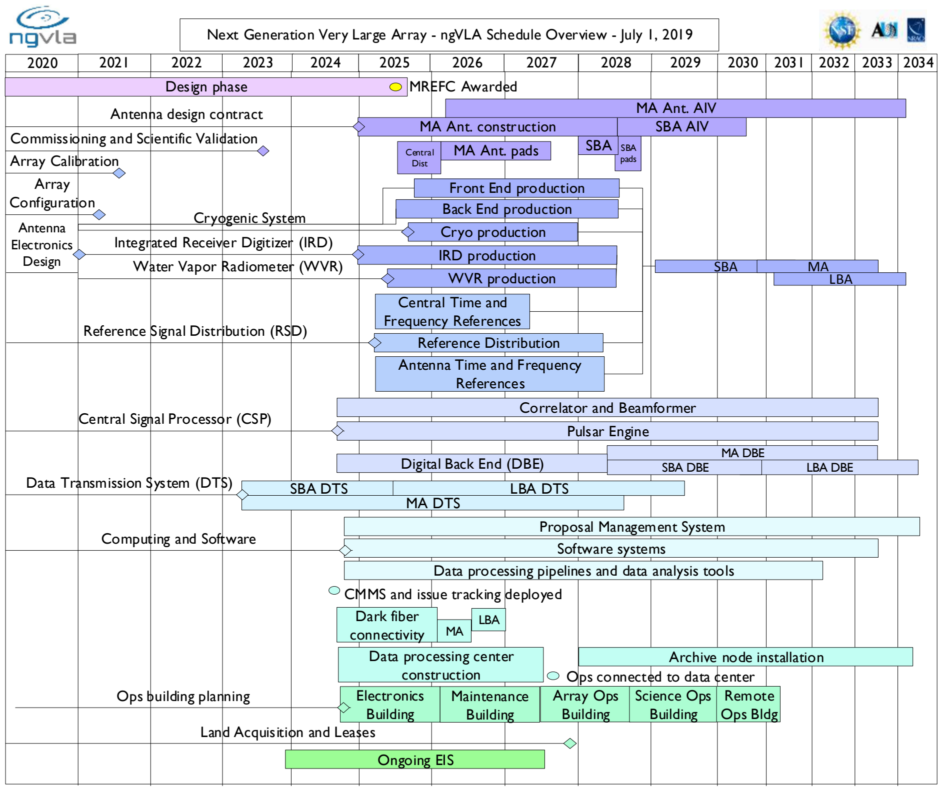

Figure 5: A high-level ngVLA project timeline from 2020 through to full science operations.

4 ORGANIZATION, PARTNERSHIPS, AND CURRENT STATUS

The ngVLA is a project of the NRAO, which is in turn managed by Associated Universities Incorporated (AUI). Founded in 1956, NRAO has a long and successful history of designing, constructing, and operating the nation's flagship radio astronomy facilities including the Atacama Large Millimeter/submillimeter Array (ALMA), the Jansky Very Large Array (VLA), the Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA).

The ngVLA project is presently transitioning from the development phase to design, and is preparing for a system conceptual design review scheduled for early 2021. The project was initiated in 2015 with the formation of an internal work group and inaugural technical workshop to engage the broader community. After the appointment of Science and Technical Advisory Councils and the formation of Science Working Groups, the science case and overall facility concept coalesced in 2017. At that point, NSF committed $11M for continued development in 2018–2019, enabling the formation of the ngVLA Project Office, the preparation of the Reference Design, and continued community engagement in advance of the Astro2020 Decadal Survey.

Currently, there are no formal industry, interagency, and/or international partners. However, international collaborators have contributed to the reference design effort[21,22,23], a first meeting of potential international partners has been held, and more detailed negotiations are underway with the respective agencies. These relationships will be formalized in parallel with the Astro2020 Decadal Survey, and *it is anticipated that international partners will contribute a minimum of 25%*

of the project design, construction, and operations budget, leaving the U.S. as the coordinating partner. Further, after a productive initial meeting, the ngVLA and SKA projects are currently investigating a process to establish a future large radio telescope alliance that may result in an exchange of observing time across both facilities.

5 PROJECT SCHEDULE

In Figure 5 we present a schedule that depicts the key elements of the design, development and construction of the major components and activities of the ngVLA. A fully resourced, Integrated Master Schedule (IMS) and schedule baseline were used as the source material for this summary.

6 COST ESTIMATES

Following NSF Large Facility Manual (LFM) guidelines, the ngVLA Sr. Cost Estimator works with the project office and engineering teams to produce a credible, well-documented, accurate, and comprehensive cost estimate. The estimate shown in Table 2 represents the latest revision as of 07/03/2019 and is reported in Base Year 2018 dollars at the 70% confidence level.

This cost estimate covers all relevant stages of the ngVLA lifecycle, including development, design, construction, operations and divestment. The Operations plan includes "core" funding required to keep ngVLA equipment and infrastructure running, as well as "extended" funding for a facility development program that may include community sub-awards analogous to ALMA.

In step with the NSF LFM, estimates will undergo further refinement as the project matures, and the lifecycle costs will evolve accordingly. To date, cost model inputs leverage appropriate methodologies, including engineering build-ups, vendor quotes, expert opinion, historical analogies, extrapolation from actuals, and parametric cost estimating relationships informed by normalized data sets and subject matter experts.

ngVLA LIFECYCLE PHASE	TOTAL (BY2018$)	FUNDING SOURCES		SCHEDULE
		USA (75%)	INT (25%)	
DEVELOPMENT*	$ 12,327,645	$ 12,327,645	$ -	FY18-19
DESIGN	$ 95,713,658	$ 71,785,243	$ 23,928,414	FY20-24
CONSTRUCTION	$ 2,263,078,238	$ 1,697,308,679	$ 565,769,560	FY25-34
OPERATIONS**	$ 2,126,363,159	$ 1,594,772,369	$ 531,590,790	FY28-54
DIVESTMENT	$ 139,413,972	$ 104,560,479	$ 34,853,493	FY55-57

*Table 2: ngVLA lifecycle cost estimate by project phase and funding source, showing the maximum anticipated U.S. investment. Risk-adjusted costs reported at the 70% confidence level in base year 2018 dollars. *Does not include in-kind contribution from the National Research Council of Canada. ** Annual operations estimate is BY2018 $92.9M/yr (core $86.9M/yr + extended $8M/yr).*

NRAO utilizes industry leading software to model, calculate, and document risk and uncertainty according to Government Accountability Office (GAO) guidelines. Cost and technical risk is applied to correlated work breakdown structure elements leveraging Monte Carlo simulations, producing program-level cumulative distribution functions, enabling the ngVLA project office to generate and analyze S-curves and report recommended confidence levels to the NSF.

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