Science Requirements

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Change Record

Version	Date	Sections	Change Description
1	2017-08-24	All	Initial Outline/Draft. Incorporated key science cases and text from Memo #19 by ngVLA Science Advisory Council (SAC).
2	2017-08-29	All	Updated text and added ADs and RDs.
3	2017-09-08	All	Edits throughout for clarity. Added definitions. Added to supporting requirements and requirements summary table.
4	2017-09-13	All	Edits to narrative, addressing review questions.
5	2017-09-19	1.4, 4	Working on definitions and summary table.
6	2017-09-20	3.4	Updated Figure 4.
7	2017-09-21	1.4, 3, 4	Cleaned up text and edits to summary table.
8	2017-10-10	All	Implemented edits based on comments from Kern, Condon, and additional requested information from SAC.
9	2017-11-09	All	Updated definitions with input from Condon & associated entries in the Table 1. Incorporated input from SAC.
10	2017-11-21	All	Based on feedback from Friday tag-up: Included mention of science use cases, traceability of requirements back to KSGs where applicable, SS definition included.
11	2017-11-22	TOC, 2.2	Minor updates for first release. Updated TOC. Added to Ref Docs. Cleaned up historical comments that were not relevant. Other minor edits.
12	2018-03-01	All	Updated Figure 3. Incorporated feedback from all-hands review: updated definitions in 1.3, split Table 1 into two tables (telescope features and performance metrics), added traceability between science requirements in Tables 1 and 3 to narrative in Section 3.
13	2018-03-05	All	Minor updates to various sections/requirement language based on comments. Version released internally for July reference design workshop.
14	2018-08-16	All	Updated template with ngVLA logo. Incorporated TB comments. Added NGA3 as a supporting use case for KSG3. Reconciled gaps identified by Christina Lorenzo. Added VLB science requirements. Updated continuum requirement for PP disks. Included molecular line list.
15	2019-02-25		Altered the transient mapping requirements. Added absorption spectroscopy requirements.
16	2019-03-27	All	A number of largely minor updated/edits. Reference to ROP in RDs. Changed “Accuracy” definitions to use “Error” and cast Sensitivities in units of rms noise (added new definition and made consistent throughout the text).
17	2019-05-13	Appendix	Fixed formatting on header, added to abbreviations table and open question in appendix.
18	2019-05-14	Appendix	Added subsection on a potential data latency requirement.
A	2019-05-20	All	Prepared document PDF for release.

Table of Contents

1 Introduction ... 4
1.1 Purpose ... 4
1.2 Scope ... 4
1.3 Definitions ... 4
1.3.1 Sensitivity ... 4
1.3.2 Sculpted Beam ... 4
1.3.3 Quality of the Synthesized Beam ... 4
1.3.4 Image Fidelity ... 5
1.3.5 Photometric Error ... 5
1.3.6 Positional Uncertainty ... 5
1.3.7 Timing Accuracy ... 5
1.3.8 Brightness Dynamic Range ... 5
1.3.9 Spectral Dynamic Range, Emissive ... 5
1.3.10 Spectral Dynamic Range, Absorptive ... 6
1.3.11 Polarization Dynamic Range ... 6
1.3.12 Instrumental Survey Speed ... 6
1.3.13 Triggered Response Time ... 6
1.4 Requirement Definitions ... 6
2 Related Documents ... 7
2.1 Applicable Documents ... 7
2.2 Reference Documents ... 7
3 The ngVLA Key Science Goals ... 8
3.1 KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales ... 9
3.1.1 Supporting Requirements ... 11
3.2 KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry ... 11
3.2.1 Supporting Requirements ... 13
3.3 KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present ... 13
3.3.1 Supporting Requirements ... 16
3.4 KSG4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity ... 17
3.4.1 Supporting Requirements ... 18
3.5 KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy ... 19
3.5.1 Supporting Requirements ... 21
4 Detailed Summary of Level-0 Science Requirements ... 21
5 Appendix ... 27
5.1 Acronyms and Abbreviations ... 27
5.2 List of Important Molecular Lines ... 28
5.3 Remaining Questions ... 30
5.3.1 Angular Resolution ... 30
5.3.2 Quality of the Synthesized Beam ... 30
5.3.3 OTF Mapping ... 30
5.3.4 Data Latency Requirement ... 30

1 Introduction

1.1 Purpose

This document describes the Level 0 Science Requirements following a solicitation from the National Radio Astronomy Observatory (NRAO) to develop key science cases for a future US-led radio telescope, the next generation Very Large Array (ngVLA). These science use cases represent some of the fundamental astrophysical problems that require observing capabilities at millimeter and centimeter wavelengths well beyond those of existing, or already planned, telescopes.

The summary of this exercise has resulted in an ngVLA that should

- have roughly ten times the sensitivity of the Jansky VLA and ALMA,
- operate at frequencies from 1.2–116 GHz with up to 20 GHz of instantaneous sampled bandwidth,
- possess a compact core for good sensitivity to low surface-brightness emission, and
- use extended baselines of at least hundreds of kilometers and ultimately across the continent to provide high-resolution imaging.

The ngVLA will build on the scientific and technical legacies of the Jansky VLA, VLBA, and ALMA, and will be designed to provide the next major leap forward in our understanding of planets, galaxies, black holes, and the dynamic sky.

1.2 Scope

The scope of this document is the Level 0 Science Requirements necessary to carry out the ngVLA key science missions [AD01] as identified by the ngVLA Science Advisory Council (ngVLA-SAC) and the broader international astronomical community. This document does not present or discuss corresponding technical requirements or potential implementation paths to achieve these science requirements. Information on the technical requirements and supporting architecture is provided in the ngVLA Preliminary System Requirements document [RD07].

1.3 Definitions

Here we provide definitions to a number of quantities used to describe the science requirements.

1.3.1 Sensitivity

Continuum and line sensitivities are defined as $\frac{1}{\sigma_{rms}}$, where σ_{rms} is the rms noise in units of flux density per beam solid angle.

1.3.2 Sculpted Beam

A manipulation [e.g., (*u,v*)-tapering and/or various weighting algorithms] of the naturally weighted synthesized beam of the array such that there are no significant inflection points down to 10% of the peak. This in turn defines the main lobe of the sculpted beam.

1.3.3 Quality of the Synthesized Beam

The combined characterization of the (sculpted) synthesized beam shape down to low levels and the main synthesized beam efficiency B_{eff} as a function of angular scale. The synthesized beam efficiency is defined as the ratio of the power in the main lobe of the sculpted beam attenuation pattern a to the power in the entire beam attenuation pattern as a function of the FWHM of the synthesized beam θ:

$$B_{eff}(\theta) \equiv \frac{\int_{MB} a(\theta)^2 d\Omega}{\int_{4\pi} a(\theta)^2\, d\Omega}$$

1.3.4 Image Fidelity

The normalized rms deviation of the image brightness I measured relative to a true sky brightness convolved with a Gaussian restoring beam M, weighted by the model brightness and integrated over the field:

$$F \equiv 1 - \frac{\sum_{pix} M_i\, |I_i - M_i|}{\sum_{pix} M_i I_i}$$

It is generally acknowledged that this quantity is exceedingly difficult to estimate in practice, since only well-understood effects can be included in a simulation. It is possible that poorly understood effects may dominate.

1.3.5 Photometric Error

The fractional error of the flux density in the image S_{img} relative to an adopted celestial flux density standard S_{std} measured for the integrated source brightness:

$$PE \equiv \frac{|S_{img} - S_{std}|}{S_{std}}$$

The photometric error is expected to vary as a function of the angular source size ϕ in units of the FWHM of the (sculpted) synthesized beam θ.

1.3.6 Positional Uncertainty

$$\sigma_{pos} \equiv \sqrt{\epsilon^2 + \sigma_n^2}$$

where $\sigma_n = \frac{\theta}{2\sqrt{\ln(2)}\, SNR}$ is the noise component of the positional uncertainty and depends on the signal-to-noise (SNR) ratio of the source, and ϵ is the rms calibration uncertainty in each coordinate and ultimately determines the astrometric accuracy of the system.

1.3.7 Timing Accuracy

The Allan standard deviation in time, relative to the adopted time standard over a given time internal.

1.3.8 Brightness Dynamic Range

The ratio of the quadrature sum of the peak brightnesses in the field relative to the rms noise of the quiescent-background (source-free regions) of the image:

$$DR_B \equiv \frac{\sum_i \sqrt{I_i^2}}{\sigma_{rms}}$$

1.3.9 Spectral Dynamic Range, Emissive

The ratio of the brightness in the strongest channel compared to the rms of the residual brightness in the instrument bandpass of nearby channels:

$$DR_{S,E} \equiv \frac{\max(I_E)}{\sigma_{rms,res}}$$

1.3.10 Spectral Dynamic Range, Absorptive

The ratio of the brightness in the strongest absorption channel to the rms of the brightness in the nearby continuum channels:

$$DR_{S,A} \equiv \frac{\max(I_A)}{\sigma_{rms,cont}}$$

1.3.11 Polarization Dynamic Range

The ratio of peak Stokes I brightness in the field to the residual polarized response (rms of stokes Q, U, V) for an unpolarized source:

$$DR_P \equiv \frac{\max(I)}{\sigma_{rms,pol}}$$

1.3.12 Instrumental Survey Speed

If σ_S is the point source rms noise on the sky achieved after an integration time τ for an interferometer having an effective area $A_e = \left(\frac{A_g}{\eta}\right)$, where A_g is the geometric collecting area of the array and η is the frequency-dependent aperture efficiency, system noise temperature T_S, and bandwidth $\Delta\nu$, the corresponding instrumental survey speed is given by:

$$\left(\frac{\dot{\Omega}}{\mathrm{deg}^2\ \mathrm{s}^{-1}}\right) \equiv \frac{\Omega_{\mathrm{FoV}}}{\tau} = \frac{\sigma_S^2 \Delta\mathrm{v}}{4k_B^2}\left(\frac{A_e}{T_s}\right)^2 \Omega_{\mathrm{PB}}$$

where $k_B = 1.38 \times 10^{-23}$J/K is the Boltzmann constant and $\Omega_{\mathrm{FoV}} = \Omega_{\mathrm{PB}}/2$ is the effective field-of-view limited by the primary beam whose beam solid angle is $\Omega_{\mathrm{PB}} = \frac{\pi\theta_{\mathrm{PB}}^2}{4\ln 2}$ and $\theta_{\mathrm{PB}} \approx 1.02\left(\frac{\lambda}{D}\right)$ is the FWHM of the primary beam of a dish having diameter D. This quantity can also be expressed as a function of the System Equivalent Flux Density, $SEFD = 2k_B\left(\frac{T_s}{A_e}\right)$.

1.3.13 Triggered Response Time

The interval of time between when the trigger is received by the array to the time when the antennas are pointing in the correct direction on the sky, with the correct receiving set up, and acquiring data.

1.4 Requirement Definitions

The following definitions of requirement "levels" are used in this document.

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases ("Science Requirements" or "Stakeholder Requirements")
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic ("System Level Requirements")
L2	Requirements that define a specification for an element of the system, presuming an architecture ("Subsystem Requirements")

2 Related Documents

2.1 *Applicable Documents*

The following documents are applicable to the extent specified. In the event of conflict between the documents referenced herein and the content of these requirements, the content of the requirements shall be considered superseding.

Reference No.	Document Title	Rev/Doc. No.
AD01	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19

2.2 *Reference Documents*

The following documents provide context or supporting material.

Reference No.	Document Title	Rev/Doc. No.
RD01	Science Working Groups Project Overview	ngVLA Memo #5
RD02	Science Working Group #1: The Cradle of Life	ngVLA Memo #6
RD03	Science Working Group #2: “Galaxy Ecosystems”: The Matter Cycle in and Around Galaxies	ngVLA Memo #7
RD04	Science Working Group #3: Galaxy Assembly through Cosmic Time	ngVLA Memo #8
RD05	Science Working Group #4: Time Domain, Fundamental Physics, and Cosmology.	ngVLA Memo #9
RD06	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD07	ngVLA: Preliminary System Requirements	V1.01
RD08	Use Case: Characterizing Planet-Disk Interactions	Use Case PF3
RD09	Use Case: Resolved Substructures in Protoplentary Disks	Use Case PF1
RD10	Use Case: Circumplanetary Disk Detection	Use Case PF5
RD11	Use Case: Prebiotic Chemistry	Use Case AC5
RD12	Use Case: Tracing the NH3 Snowline in Protoplanetary Disks: A Proxy for Water	Use Case AC1
RD13	Use Case: Deuteration in Starless and Protostellar Cores	Use Case AC4
RD14	Use Case: Mapping Molecular Emission in the Near- Nucleus Coma of Comets	Use Case AC6
RD15	Use Case: Giant Planet Atmospheres	Use Case SS06
RD16	Use Case: Mapping the Organic Content in a Protoplanetary Disk Midplane	Use Case AC2
RD17	Use Case: Complex molecules in Hot Molecular Cores/Corinos	Use Case AC3
RD18	Use Case: Cold Gas in High-z Galaxies 1 – The Molecular Gas Budget	Use Case HiZ1
RD19	Use Case: Mapping High-z CO Gas	Use Case HiZ5
RD20	Use Case: Atomic Hydrogen in the Local Universe	Use Case NGA2
RD21	Use Case: Parsec-Scale Cold Gas Structure Across the Whole Local Galaxy Population	Use Case NGA8
RD22	Use Case: Cold Gas in High-z Galaxies 2 – CO as Redshift Beacon	Use Case HiZ2

Reference No.	Document Title	Rev/Doc. No.
RD23	Use Case: Cold Gas in High-z Galaxies 3 – The Dense ISM	Use Case HiZ3
RD24	Use Case: Low-Surface-Brightness CO	Use Case HiZ6
RD25	Use Case: Continuum Surveys	Use Case HiZ7
RD26	Use Case: Observing AGN Feedback Over Cosmic Time Through Deep, Individual Observations	Use Case HiZ8
RD27	Use Case: Probing Obscured MBH Accretion and Growth at Cosmic Dawn	Use Case HiZ10
RD28	Use Case: A High-Resolution Kinematic View of Nearby Galaxy Nuclei	Use Case NGA5
RD29	Use Case: Star Formation in a Range of Extreme Physical Environments	Use Case NGA6
RD30	Use Case: Direct Measurements of Density and Temperature in Star-Forming Gas	Use Case NGA7
RD31	Use Case: A Complete Line Survey and Sub-pc Map of Every Local Group Molecular Cloud	Use Case NGA9
RD32	Use Case: Gas Density Across the Local Universe	Use Case NGA10
RD33	Use Case: Galactic Center Pulsars	Use Case TDCP1
RD34	Use Case: Gravitational Wave Follow-Up	Use Case TDCP2
RD35	Use Case: Dual Active Galactic Nuclei	Use Case TDCP5
RD36	Use Case: Pulsar Timing and Gravitational Waves	Use Case TDCP7
RD37	Use Case: Cosmic Explosions and Collisions in the ngVLA Era	Use Case TDCP8
RD38	Use Case: Accurate Massive Black Hole Mass	Use Case NGA12
RD39	Imaging Capabilities: High Redshift CO	ngVLA Memo #13
RD40	Use Case: Radio Continuum Emission from Galaxies: An Accounting of Energetic Processes	Use Case NGA3
RD41	ngVLA Reference Observing Program	020.10.15.05.10-0001-REP

3 The ngVLA Key Science Goals

The ngVLA SAC, a group of leading scientists with a wide range of interests and expertise appointed by NRAO, in collaboration with the broader international astronomical community, recently developed approximately 80 compelling science cases requiring observations between 1.2–116 GHz with sensitivity, angular resolution, and mapping capabilities far beyond those provided by the Jansky VLA, VLBA, ALMA, and the SKA. These science cases span a broad range of topics in the fields of planetary science, Galactic and extragalactic astronomy, as well as fundamental physics. Consequently, the 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.

Each science case was objectively reviewed via an online questionnaire and thoroughly discussed by the Science Working Groups within the ngVLA-SAC with the goal of distilling the top scientific goals for a future radio/mm telescope. The Key Science Goals (KSGs) were chosen to satisfy three criteria:

1. Each addresses an important, unanswered question in astrophysics that has broad scientific and societal implications.
2. Progress in each area is uniquely addressed by the capabilities of the ngVLA.

3. Each exhibits key synergies and complementarity with science goals being pursued by existing or planned facilities in the 2025 and beyond time frame.

The initial key science goals, along with the results from the entire list of approximately 80 science use cases [RD06] were then presented and discussed with the broader community at the ngVLA Science and Technology Workshop, June 26–29, 2017, in Socorro, NM.[1] The goal was to build consensus around a single vision for the key science missions of the ngVLA.

In this section, we describe the five KSGs to come out of this process along with their corresponding requirements. These include

- **KSG1:** Unveiling the Formation of Solar System Analogs on Terrestrial Scales
- **KSG2:** Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
- **KSG3:** Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present
- **KSG4:** Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity
- **KSG5:** Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

In the following sections, we provide additional scientific background for each science goal, along with a summary of supporting requirements. A detailed description of ngVLA KSGs can be found in [AD01].

3.1 KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales

Summary: The ngVLA shall be able to measure the planet initial mass function down to a mass of 5–10 Earth masses and 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. [See RD08]

Driving Science Use Cases: PF3

Supporting Science Use Cases: PF1, PF5

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. These efforts resulted in the discovery of morphological features (rings, spirals, and crescents) in the distribution of circumstellar gas and dust with characteristic sizes larger than 20 AU (e.g., Casassus et al. 2013; van der Marel et al. 2013; Perez et al. 2014; ALMA Partnership 2015; Andrews et al. 2016; Isella et al. 2016).

These structures are suggestive of gravitational perturbations of yet unseen giant planets and provide a powerful tool to measure planet masses and orbital radii, study the circumplanetary environment, and investigate how forming planets interact with the circumstellar material (e.g., Jin et al. 2016). 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, and to

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[1] https://science.nrao.edu/science/meetings/2017/ngvla-science-program/index

probe for the presence of planets with masses as low as 5–10 Earth masses. Such capabilities are not achievable with ALMA or proposed space missions. The design of the ngVLA shall enable such imaging and permit measuring the initial mass and the birth radius functions of giant and massive rocky planets. Such observations will provide key information to understand the diverse demographics of exoplanetary systems and, ultimately, unveil the formation of planetary systems similar to our own Solar system.

Figure 1 illustrates the requisite capabilities of the ngVLA for imaging planetary systems in the act of forming. The figure compares simulated ngVLA observations at a frequency of 100 GHz to simulated ALMA observations at a frequency of 345 GHz, which provide the best compromise between angular resolution and sensitivity to the dust thermal emission. Observations with the ngVLA will be able to clearly reveal the presence of planets with masses as low as 10 Earth masses at orbital radii as small as 2.5 AU (central and right panels). These planets could not be detected by ALMA because of the high optical depth of the dust emission at 345 GHz, and the lower angular resolution of its observations at lower, optically-thin frequencies.

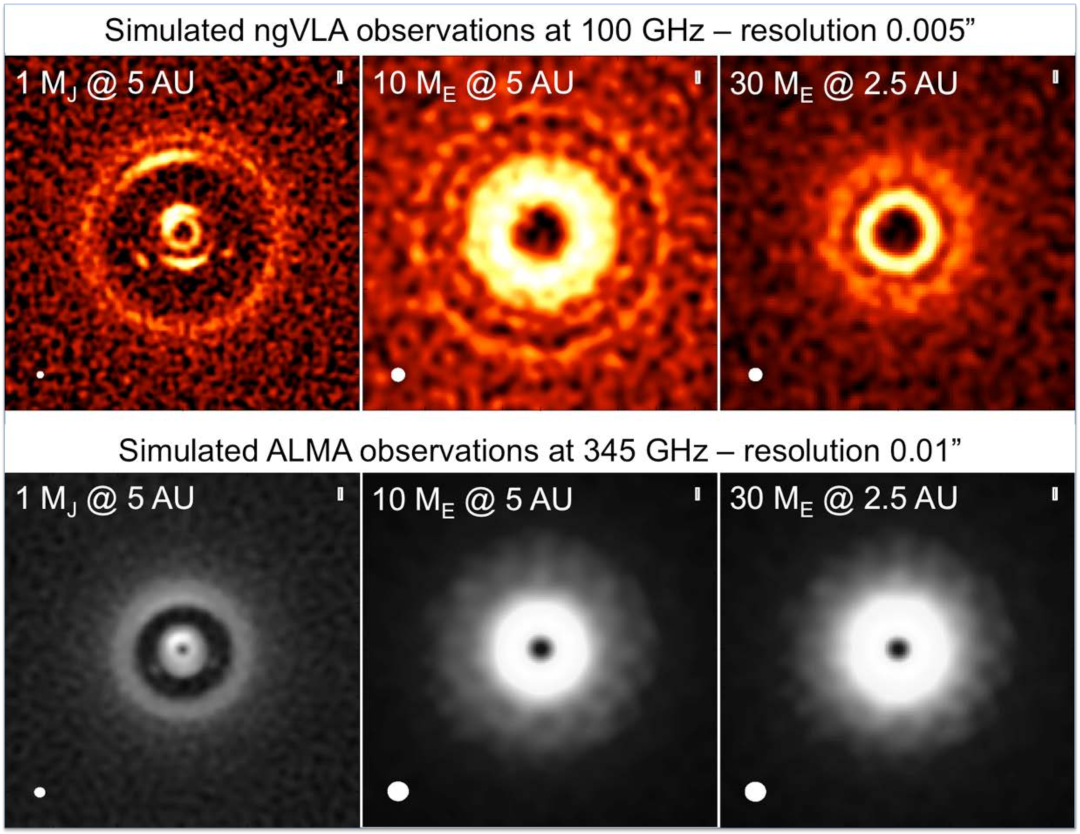

Figure 1 - Ricci et al. (2018): ngVLA–simulated (top row) and ALMA–simulated (bottom row) observations of the continuum emission of a protoplanetary disk perturbed by a Jupiter mass planet orbiting at 5 AU (left column), a 10 Earth mass planet orbiting at 5 AU (center column), and a 30 Earth mass planet orbiting at 2.5 AU (right column). The ngVLA observations were simulated with a 5 mas beam and an rms noise of 0.5 μJy/bm. ALMA observations were simulated using the most extended (16 km baseline) configuration and an rms noise of 8 μJy/bm.

The ngVLA shall also be superior to ALMA at imaging perturbations generated by giant planets orbiting close to the central star (left panels). In particular, the ngVLA shall have the potential to detect circumplanetary disks and Trojan satellites around young Jupiter analogs. With exquisite angular resolution, the ngVLA will enable the measurement of the orbital motions of all these structures on monthly timescales, opening a completely new dimension to the study of planet formation.

3.1.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG1-001**: Continuum observations for center frequencies between 20–110 GHz with angular resolution better than 5 mas at 100 GHz are required to study the formation of planets in the innermost 10 AU of nearby (<140 pc) proto-planetary disks.
- **KSG1-002**: Extensive simulations of the disks perturbed by planets (Ricci et al. 2018, Figure 1) suggest that an rms noise of 0.5 μJy/bm in the continuum at 100 GHz is required to map structures in the dust distribution created by planets of mass down to 10 Earth-masses and orbital radius of 2.5 AU in a couple hundred systems out to a distance of 400 pc. There is a desire to reach 0.3 μJy/bm to extend this work to several hundred systems out to a distance of 700 pc.
- **KSG1-003**: Matching resolution (i.e., 5 mas) and achieving a continuum rms noise of order 0.07 μJy/bm at 30 GHz will map the planet–disk interactions where the disk emission is expected to be optically thin. There is a desire to reach 0.04 μJy/bm to extend this work to a couple hundred systems out to a distance of 400 pc.
- **KSG1-004**: Observations would benefit from the largest possible aggregate bandwidth to maximize continuum sensitivity, and from full polarization capabilities to better constrain the properties of the dust grains.
- **KSG1-005**: A field of view larger than 2” is required to map the entire disk in a single pointing.
- **KSG1-006**: A maximum recoverable scale of at least 1”–2” is required to minimize the effects of spatial filtering.

3.2 KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

Summary: The ngVLA shall 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. It shall 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. [See RD11]

Driving Science Use Cases: AC5

Supporting Science Use Cases: AC1, AC4, AC6, SS06, AC2 (rms amended), AC3 (rms amended)

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. The ngVLA shall enable unprecedented observations of interstellar chemistry from the densest star-forming regions of the Galaxy to protoplanetary disks. Existing facilities have already shown the stunning degree of molecular complexity present in these systems.

With a unique combination of sensitivity and spatial resolution, the ngVLA shall permit the observation of both highly complex and very low-abundance chemical species that are exquisitely sensitive to the physical conditions and evolutionary history of their sources, which are out of reach of current observatories. In turn, by understanding the chemical evolution of these complex molecules, unprecedentedly detailed astrophysical insight can be gleaned from these astrochemical observations.

The ngVLA shall enable an unprecedented view into complex organic (prebiotic) chemical evolution in the ISM. Observations of a substantial number of predicted, but as yet undetected, complex prebiotic species are needed to truly understand chemical evolution toward amino acids and other biogenic molecules. We are rapidly approaching the point of diminishing returns at which deep observations with ALMA and the GBT will no longer reveal new spectral lines, due to a combination of sensitivity limits and line-confusion at higher frequencies. A unique combination of sensitivity and resolution is required to enable better depth than any pre-existing surveys for prebiotic molecules in the Galaxy. For example, the deepest current survey for prebiotic molecules is being done with the GBT, but its spatial resolution limitations preclude any benefits from pushing any deeper in sensitivity.

Both problems can be solved by sensitive observations in the cm-wave regime. State-of-the-art models predict these molecules will display emission lines with intensities that should be clearly 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 shall 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.

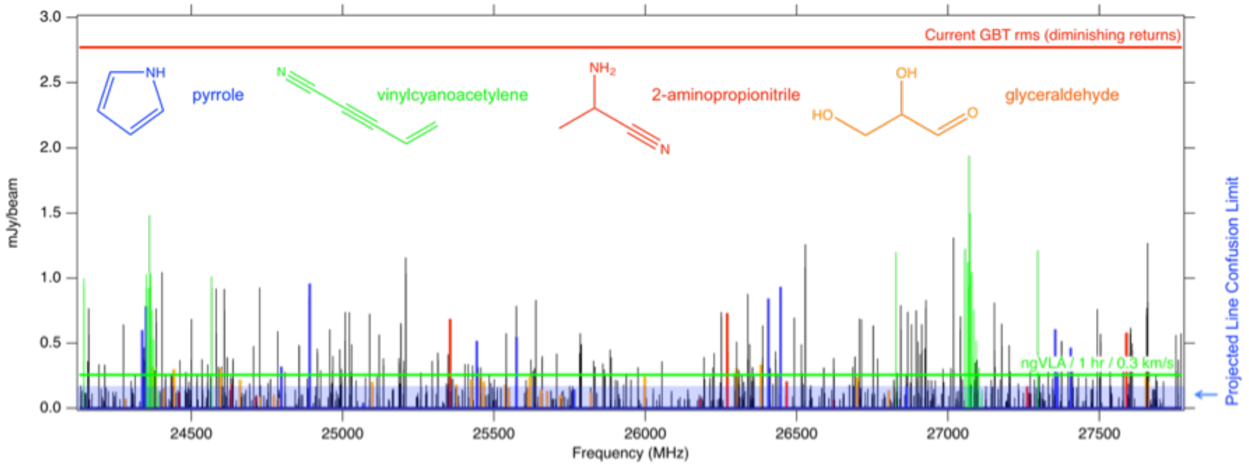

Figure 2 - A conservative simulation of a representative set of 30 currently undetected complex interstellar molecules (in black) that are likely to be detectable by the ngVLA above the confusion limit of an ngVLA survey in and around "hot" cores with source sizes typically of ~1"–4". These lines are not observable with current facilities. A few key molecules are highlighted in color.

A highlight of the unique prebiotic science that shall be made possible by the ngVLA is the study of chirality and its drivers, particularly the origin of homochirality in biological systems. Chiral molecules, that is, molecules whose mirror image is not identical to the original, are central to biological function. Indeed, the mystery of homochirality, nature's use of only one of the mirror images in most biological processes, plays a central role in our quest to understand the origins of life, as well as being considered a nearly unambiguous biomarker. There is no energetic basis for the dominance in life of one handedness of a chiral molecule over another, but rather, a slight excess was likely inherited at some point in the evolutionary process and amplified by life. Given that material in planetary systems has been shown to be inherited from their parent molecular clouds, an excess of a particular handedness in that cloud may be the spark that drives homochirality in a certain direction.

One possible route to generate a chiral excess is through UV-driven photodissociation of chiral molecules by an excess of left or right circularly polarized light. The ability not only to detect, but to image the abundance of chiral species at spatial scales commensurate with observations of circularly polarized light toward star-forming regions, would be a giant leap forward. Using known, polarization-dependent photodissociation cross sections from laboratory studies, these observations would enable quantitative estimates of potential UV-driven excess.

While such studies are well beyond the capability of existing observatories, they shall be achievable with the ngVLA. Chiral molecules, like other complex species detected earlier, are necessarily large, with propylene oxide, the only detected chiral species to date (McGuire et al. 2016), being perhaps the only example simple enough for detection with existing facilities. The ngVLA shall provide the sensitivity and angular resolution required to detect additional, biologically relevant chiral species, such as glyceraldehyde.

3.2.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG2-001**: An angular resolution on the order of 50 mas is needed near 30 GHz.
- **KSG2-002**: An rms of 30 μJy/bm/km/s for frequencies between 16–50 GHz is required.
- **KSG2-003**: A spectral resolution of 0.1 km/s is required, preferably concurrent with broadband (4+ GHz) observations.
- **KSG2-004**: Recovery of angular scales up to the expected range of 2”–10”.
- **KSG2-005**: At the desired sensitivity, the spectra must not be corrupted by spurious self-generated signals or changes in bandpass structure that cannot be removed through calibration.
- **KSG2-006**: An emissive spectral dynamic range better than 50 db is required to enable imaging of faint prebiotic molecules in the presence of bright line emission within the field of view.

3.3 KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

Summary: The ngVLA shall 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 reservoirs and circumgalactic regions. The ngVLA shall also have enough sensitivity to map the physical and chemical properties of molecular gas over the entire local galaxy population. These studies will reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the universe. [See RD21, RD19.]

Driving Science Use Cases: HiZ1, HiZ5, NGA2, NGA8

Supporting Science Use Cases: HiZ2, HiZ3, HiZ6, HiZ7, HiZ8, HiZ10, NGA3, NGA5, NGA6, NGA7, NGA9, NGA10

The processes that lead to the formation and evolution of galaxies throughout cosmic history involve the complex interplay between hierarchical merging of dark matter halos, accretion of primordial and recycled gas, transport of gas within galaxy disks, accretion onto central super-massive black holes, and the formation of molecular clouds that subsequently collapse and fragment. The resulting star formation and black-hole accretion provide large sources of energy and momentum that not only light up galaxies but also bring about large changes in their gas reservoirs that we call feedback. How is gas accreted onto galaxies? What regulates the growth of galaxies throughout cosmic history? How is gas transported within galaxies and expelled by fountains and winds? How is gas inside galaxies influenced by local processes of star formation and black-hole accretion? How do the energetics, turbulent structure, self-gravity, density, and chemical state of the gas change as the gas cycles between different phases, and how do these processes depend on galaxy properties or location in a galaxy?

Observations of these processes not only constrain the dominant feedback mechanisms and timescales, but also establish useful chemical clocks and produce the observations necessary for interpreting spectroscopy across the universe out to the highest redshifts.

The ngVLA shall have the capability to carry out unbiased, large cosmic volume surveys at virtually any redshift down to an order of magnitude lower gas masses than currently possible, thus exposing the evolution of gaseous reservoirs from the earliest epochs to the peak of the cosmic history of star formation. The ngVLA shall have the sensitivity to detect and image small amounts of low-excitation molecular material, thereby opening up the study of the formation, growth, and evolution of disks through the influx and accretion of material in the form of minor mergers (Figure 3).

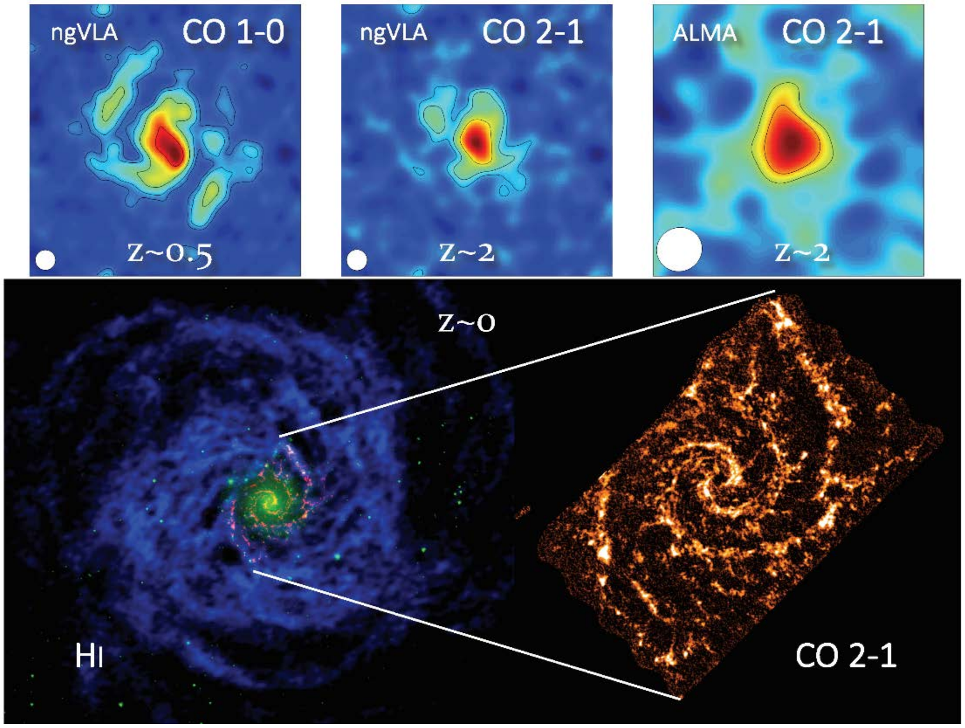

Figure 3 - ngVLA simulations of M51 (the Whirlpool Galaxy), top frames; and the grand-design spiral galaxy NGC 628 (M74), bottom frames. Details provided in main text.

The top panels of Figure 3 illustrate the results of simulations based on M51 (the Whirlpool galaxy) with molecular mass scaled by factors of 1.4 ($z = 0.5$) and 3.5 ($z = 2$) to match it to the lowest molecular mass galaxies currently observable at ALMA and NOEMA [RD39]. The corresponding SFR for the $z = 2$ model is 25 $M_{\odot}$/yr. The synthesized beam shown in the bottom left corner is (left to right) $\theta = 0.19''$, 0.20'', and 0.43'', corresponding to linear scales L = 1.2, 1.7, and 3.7 kpc, respectively. The corresponding maximum surface brightness is T_B = 6.7, 2.1, and 1.0 K, and the black contours enclose regions with SNR $\geq$ 3, 5, 10, and 20. The tapering of the beam is designed to provide the best compromise between angular resolution and SNR, and the integration times are 30 hours in all cases. The spatial and kinematic information recovered by the ngVLA allows the measurement of a precise rotation curve, which would only be possible to obtain from ALMA with an extremely large time investment. For full details see [RD39].

The bottom panels of Figure 3 show an example from the nearby universe: the grand-design spiral galaxy NGC 628 (M74) located 7.3 Mpc away. This composite illustrates the molecular disk imaged in CO by ALMA (red), the stellar disk imaged at 4.5 μm by *Spitzer* (green), and the atomic disk imaged in HI by the VLA (in blue), showing the atomic and molecular gas phases to which the ngVLA shall be sensitive. The right panel shows a close-up of the area mapped in CO $J = 2 \rightarrow 1$ at 1” resolution: the ngVLA would be capable of quickly producing a significantly deeper map at similar angular resolution that would include not only CO $J = 1 \rightarrow 0$, but also dense gas tracers, molecular isotopologues, and many other molecules throughout the λ = 3–4 mm band. In doing this, the ngVLA shall image the physical and chemical state and structure of the cold ISM at high resolution on statistically significant galaxy samples, providing unique insights into these processes.

By providing access to the cold molecular gas content and kinematics in galaxies at all redshifts, the ngVLA offers a critical missing component to high-resolution multi-wavelength studies that will be undertaken with 30 m class optical telescopes, JWST, ALMA, and upcoming large NASA missions to image the process of galaxy assembly throughout the formative times of cosmic history. The nearby universe, in particular, provides the ideal laboratory to study the mechanisms that drive some aspects of galaxy evolution. Galaxies continue to accrete material from their surroundings throughout their existence. This material gathers in their outer disks as HI gas, constituting the largest gas reservoir in galaxies. The ngVLA shall provide the combination of surface brightness sensitivity and resolution necessary to understand the physical makeup of these reservoirs (Figure 3) by being able to survey the structure of the cold, star-forming interstellar medium at the parsec-resolution of star-forming units beyond the Virgo cluster (~20–30 Mpc distances).

In addition to CO, the ngVLA shall have the sensitivity to image a host of other molecular tracers with transitions that are more than an order of magnitude weaker. These other molecular species provide a range of cold interstellar medium diagnostics that will yield maps of the motion, distribution, and physical and chemical state of the gas as it flows in from the outer disk, assembles into clouds, and experiences feedback due to star formation or accretion into central super-massive black holes. The ngVLA shall enable large systematic studies, taking advantage of chemical footprints that are beyond the limits of current capabilities to yield key insights on the processes that shape galaxies. The deep imaging of the atomic gas in the outskirts of galaxies, the outer regions that constitute the interface between the inner star-forming disk, and the cosmic web will distinguish between settled extended HI disks, compact high velocity clouds, merger remnants, and tidal dwarfs and other tidal features.

Simultaneous imaging of free-free and synchrotron continuum emission provides the full context of star formation and accretion activity. The ngVLA shall provide sensitive (i.e., rms noise of 0.15 μJy/bm at 33 GHz and 1” resolution) continuum imaging over multiple bands spanning the frequency range of 1.2–116 GHz to enable accurate separation of non-thermal and free-free emission. This in turn will yield star formation maps for a large, heterogeneous sample of nearby galaxies, delivering Hα-like images that optical astronomers have relied on heavily without having the additional complications of extinction and contamination by nearby [NII] emission. These maps would also significantly improve upon current integral field unit spectroscopic maps (e.g., CALIFA, MANGA, ATLAS^{3D}) that, even when able to extinction correct via the Balmer decrement, still miss the youngest and most heavily enshrouded star formation active in galaxies. At an rms noise of 0.15 μJy/bm at 33 GHz, such radio maps will reach a sensitivity of ~0.005 $M_\odot$/yr/kpc^2 out to a distance of Virgo (the nearest massive cluster at d ~16.6 Mpc), matching the sensitivity of extremely deep Hα images. Furthermore, at 1” resolution, which is similar to that delivered by ground-based optical facilities, such maps will sample ~100 pc scales out to the distance of Virgo which are the typical sizes of GMCs and giant HII regions.

Then ngVLA shall also be able to use the same data to create finer resolution (i.e., 0.1” or even higher for brighter systems) to perform the same multi-frequency radio continuum analysis for discrete HII regions and supernova remnants to complement high-resolution, spaced-based optical/NIR observations (e.g., HST, JWST, etc.). At 0.1” resolution, the data will sample ~10pc scales in galaxies out to the distance of Virgo to resolve and characterize (e.g., size, spectral shape, density, etc.) discrete HII regions and supernova remnants with a sensitivity to diffuse free-free emission of ~0.5 $M_\odot$/yr/kpc^2.

It is worth pointing out that neither ALMA nor the SKA Phase 1 have the power to carry out these observations. The ngVLA shall have a much broader frequency coverage than the SKA Phase I. And, although ALMA is able to tackle some of these observations, the ngVLA shall have enough collecting area to survey large samples of galaxies. ALMA Band 1, for example, is roughly equivalent to the Jansky VLA performance at Q-band, and ALMA Band 3 will be almost an order of magnitude less sensitive than the ngVLA at 90 GHz. Given these science requirements, only the ngVLA shall be able to study these processes on significant galaxy samples, distant or nearby.

3.3.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG3-001**: A line rms noise 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 is required for detailed studies of CO kinematics of high-z galaxies and blind CO searches of >1000 galaxies, respectively.
- **KSG3-002**: A large instantaneous bandwidth (minimum 1.6:1 BW ratio, up to 20 GHz instantaneous bandwidth) to conduct wideband observations at 5 km/s resolution is required to efficiently perform blind surveys of large cosmic volumes in a single observation to provide routine access molecular species in addition to CO (e.g., HCN, HCO^+, or N_2H^+).
- **KSG3-003**: Frequency coverage to access the transitions of formaldehyde (5 GHz and 14 GHz), ammonia (23–27 GHz), methanol (particularly the 36 GHz masers), deuterated molecules (~ 70 GHz), and a host of dense gas tracers (~ 90 GHz) besides CO (115 GHz) and HI (1.4 GHz) are required.
- **KSG3-004**: Thermal line imaging of CO (115 GHz) with an rms noise of 0.75 K at 0.1" angular resolution and 1 km/s spectral resolution is required for detailed studies of CO in the nearby universe. A spectral dynamic range of 30 db is also required, while 40 db is desired.
- **KSG3-005**: Thermal imaging with an rms noise of 1–5 mK 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. A spectral dynamic range of 30 db is also required, while 40 db is desired.
- **KSG3-006**: 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. A spectral dynamic range of better than 40 db is required for accurate RRL line-to-continuum ratios.
- **KSG3-007**: Angular resolutions of 0.1–1" for continuum imaging at all available frequencies are required.
- **KSG3-008**: A continuum rms noise of 0.15 μJy/bm at 33 GHz for a 1" synthesized beam is required for robustly studying star formation within nearby, star-forming galaxies. Given the expected 33 GHz peak brightnesses within such galaxies, the resulting dynamic range requirement is ~37dB.
- **KSG3-009**: Accurate recovery of flux density for extended objects on arcminute scales at all frequencies is required.
- **KSG3-010**: The ability is needed 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.
- **KSG3-011**: 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.
- **KSG3-012:** An absorptive dynamic range of 40 dB to measure the physical properties of Galactic neutral Hydrogen for ~1000 sight lines with a velocity resolution of 0.4 km/s and +/- 150 km/s velocity range at an angular resolution of 0.1".

3.4 KSG4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity

Summary: Pulsars in the Galactic Center represent clocks moving in the space-time potential of a super-massive black hole and would enable 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. The ngVLA shall achieve 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. [See RD33.]

Driving Science Use Cases: TDCP1

Supporting Science Use Cases: N/A

Testing theories of gravity requires probing as close as possible to the strong field regime. This is illustrated in the left panel of Figure 4 where the abscissa shows the depth of the potential probed and the ordinate shows the space-time curvature for the orbit of a test mass around a central mass. It is by finding ways to probe as far as possible into the upper right corner of this figure that one can begin to highly constrain theories of gravity beyond General Relativity. Pulsars near Sgr A* (i.e., within 0.5"~0.02 pc) probe regimes comparable to the infrared S stars but, as they represent clocks, pulsars probe different aspects of theories of gravity. Pulsars in compact binaries, such as might form from three-body exchanges in the dense nuclear cluster, lie in the top right of the left panel of Figure 4. Consequently, pulsars in the Galactic Center offer a powerful way to test theories of gravity.

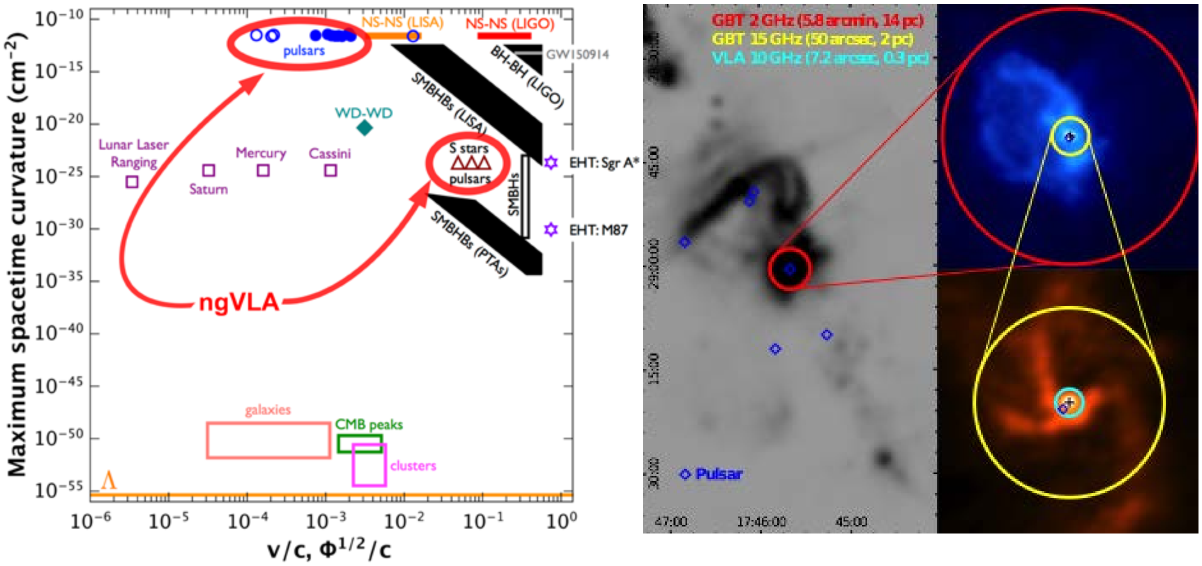

Figure 4 - Left: The abscissa shows the depth of the potential probed and the ordinate shows the spacetime curvature for the orbit of a test mass around a central mass—probing as far as possible into the upper right corner is most constraining on theories of gravity beyond General Relativity. Pulsars near Sgr A* (i.e., within 0.5"~0.02 pc) probe regimes comparable to the infrared S stars, but, as they represent clocks, pulsars probe different aspects of theories of gravity. Pulsars in compact binaries, such as might form from three-body exchanges in the dense nuclear cluster, are in the upper center of the figure. Right (credit: R. Wharton): The distribution of known pulsars near the Galactic center. Despite being the region of highest density in the Galaxy and despite having been searched multiple times at a range of frequencies with sensitivities comparable to that of the VLA, only a small number of pulsars are known. Even more puzzling, the closest pulsar to Sgr A* is the magnetar PSR J1745-2900, yet radio-emitting magnetars are an extremely rare sub-class of the field pulsar population (i.e., <1%).

Various indications suggest that the Galactic Center region contains several neutron stars. These range from the currently observed population of young, hot stars, to candidate pulsar wind nebulae and X-ray binaries, to estimates of the supernova rate derived from the diffuse X-ray emission. Millisecond pulsars in the inner Galaxy are the astrophysical alternative to dark matter annihilation to explain the observed γ-ray *Fermi* excess. Relevant reviews on the expectations for millisecond pulsars in the Galactic Center include Wharton et al. (2012) and Eatough et al. (2015). The resulting estimates for the number of active pulsars beamed toward the Earth are as high as 1,000. Notably, given the possibility of exotic compact binaries and the strong space-time potential near Sgr A*, it is possible for even canonical pulsars (with spin periods ~1 s) to provide useful measurements.

While as many as 1000 are predicted, only a handful of pulsars in the central half-degree of the Galaxy are currently known (right panel of Figure 4). Several factors make finding pulsars in the Galactic Center difficult. Pulsars are generally faint: pulsars at distances comparable to or greater than the distance to the Galactic Center represent only 20% of the current census (480/2613), and nearly half of these have been discovered in the past ten years even though pulsar searches have been conducted for half a century. The steady increase in the discovery of more distant pulsars results from a combination of larger and more sensitive telescopes, larger bandwidth systems, and improved detection algorithms.

Moreover, not only are pulsars faint, but the intense emission from other sources toward the inner Galaxy increases the system temperature substantially at lower frequencies, leading to searches generally being less sensitive. Finally, enhanced radio wave scattering toward the inner Galaxy further decreases the effective sensitivity of searches, by increasing both the dispersion measure smearing and pulse broadening. Indeed, the first magnetar (highly magnetized pulsar) discovered near Sgr A*, PSR J1745-2900, shows substantial pulse broadening relative to most other pulsar lines of sight, although it is below original estimations.

Observing at higher frequencies than those 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. The ngVLA shall have the necessary collecting area at high (i.e., >3 GHz) frequencies to find these objects within the central 1 arcmin (50 pc) diameter surrounding the Galactic Center (Figure 4).

Beyond the Galactic center, the ngVLA shall have the capabilities to enable another approach to probing gravity via pulsar–black hole binaries, for which a small number are expected in the Galaxy. Given that they are likely to be rare and therefore distant (for example, in the current census of approximately 2,500 pulsars, no pulsar–black hole binaries are known, though there are several neutron star-neutron star binaries) any pulsar–black hole binaries in the Galactic disk could experience significant pulse broadening. Moreover, a significant limitation to finding highly relativistic binaries could be the accelerations experienced by the pulsars.

The ngVLA shall have imaging capabilities that enable hybrid approaches to finding pulsars, conducting a search first for compact sources (potentially with steep spectra), followed by a targeted periodicity search on candidates. For example, Bhatka et al. (2017) used this hybrid imaging periodicity technique in their recent successful detection of the recycled pulsar PSR 1751-2737. The achieved sensitivity of the ngVLA at radio frequencies of 3–30 GHz shall open a new door for the discovery and study of pulsars not only in orbit around Sgr A* but throughout the inner Galaxy.

3.4.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG4-001**: The ngVLA shall support pulsar search and timing observations from ~1 to 30 GHz for Galactic Center pulsars. Pulsar searching requires 100 μs scales (20 μs scales desired), while timing requires 20 μs resolution. While there are uncertainties and the distribution could be inhomogeneous, mitigating radio wave scattering is likely to require a frequency range that includes the lower range anticipated for the ngVLA (≥3 GHz).

- **KSG4-002**: A continuum rms noise of order 50 nJy/bm is desired at 20 GHz. This is a significant improvement compared to existing 100 m class radio telescopes that have found few pulsars, indicating that substantial additional sensitivity is necessary.
- **KSG4-003**: The system timing accuracy shall be better than 10 ns (1 ns desired) over periods correctable to a known standard from 30 minutes to ten years.
- **KSG4-004**: The array shall have the ability to make multiple (minimum ten) beams (i.e., phase centers within the primary beam) within a single sub-array, or distributed amongst multiple sub-arrays.
- **KSG4-005**: Timing multiple pulsars within a single primary beam is desirable. Support for five or more independent de-dispersion and folding threads is desired.

3.5 KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

Summary: The ngVLA shall 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. The ngVLA shall also be able to identify the radio counterparts to transient sources discovered by gravitational wave, neutrino, and optical observatories. 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.

Driving Science Use Cases: TDCP2, TDCP5, TDCP7, TDCP8

Supporting Science Use Cases: NGA12

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. LIGO is now detecting black holes that are substantially more massive than previously known stellar-mass black holes, and is 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. The ngVLA shall have the sensitivity and (high) angular resolution to make dramatic progress on answering these outstanding questions.

The ngVLA shall enable a census of black holes on all scales, from stellar-mass to supermassive. In the Milky Way Galaxy, the number of X-ray binaries (containing stellar-mass black holes) is only weakly constrained to be somewhere in the range 10^2–10^8 (Tetarenko et al. 2016), based on a small sample of just 20–30 known stellar-mass black holes (McClintock & Remillard 2006). Unaffected by dust obscuration, and with the angular resolution to separate Galactic sources from background objects using proper motions, the ngVLA shall be able to survey the Galaxy to detect jet-powered synchrotron emission from weakly accreting black holes and increase the black hole sample by at least an order of magnitude.

Simply measuring the size of the population would have profound implications for key parameters impacting binary black hole formation, such as common envelope evolution and the strength of dynamical "kicks" delivered to black holes at birth (caused by asymmetries in the parent core-collapse supernovae). These parameters are key inputs into one of the core problems that has already developed in gravitational wave astronomy—whether double black holes form through normal binary stellar evolution, or whether they require globular cluster formation mechanisms.

The ngVLA shall also directly measure black hole natal kicks through determination of proper motion and parallax. Finally, with these requirements, the ngVLA will be a superb tool for multi-wavelength follow-up of these discoveries to measure the black hole mass distribution. The ngVLA should be uniquely positioned for black hole survey science, as black holes in the Galaxy will be scatter broadened at lower frequencies precluding high-resolution imaging.

While SMBHs dwell at the centers of many, if not all galaxies, we still do not understand how black holes manage to grow to masses of 10^6–10^{10} $M_\odot$. Lead contender models include the merger of less massive black hole "seeds" (i.e., remnants of Population III stars) and direct collapse of more massive black holes in early dark matter halos (Volonteri et al. 2003). These models can be best tested by measuring the occupation fraction of SMBHs in nearby, low-luminosity galaxies. Deep, high-resolution imaging of nearby galaxies will provide proper motion distinction between nearby low-luminosity active galactic nuclei and background sources (~10 μas yr^{-1}). Thereby, the ngVLA shall enable the best search possible for SMBHs, measure their occupation fraction in dwarf galaxies, and test models of SMBH formation.

By enabling both pulsar timing arrays and high-resolution imaging, the ngVLA shall be able to survey the population of binary SMBHs, measure the rate of super-massive black hole mergers through their contributions to the stochastic gravitational wave background, and image the evolution of binary SMBHs in the lead up to merger. Recently, Bansal et al. (2017) made the first measurements of the orbit of a SMBH binary with the VLBA (Figure 5). With the specified sensitivity, the ngVLA will be able to identify and measure the proper motions of double AGN in much tighter orbits, where precision tests of General Relativity could be made. Meanwhile, the ngVLA will be a key facility for monitoring millisecond pulsars to detect and characterize the nanohertz gravitational wave background from SMBH mergers, and will be complementary to gravitational wave observatories in the kHz and mHz bands.

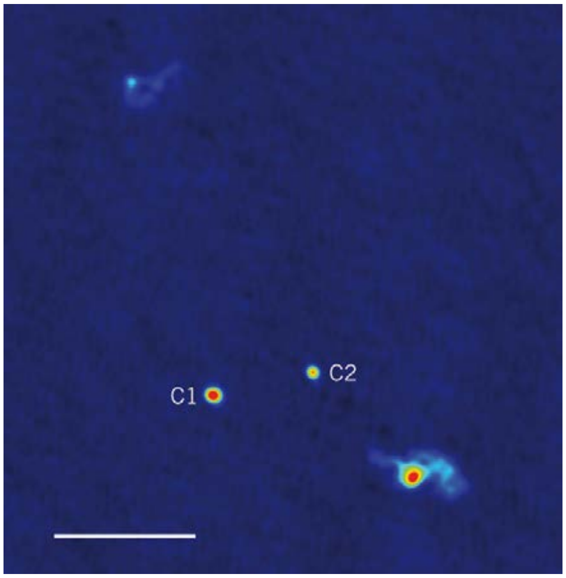

Figure 5 - The ngVLA should be an excellent tool for hunting black holes, including binary supermassive black holes. Here we show a binary system of SMBHs at z = 0.06. The black holes are separated by 7 pc (the white scale bar denotes 10 pc) with an orbital period of 30,000 yr, and jet emission is observed extending from the black hole C2. The ngVLA shall have the sensitity and high-resolution imaging capabilities to enable discovery of many more such systems, with intimate synergies to LISA and Pulsar Timing Arrays. Image from Taylor (2014).

3.5.1 Supporting Requirements

The following requirements are necessary to support this science case:

- **KSG5-001**: High-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$100) point source, is required for surveying black holes. Such high-resolution (mas – µas) imaging will enable proper motion separation of local black holes (both Galactic and in nearby galaxies, out to 15 Mpc) from background sources.
- **KSG5-002**: Long baselines are required to enable imaging the SMBH binaries that will be detected in gravitational waves by LISA and pulsar timing arrays. These astrometric science goals benefit from the implementation of very long baselines ($\gtrsim$1000 km for mas–µas accuracy). Associated VLBI recording capabilities shall be available for three or more beams (two calibrators and the science target).
- **KSG5-003**: While the key frequency range is 5–20 GHz, the availability of higher (20–50 GHz) frequencies are required for regions with high interstellar scatter broadening.
- **KSG5-004**: Multiple (i.e., a minimum of ten) sub-arrays with independent beams and pulsar timing support are desired. Precision timing of pulsars may not be sensitivity limited, but require long observations to oversample the pulse period and remove pulse jitter.
- **KSG5-005**: Pulsar timing will require 20 µs resolution and frequency coverage down to 1–2 GHz.
- **KSG5-006:** Mapping a ~7 square degree region (i.e., the localization uncertainty expected by gravitational wave detectors when ngVLA is operational; Nissanke et al. 2013) to a depth of ~1 µJy/bm at 2.5 GHz for detection of Adv. LIGO-detected NS-NS and NS-BH mergers is required. Completing the on-the-fly mapping of each epoch within ~10 hr is desirable.
- **KSG5-007:** Mapping a ~10 square degree region (i.e., the localization uncertainty expected by LISA; Lang et al. 2008) at 28 GHz to a depth of ~10 µJy/bm with on-the-fly mapping is required for localization of LISA-detected SMBH mergers. Completing the on-the-fly mapping of each epoch within ~10 hr is desirable.
- **KSG5-008**: The ability to receive and respond to external triggers rapidly is also an essential requirement to enable multi-messenger science. Triggered response time not to exceed ten minutes is required, while response time of better than three minutes is desired.
- **KSG5-009**: The ability to perform time-domain transient searchers (e.g., for fast radio bursts) requires a search capability on 100 µs scales, with 20 µs scales desired.
- **KSG5-010**: An rms noise of 0.23 µJy/bm at 10 GHz is required for a 0.6 mas beam to detect a source like GW170817 with a SNR $\approx$10 at the Adv. LIGO horizon distance of 200 Mpc and allow for the measurement of its expansion at the 5σ level.

4 Detailed Summary of Level-0 Science Requirements

Here we list specifically, and in more detail, the requirements necessary to carry out the key ngVLA science goals as identified by the community and discussed above. The Science Requirements are placed into two categories: Telescope Features (Table 1) and Performance Requirements (Table 2).

While specific integration times are not given, the science requirements must be able to achieve all five ngVLA Key Science Goals within ten years of full science operations as described in the ngVLA Reference Observing Program [RD41]. This list is meant to serve as a minimum set of requirements as there are instances where other science cases received may have needed more stringent requirements, so performance in excess of these minima are desired.

However, as stated in Section 3 above, the 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. Thus, it is vital that the observatory provide broad and balanced capabilities in order to allow for the unanticipated discoveries that have proven the most fundamental legacy of large astronomical observatories.

Parameter	**Req. #**	**SciCase**	**Value**
Frequency Coverage	SCI0001	All	The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits bracket spectral line emission from H_I and CO (J=1→ 0) respectively.
Observing Bands	SCI0002	KSG2-003, KSG3-003	ngVLA observing band edges should in all possible cases avoid astronomically interesting spectral lines for redshifts between z=0 and z=0.1 (See Appendix Section for a list of lines). Overlap of 1% in band edges is therefore desirable.
Frequency Selection	SCI0003	KSG1-001, KSG1-004 KSG2-003, KSG3-002, KSG3-003	The system shall support full bandwidth selection of the front end(s) without gaps in frequency coverage that is instantaneously available. Selectable bandwidth steps may be discrete if necessary. Observing multiple line diagnostics within a single band is also desirable.
Mosaics and On-the-Fly Mapping	SCI0004	KSG3-010, KSG5-006, KSG5-007	The system shall support both mosaicking and on-the-fly mapping of fields of view larger than the primary beam with full spectral capabilities in support of the survey speed requirement (SCI0106).
Triggered Observations	SCI0005	KSG5-008	The array shall have a mechanism to receive and rapidly respond to external triggers. Triggered response times not to exceed 10 minutes are required for transient science, while response times of 3 minutes are desired.
Observing Modes	SCI0006	All	The system shall observe in both narrow (spectral line) and wide-band (continuum) modes simultaneously. The goal is to maximize flexibility and sensitivity of both modes. This does not preclude a single configurable 'mode' that meets the requirements of both general use cases.
Phased Array Capability	SCI0007	KSG4-004, KSG5-004	The system shall operate both as an interferometer and phased-array simultaneously.
Beam Forming	SCI0008	KSG4-004, KSG5-004	The array shall have the ability to make multiple (minimum 10) beams (phase centers within the primary beam) within a single sub-array, or distributed amongst multiple sub-arrays, in the phased array mode.
Sub-Array Capabilities	SCI0009	KSG5-004	The system shall be divisible into multiple (i.e., at least 10) sub-arrays for operation and calibration purposes. All functional capabilities listed above should be available in a sub-array.
Sub-Array Commensality	SCI0010	N/A	Sub-arrays must concurrently function in different observing modes and should be supported at their full specification. In particular, full-bandwidth cross-correlation must be supported in a sub-array, concurrent with phased array and time-domain search capabilities in a separate sub-array.

Pulsar Timing Capabilities	SCI0012	KSG4-001 KSG4-005, KSG5-004, KSG5-005	Timing multiple pulsars within a single primary beam is required. Support for 5 or more independent de-dispersion and folding threads is desired.
Time Domain Search Capabilities	SCI0013	KSG4-001 KSG5-009	The system shall provide time-domain transient search capabilities on 100 μs scales in the phased array mode, with 20 μs scales desired.
Timing Capabilities	SCI0014	KSG4-001, KSG5-005	The system shall provide transient timing capabilities with resolution of order 20 μs.
Polarization Products	SCI0015	KSG1-004, KSG3-011	The system shall measure all polarization products simultaneously.
Solar Observation Capabilities	SCI0016	N/A	It shall be possible to observe the sun at all available frequencies.
VLBI Capabilities	SCI0017	KSG5-002 KSG5-010	It shall be possible to use the system for VLBI observations with a single element, or phased array output, at all available frequencies. Recording capabilities shall be included for a minimum of 3 beams (10 beams desired). The format should be compatible with expected VLBI arrays.
Multi-Frequency Observations	SCI0018	N/A	The system shall support either multi-frequency observations or rapid switching between bands. Switching time of 10–20 sec is desired.
Accessible Sky	SCI0019	All	The system shall be capable of observations from –40° declination to 90° declination, ensuring adequate overlap with planned southern hemisphere arrays.

Table 1 - Telescope features.

Parameter	Req. #	SciCase	Value
Continuum Sensitivity	SCI0100	KSG1-002, KSG1-003, KSG3-008, KSG4-002	An rms noise of ~0.07 μJy/bm @30 GHz and 0.5 μJy/bm @100 GHz is required for studying protoplanetary disks. See SCI01017 for corresponding VLB continuum sensitivity requirement.
Line Sensitivity	SCI0102	KSG2-002, KSG3-001, KSG3-004, KSG3-005	A line rms noise of 30 μJy/bm/km/s for frequencies between 10–50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line rms noise 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 simultaneously support detailed studies of CO and variations in gas density across the local universe.
Angular Resolution	SCI0103	KSG1-001, KSG1-003, KSG5-001, KSG2-001	A synthesized beam having a FWHM ~5 mas with uniform weights is required at both 30 and 100 GHz. See SCI01018 for corresponding VLB angular resolution requirement.
Largest Recoverable Scale	SCI0104	KSG1-006, KSG2-004, KSG3-009	Angular scales of >20" x (116 GHz/ν) must be recovered at frequencies ν <116 GHz. A more stringent desire is accurate flux density recovery on arcminute scales at all frequencies.
Spectral Resolution	SCI0105	KSG2-003	A spectral resolution of at least 0.1 km/s is required. It is desirable that this spectral resolution be available over a broad (4+ GHz) bandwidth.
Survey Speed	SCI0106	KSG5-006, KSG5-007	The array shall be able to map a ~7 square degree region to a depth of ~1 μJy/bm @ 2.5 GHz and a 10 square degree region to a depth of ~10 μJy/bm @ 28 GHz within a 10 hr epoch.
Quality of the Synthesized Beam	SCI0107	All Imaging Cases	The (sculpted) synthesized beam shall be elliptical down to the attenuation level of the first side lobe and display a beam efficiency of >90% at all angular scales and frequencies, while still meeting continuum sensitivity requirements (SCI0100).
Imaging Fidelity	SCI0108	KSG1-001, KSG3-004, KSG3-005, KSG3-007, KSG3-009	The ngVLA should produce high fidelity imaging (>0.9) over a wide range of scales, spanning from a few arcmin to a few mas.
Snapshot Image Fidelity	SCI0109	KSG1-001, KSG3-005, KSG3-006	The ngVLA snapshot performance should yield high fidelity imaging on angular scales >100mas at 20 GHz for strong sources.
Photometric Error	SCI0110	KSG3-006	The photometric error for point sources shall be less than 1% at frequencies where a sufficiently accurate flux density scale is known for programs requiring highly accurate photometry.

Relative Astrometric Error	SCI0111	KSG5-001 KSG5-002	The instrument shall achieve an astrometric error that is <1% of the synthesized beam FWHM or the positional uncertainty in the reference frame, for a bright (SNR $\gtrsim$100) point source.
Timing Error	SCI0112	KSG4-003	The system timing error shall be less than 10 ns (1 ns desired) over periods correctable to a known standard from 30 min to 10 yr.
Brightness Dynamic Range	SCI0113	KSG3-011 KSG3-008	The system brightness dynamic range shall be >50 db to support deep field studies at 10 GHz.
Polarization Dynamic Range	SCI0114	KSG3-011	The polarization dynamic range shall be >40 db to support deep field studies at the center of the field of view at 10 GHz.
Spectral Dynamic Range (Emissive)	SCI0115	KSG2-006	The emissive spectral dynamic range shall be >50 db to enable imaging of faint prebiotic molecules in the presence of bright emission lines within the field of view.
Spurious Spectral Features	SCI0116	KSG2-005	Self-generated spurious spectral feature flux density must be below ~95 µJy/bm in any 0.1 km/s channel, post calibration between 16–50 GHz.
VLB Continuum Sensitivity	SCI0117	KSG5-010	The continuum rms noise shall be less than ~0.23 µJy/bm at 10 GHz to detect GW events at a distance of 200 Mpc.
VLB Angular Resolution	SCI0118	KSG5-010	A 0.6 mas synthesized beam at 10 GHz is required to support measurement of proper motions for GW events at a distance of 200 Mpc
Spectral Dynamic Range (Absorptive)	SCI0119	KSG3-012	The absorptive spectral dynamic range shall be better than 40 db to measure the physical properties of Galactic neutral Hydrogen.

Table 2 - Performance requirements.

5 Appendix

5.1 Acronyms and Abbreviations

A limited set of basic acronyms used in this document are given below:

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter Array
AU	Astronomical Unit
BH	Black Hole
BW	Bandwidth
DR	Dynamic Range
FWHM	Full Width Half Max
GBT	Green Bank Telescope
GMC	Giant Molecular Clouds
GW	Gravitational Wave
IRAM	Institut de radioastronomie millimétrique
JWST	James Webb Space Telescope
KSG	Key Science Goal
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
mas	milli-arcsecond
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
ngVLA	next generation Very Large Array
NOEMA	NOrthern Extended Millimeter Array
NRAO	National Radio Astronomy Observatory
NS	Neutron Star
pc	parsec
RD	Reference Document
rms	root-mean-square
SAC	Science Advisory Council
SEFD	System Equivalent Flux Density
SKA	Square Kilometre Array
SMBH	Super Massive Black Hole
SWG	Science Working Group
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry

5.2 *List of Important Molecular Lines*

A more comprehensive list of molecular lines, including H and He recombination lines, is available.

Species	**Chemical Name**	**Ordered Freq (GHz)**	**Resolved QNs**		**Species**	**Chemical Name**	**Ordered Freq (GHz)**	**Resolved QNs**
C18O	Carbon Monoxide	109.7821734	1–0		**HNCO v=0**	Isocyanic Acid	21.9815726	1(0, 1)–0(0, 0)
13CO v=0	Carbon Monoxide	110.2013543	1–0		**HNCO v=0**	Isocyanic Acid	43.9630395	2(0, 2)–1(0, 1)
CO v=0	Carbon Monoxide	115.2712018	1–0		**HNCO v=0**	Isocyanic Acid	87.925237	4(0, 4)–3(0, 3)
					HNCO v=0	Isocyanic Acid	109.905749	5(0, 5)–4(0, 4)
HDO	Water	80.578295	1(1, 0)–1(1, 1)					
H2O v=0	Water	22.2350798	6(1, 6)–5(2, 3)		**SO2 v=0**	Sulfur dioxide	12.256583	1(1, 1)–2(0, 2)
					SO2 v=0	Sulfur dioxide	100.8781053	2(2, 0)–3(1, 3)
HCN v=0	Hydrogen Cyanide	88.631847	J=1–0		**SO2 v=0**	Sulfur dioxide	104.0294183	3(1, 3)–2(0, 2)
HNC v=0	Hydrogen Isocyanide	90.663568	J=1–0					
					SO 3Σ v=0	Sulfur Monoxide	13.0437	1(2)–1(1)
H13CO+	Formylium	86.7542884	1–0		**SO 3Σ v=0**	Sulfur Monoxide	30.0015235	1(0)–0(1)
HCO+ v=0	Formylium	89.1885247	1–0		**SO 3Σ v=0**	Sulfur Monoxide	100.02964	4(5)–4(4)
					SO 3Σ v=0	Sulfur Monoxide	109.25222	2(3)–1(2)
SiO v=0	Silicon Monoxide	43.42376	1–0					
SiO v=0	Silicon Monoxide	86.84696	2–1		**CN v=0**	Cyanide Radical	113.4881202	N=1–0, J=3/2–1/2, F=3/2–1/2
N2H+ v=0	Diazenylium	93.1737	J=1–0		**CH**	Methylidyne	3.3491926	J=1/2–1/2, Ω=1/2, F=1/2-–1/2+
N2D+	Diazenylium	77.1092433	J=1–0		**CH**	Methylidyne	4.8793511	J=5/2–5/2, Ω=3/2, F=5/2+–7/2-
					CH	Methylidyne	7.398618	J=3/2–3/2, Ω=1/2, F=3/2+–1/2-
CS v=0	Carbon Monosulfide	48.9909549	1–0					
CS v=0	Carbon Monosulfide	97.9809533	2–1		**OH v=0**	Hydroxyl	1.6122309	N=1-–1+, J=3/2–3/2, F=1–2
					OH v=0	Hydroxyl	1.6654018	N=1-–1+, J=3/2–3/2, F=1–1
H2CO	Formaldehyde	1.0658686	4(2, 2)–4(2, 3)		**OH v=0**	Hydroxyl	1.667359	N=1-–1+, J=3/2–3/2, F=2–2
H213CO	Formaldehyde	2.2381367	5(2, 3)–5(2, 4)		**OH v=0**	Hydroxyl	1.7205299	N=1-–1+, J=3/2–3/2, F=2–1
H2CO	Formaldehyde	2.483408	5(2, 3)–5(2, 4)					
H213CO	Formaldehyde	13.7788041	2(1, 1)–2(1, 2)		**HC3N v=0**	Cyanoacetylene	9.0981152	J=1–0
H2CO	Formaldehyde	14.488479	2(1,1)–2(1,2)		**HC3N v=0**	Cyanoacetylene	18.196226	J=2–1
H213CO	Formaldehyde	27.555673	3(1, 2)–3(1, 3)		**HC3N v=0**	Cyanoacetylene	27.294289	J=3–2
H2CO	Formaldehyde	28.974805	3(1,2)–3(1,3)					
H213CO	Formaldehyde	45.920064	4(1, 3)–4(1, 4)		**c-HCCCH v=0**	Cyclopropenylidene	18.343143	1(1, 0)–1(0, 1)
H2CO	Formaldehyde	48.284547	4(1,3)–4(1,4)		**c-HCCCH v=0**	Cyclopropenylidene	35.360929	4(4, 0)–4(3, 1)

Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs		Species	Chemical Name	Ordered Freq (GHz)	Resolved QNs
H213CO	Formaldehyde	71.024788	1(0, 1)–0(0, 0)		**c-HCCCH v=0**	Cyclopropenylidene	46.6450454	5(5, 0)–5(4, 1)
H2CO	Formaldehyde	72.4090832	5(1,4)–5(1,5)		**c-HCCCH v=0**	Cyclopropenylidene	109.8738163	9(9, 0)–9(8, 1)
H2CO	Formaldehyde	72.837948	1(0,1)–0(0,0)					
H213CO	Formaldehyde	96.3757508	6(1, 5)–6(1, 6)		**CH3CN v=0**	Methyl Cyanide	18.397783	1(0)–0(0)
H2CO	Formaldehyde	101.332991	6(1,5)–6(1,6)		**CH3CN v=0**	Methyl Cyanide	36.7954747	2(0)–1(0)
					CH3CN v=0	Methyl Cyanide	91.9870876	5(0)–4(0)
H2CS	Thioformaldehyde	1.0464877	1(1, 0)–1(1, 1)		**CH3CN v=0**	Methyl Cyanide	110.3834999	6(0)–5(0)
H2CS	Thioformaldehyde	3.13938	2(1, 1)–2(1, 2)					
H2CS	Thioformaldehyde	10.46397	4(1, 3)–4(1, 4)		**NH3 v=0**	Ammonia	18.391562	6(1)0a–6(1)0s
H2CS	Thioformaldehyde	15.69512	5(1, 4)–5(1, 5)		**NH3 v=0**	Ammonia	18.884695	6(2)0a–6(2)0s
H2CS	Thioformaldehyde	21.97171	6(1, 5)–6(1, 6)		**NH3 v=0**	Ammonia	21.134311	4(1)0a–4(1)0s
					NH3 v=0	Ammonia	21.285275	5(3)0a–5(–3)0s
CH3OH vt=0	Methanol	12.178597	2(0, 2)–3(-1, 3)		**NH3 v=0**	Ammonia	21.7033582	4(2)0a–4(2)0s
CH3OH vt=0	Methanol	19.9673961	2(1, 1)–3(0, 3)		**NH3 v=0**	Ammonia	22.2345058	3(1)0a–3(1)0s
CH3OH vt=0	Methanol	44.901825	2(2, 0)–3(0, 3)		**NH3 v=0**	Ammonia	22.653022	5(4)0a–5(4)0s
CH3OH vt = 0	Methanol	48.376892	1(0, 1)–0(0, 0)		**NH3 v=0**	Ammonia	22.688312	4(3)0a–4(–3)0s
CH3OH vt=0	Methanol	96.74455	2(0, 2)–1(0, 1)		**NH3 v=0**	Ammonia	22.8341851	3(2)0a–3(2)0s
CH3OH vt=0	Methanol	97.582804	2(1, 1)–1(1, 0)		**NH3 v=0**	Ammonia	23.098819	2(1)0a–2(1)0s
CH3OH vt=0	Methanol	108.893963	0(0, 0)–1(-1, 1)		**NH3 v=0**	Ammonia	23.6944955	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	14.78227	2(0, 2)–3(-1, 3)		**NH3 v=0**	Ammonia	23.7226333	2(2)0a–2(2)0s
13CH3OH vt=0	Methanol	23.14544	4(0, 4)–3(1, 2)		**NH3 v=0**	Ammonia	23.8701292	3(3)0a–3(-3)0s
13CH3OH vt=0	Methanol	23.98025	2(1, 1)–3(0, 3)		**NH3 v=0**	Ammonia	23.6944955	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	47.20521	1(0, 1)–0(0, 0) + +		**15NH3**	Ammonia	22.6249295	1(1)0a–1(1)0s
13CH3OH vt=0	Methanol	47.20955	(0, 1)–0(0, 0)		**NHD2**	Ammonia	28.561699	2(1, 2)0s–2(0, 2)0a
13CH3OH vt=0	Methanol	71.15521	1(1, 0)–2(0, 2)		**NHD2**	Ammonia	38.738586	2(1, 2)0a–2(0, 2)0s
13CH3OH vt=0	Methanol	94.411016	2(0, 2)–1(0, 1)		**NH2D**	Ammonia	85.926278	1(1, 1)0s–1(0, 1)0a
13CH3OH vt=0	Methanol	95.20866	2(1, 1)–1(1, 0)		**NH2D**	Ammonia	110.153594	1(1, 1)0a–1(0, 1)0s
13CH3OH vt=0	Methanol	103.084391	2(-2, 1)–2(1, 1)		**NHD2**	Ammonia	110.81285	1(1, 0)0a–1(0, 1)0a
13CH3OH vt=0	Methanol	109.16412	0(0, 0)–1(-1, 1)		**NHD2**	Ammonia	110.8967	1(1, 0)0s–1(0, 1)0s

5.3 Remaining Questions

The following science requirements have been identified as possibly needing further input and will be addressed in future releases of this document.

5.3.1 Angular Resolution

Characterizing the evolution of black holes (ngVLA KSG5; Section 3.5) could benefit from more quantitative substantiation. It is currently thought that 2.5 mas angular resolution at 30 GHz may be required. This would allow for statistically significant proper motion measurements of nearby low-luminosity active galactic nuclei against background sources (~10 μas yr^{-1}) assuming <~1% relative astrometric accuracy for SNR~100 detection. This is currently accommodated by our 1000 km baselines.

5.3.2 Quality of the Synthesized Beam

Current requirement may be infeasible when combined with the sensitivity requirements. This needs to be reconciled during the internal configuration study.

5.3.3 OTF Mapping

Is full spectral resolution required in the OTF mode?

5.3.4 Data Latency Requirement

Is there a subset of science observations that require data be delivered to the PI in rapid fashion to enable self-triggering of new observations? Observational modes that support a “quick-look” reduction to trigger new observations on the ngVLA or other observatories may be required, and a maximum data delivery delay may need to be supported by the post-processing system. Such a latency requirement on data/science product delivery for certain science cases should be further explored.