Array Configuration: Preliminary Technical Requirements

020.23.00.00.00-0001-REQ

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
C. Carilli, V. Rosero, A. Erickson	ngVLA/Electronics, NRAO	2019-07-09
E. Murphy	ngVLA/NM-Operations	

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer — 2019.07.09 17:39:35 -06'00'	Electronics Division, NRAO	2019-07-09
E. Murphy, Project Scientist — Digitally signed by Eric J. Murphy Date: 2019.07.10 13:43:49 -04'00'	ngVLA/NM-Operations, NRAO	2019-07-09
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.11 07:03:29 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-09

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.11 07:03:46 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-09

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-07-05	Carilli		Preliminary Reference Design Review
02	2018-07-09	Selina	All	Corrections to first draft throughout; mostly excisions of irrelevant pieces of the template; significant edits to Section 4
03	2018-07-17	Mason	3.4.1, 4.4	Clarified SBA, TP requirements; fixed other minor typos
04	2018-07-17	Rosero	All	Editorial corrections; added most of E. Murphy's suggestions/comments
05	2018-09-17	Rosero	3.2, 3.3, 3.5, 4.1, 4.2	Updated information about the current configuration; rewrote section 3.3
06	2018-11-30	Carilli, Rosero, Erickson	All	Respond to RIDs from reference design review
07	2019-05-31	Selina	3.5, 4	Updated Req. IDs and traceability
A	2019-07-09	Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document presents a set of technical requirements for the ngVLA Array Configuration Reference Design. Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow down from the preliminary ngVLA Science Requirements [AD01].

The Science goals are presently being elaborated by the Science Advisory Council (SAC) and Science Working Groups (SWGs), and are captured in a series of draft use cases. A preliminary analysis of these use cases, and the flow down recursively to the science, system, and subsystem requirements, is reflected in this draft.

1.2 Scope

The scope of this document is the ngVLA array configuration. Described in the Design Description Document [AD04], it is designed to meet the science requirements determined in the detailed community analysis of the broad ngVLA science case, as captured in the science use case spreadsheet [RD01] and summarized in ngVLA memos 17, 18, and 19, and in [AD01] and [AD02].

The requirements establish the performance and functional requirements applicable to the ngVLA array configuration based on the science program analysis. These requirements then dictate the reference design, described in [AD04].

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Technical Specification to the extent specified. In the event of conflict between the documents referenced herein and the content of this Technical Specification, the content of this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Array Configuration Reference Design	020.23.00.00.00-0002-DSN
AD05	Antenna Preliminary Technical Requirements	020.25.00.00.00-0001-SPE
AD06	Short Baseline Array Antenna Preliminary Technical Requirements	020.47.05.00.00-0001-SPE

2.2 Reference Documents

The configuration requirements draw extensively from work presented in the ngVLA memo series. The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	Science Use Case Parameterization Spread Sheet	2017-06-20 V24
RD02	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo #17
RD03	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD04	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19
RD05	Image Capabilities: High Redshift CO	ngVLA Memo #13
RD06	Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array	ngVLA Memo #33
RD07	More on Synthesized Beams and Sensitivity	ngVLA Memo #16
RD08	ngVLA Dynamic Range	ngVLA Memo #30
RD09	Deep Fields at 8GHz	ngVLA Memo #35
RD10	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo #41
RD11	Resolution and Sensitivity of ngNLA-revB	ngVLA Memo #47
RD12	The ngVLA Short Baseline Array	ngVLA Memo #43
RD13	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo #1
RD14	Possible Configurations for the ngVLA	ngVLA Memo #3

We refer the reader to these memos for more details on science simulations that relate to the configuration design and characterization of the design.

3 Overview of the Array Configuration Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA array configuration. These parameters determine the overall form and performance of the array configuration.

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes elaborate on the meaning, intent, and scope of the requirements. These notes form an important part of the requirements definition and should guide the verification procedures. In many cases the notes explain or analyze how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the required analysis and trade-space available is apparent to scientists and engineers who will guide evolution of the ngVLA array configuration concept.

Section 3.4 identifies Key Performance Parameters (KPP) that should be estimated and monitored throughout the design phase. These metrics facilitate trade-off analysis of various concepts and help identify and resolve tensions between requirements as the design progresses.

3.2 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 cm to 0.26 cm, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a non-reconfigurable synthesis radio telescope operating in a phased or interferometric mode.

The signal-processing center and the majority of antennas will be located at the Very Large Array site on the Plains of San Agustin, New Mexico. Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM.

3.3 General Array Configuration Description

The description of the array that satisfies the following requirements can be found in the subsystem Reference Design Description document. We briefly review it here for completeness.

The ngVLA array design includes three fundamental subarrays: the main interferometric array, the short baseline array, and the long baseline array. Antennas within the main array are distributed over a range of physical scales and with different geometries in order to fulfill different science use cases:

- A dense core which provides high surface brightness sensitivity at ~1,000 mas resolution.
- A multi-arm spiral capable of high-fidelity snapshot imaging at ~10 mas scales.
- Longer arms which provide mid-scale baselines for imaging at ~1 mas.

The main array will be augmented by a compact array of smaller antennas that will provide sensitivity on larger angular scales, and four antennas of the main array will be equipped to measure total power in order to fill in the center of the (u,v)-plane. Additionally, a long baseline array (LBA) consisting of several outlying stations will provide intercontinental-scale baselines for achieving resolutions of ~0.1 mas.

3.4 Key Performance Parameters

This section provides Key Performance Parameters (KPPs) that the designer should estimate and NRAO should monitor throughout the project design phase. The KPPs strongly influence the eventual effectiveness of the facility and are useful high-level metrics for trade-off decisions. These parameters are of higher importance to NRAO, so improved performance above the requirement is desirable. Section 4 discusses the KPPs' impact on system-level performance.

The technical requirements are generally specified as *minimum* values to give the designer latitude in optimization for a balanced design. Understanding anticipated performance of the array configuration (not just its specified minimum) based on these parameters assists in system-level analysis and performance estimation. These parameters may also be useful for determining the relative priority of the requirements documented in Section 4 and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

Table 1 shows the KPPs identified for monitoring. For the configuration imaging performance, the primary points of reference are the simulations of sensitivity vs. resolution, with weighting appropriate to obtain a synthesized beam adequate to perform the Key Science Programs. This analysis will be presented in an Imaging Performance Report. Figure 1 shows the current analysis on sensitivity versus resolution.

Key Performance Parameter	Req. #
Highest angular resolution, Main Array @ 30 GHz	SYS1310, SCI0103, SCI0108
Highest angular resolution, LBA @ 30 GHz	SCI0118
rms/rms$_{NA}$ versus angular resolution	SCI0100, SCI0102, SCI0107
Largest Recoverable Scale with the SBA	SCI0104
Fiber Utility Length	-
Percentage of Sites off Private or BLM land	-

Table 1 - Key performance parameters for monitoring during design.

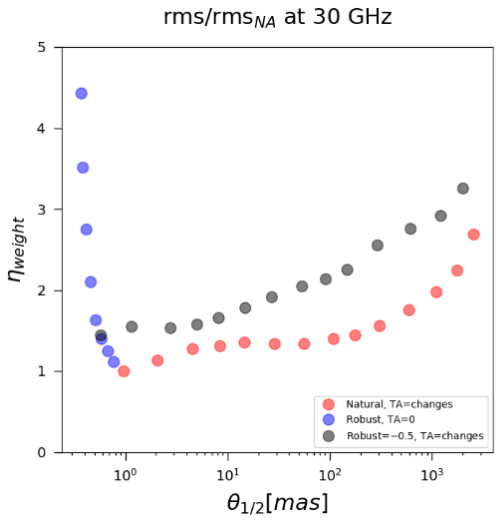

Figure 1 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz. The noise has been scaled relative to that of the naturally weighted image (rms$_{NA}$). The red symbols correspond to use of a uv-taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = –0.5 and a varying uv-taper, which has a large effect on beam quality.

3.5 Summary of Array Configuration Requirements

Following is a summary of the major requirements in order to provide the reader with a high-level view of the desired system. Should there be a conflict between the requirements listed here and the descriptions in Section 4, the latter shall take precedence.

The array configuration is designed to perform the broad range of science programs, ranging from:

1. very high resolution (10 mas at 30 GHz), sensitive observations of exoplanets forming on AU-scales (T_B ~3 K in one hour at 10mas resolution at 30GHz in continuum), to
2. good surface brightness sensitivity observations at 100 mas of molecular gas in distance galaxies (T_B ~8K at 100mas resolution at 30GHz and 10 km s^{-1} spectral resolution), to
3. imaging of large scale structures in nearby galaxies at ultra-low surface brightness at 1000 mas resolution (T_B ~1mK in one hour in the continuum at 30GHz).

The reference design reflects the multi-scale requirements from the array science case. The ultimate sensitivity as a function of resolution will depend critically on the specific synthesized beam for the science application in question, but as a guiding principle, we have adopted the goal of roughly a factor two loss in sensitivity from spatial resolutions ranging from ~0.3 mas to 1000 mas at 30 GHz. For the PSF metric, we have adopted the goal of a <10% skirt at a radius from the beam center = FWHM. Current simulations suggest this is adequate for many of the key science goals. Further testing is in progress in this area.

The primary parameter defining the configuration is total collecting area, which dictates the ultimate sensitivity of the array. Related to this is the distribution of antennas across the array, which dictates the relative sensitivity at a desired spatial resolution. This total collecting area requirement derives ultimately from spectral line sensitivity requirements (SCI0102), which states: *A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1–100 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.*

The maximum baseline requirement flows from the angular resolution requirement, SCI0103: *A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz.*

The number of antennas on the Plains is dictated by image fidelity requirements and sensitivity on scales of 100 mas at 30 GHz, SCI0108: *The ngVLA should produce high fidelity imaging (>0.9) over a wide range of scales, spanning from a few arcmin to a few mas*. The snap shot fidelity requirement, SCI0109, states: *The ngVLA snapshot performance should yield high fidelity imaging on angular scales >100 mas at 20 GHz for strong sources.*

The diameter and number of antennas in the core is set by surface brightness sensitivity requirements, SCI0113: *The system brightness dynamic range shall be better than 50 dB deep field studies at 10 GHz.*

The parameters for the SBA and total power system are derived to perform very low surface brightness observations of extended objects. The details relating to the science and the requirements are given in ngVLA memo 43. The requirements flow from the Largest Recoverable Scale (SCI0104), and the need to have matched surface brightness sensitivity on the longer baselines of the SBA and the main array core. For reference, SCI0104 states: *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.*

3.5.1 General Functional Specifications

Parameter	Req. #	Summary of Requirement	Reference Reqs.[1]
Geometric collecting area, main array	AAC0001	The system gross geometric collecting area shall be 61,700 m^2 or greater.	SYS1021, SYS1308, SCI0100, SCI 0102, SCI0106
Maximum baseline, main array	AAC0002	The longest baseline between antennas shall be greater than 650 km. It is a goal to have baselines longer than 1000 km.	SYS1310, SCI0103, SCI0108
Geometric collecting area, core array	AAC0003	The system shall include a compact core. A minimum of 40% of array collecting area shall be located within 1.25 km of array vertex.	SYS1305, SCI0104, 0102, 0106
Maximum baseline, core	AAC0004	1.25 km	SCI0104, SCI0106
Geometric collecting area, Plains array (includes core)	AAC0005	46,300 m^2	SYS1306, SCI0106, SCI0109, SCI0108

3.5.2 Other General Desirables

Antenna locations should, as best as possible, conform to practical considerations in terms of access, roads, power, fiber, interference environment, safety and security. The site quality should also allow for observations up to 116 GHz.

Parameter	Req. #	Value	Reference Reqs.
Station proximity to appropriate power lines	AAC0010	2 km distance	TBD
Station proximity to high bandwidth optical fiber network	AAC0011	2 km distance	TBD
Station access for construction (roads, land rights)	AAC0012	TBD	TBD
Good performance up to 3mm	AAC0013	Opacity <10% at 90 GHz for >30% of the year. Phase stability allows for residual rms phase <30 deg using fast switching phase calibration with 30 sec cycle time at 90 GHz, for >30% of the year.	ngVLA Memo #1 SCI0001
Maximum baseline, Plains array	AAC0014	36 km	ngVLA Memo #13 SCI0108
Geometric collecting area, LBA	AAC0015	7634 m^2	SCI0117
Maximum baseline, LBA	AAC0016	8856 km	SCI0118
Geometric collecting area, SBA	AAC0017	530 m^2	ngVLA Memo #43 SCI0104

[1] All the SCI requirement numbers and the KSG cases are listed in [AD01]. The SYS numbers are listed in [AD02].

Parameter	Req. #	Value	Reference Reqs.
Maximum Baseline, SBA	AAC0018	44 m	ngVLA Memo #43 SCI0104 KSG1-006, KSG2-004, KSG3-009
Minimum Baseline SBA	AAC0019	The shortest baselines between antennas shall be shorter than 16 m, with a goal of <10 m.	SYS1302 SCI0104 ngVLA Memo #43
Total power antennas	AAC0020	Measure total power with apertures larger than 1.5x the shortest baseline.	SYS1303, SCI0104 ngVLA Memo #43
Total power sensitivity	AAC0021	Total power antenna(s) shall have sufficient sensitivity in aggregate to match the surface brightness sensitivity of SBA in observing times that are equal within a factor of four with a goal of equal times.	SCI0104 ngVLA Memo #43

4 Array Configuration Functional and Performance Requirements

These requirements apply to a properly functioning system, under the normal operating environmental conditions unless otherwise stated.

4.1 Total Collecting Area and Antenna Requirements

Parameter	Req. #	Value	Traceability
Main interferometric antenna aperture	AAC0101	18 m diameter	ANT0202, SCI0104, SCI0100, SCI0102
Main interferometric array: number of elements	AAC0102	214 elements	ANT0401, SCI0100, SCI0102
Long baseline antenna aperture	AAC0105	18 m diameter	SCI0118
Long baseline array: Number of elements	AAC0105	30 elements	SCI0118
Short baseline antenna aperture	AAC0103	6 m diameter	SBA0202
Short baseline array: Number of elements	AAC0104	19 elements	SBA0401

Note that the total number of elements within the main interferometric array and short baseline array can be adjusted so long as the total system construction and operations cost requirements (STK0100-0101) are not violated. Values in AAC0102 and AAC0104 are derived from these requirements, as defined in the antenna and short baseline requirements respectively. Aperture diameters are provided here as requirements based on the selected system architecture with traceability back to the antenna requirements. Both aperture sizes can be revisited within small ranges but have practical constraints that are accounted for in AAC0101 and AAC0203.

4.2 Spatial Scales

Parameter	Req. #	Value	Traceability
Main interferometric array: Longest baseline	AAC0201	The longest baseline between antennas shall be greater than 650 km, preferably longer than 1000 km.	SYS1301, SCI0103, [KSG1-001, KSG1-003, KSG2-001]
Main interferometric array: Shortest baseline	AAC0202	The shortest baselines between antennas in the main interferometric array shall be no less than 30 m.	ANT0301, SCI0104
Long baseline array: Longest Baseline	AAC0205	8856 km	SCI0118 [KSG5-001, KSG5-002]
Short baseline array: Shortest Baseline	AAC0203	The shortest baselines between antennas shall be no less than 11 m.	SBA0301, SCI0104, KSG3-005 KSG2-004
Zero spacing/single dish total power	AAC0204	It is a goal that the system measure total power, with apertures larger than 1.5x the shortest baseline.	SYS1303, SCI0104, KSG3-005, KSG2-004

The combination of spatial scales, when combined with practicalities of the antenna design, lead to a multi-component configuration:

1. A main interferometric array of 214 x 18 m apertures,
2. A long baseline array of 30 x 18 m apertures,
3. A short baseline array of 19 x 6 m apertures, and
4. A total power array of 4 x 18 m apertures (that are part of the 214 main array).

4.3 Distribution of Collecting Area

Parameter	Req. #	Value	Traceability
Fraction of occupied cells	AAC0301	It is a goal to fill at least 50% [TBC] of (u,v)-cells before gridding out to 36 km baselines (out to the longest baseline) in a snapshot observation traversing the meridian. Goal to achieve this fill ratio out to 50 km+ scales.	SYS1306, SCI0108 SCI0109 SCI0107
Compact core	AAC0302	The system shall include a compact core. At minimum, 40% of the array collecting area shall be located within 1.25 km of the array vertex.	SYS1305 SCI 0104
Distribution of baselines	AAC0303	TBD (Need to describe desired radial distribution function)	SYS1307, SCI 0107
Integration time ratios	AAC0304	The main interferometric array, short baseline array, and total power array shall sample overlapping spatial scales. The ratio of integration time on one array to the other on these scales shall not exceed a factor of four with a goal of matched integration times.	SYS1304, SCI0104
Weighting of visibilities	AAC0305	It is a goal to achieve a Gaussian distribution via weighting, with the geometric mean of the weights greater than 0.5 over the full range of scales that correspond to 1 km to 650 km baselines on an 8 hr. observation.	SYS1308 SCI0108 SCI0109 SCI0107

The array collecting area is distributed to provide high surface brightness sensitivity on a range of angular scales spanning from approximately 10 mas to 1000 mas. A large fraction of the collecting area is in a randomly distributed core to provide high snapshot imaging fidelity and there are arms extending asymmetrically out to ~1000 km baselines to fill the (u,v)-plane via Earth rotation and frequency synthesis.

4.4 Total Power Recovery

Parameter	Req. #	Value	Traceability
TP antennas	AAC0401	Total power antennas and subsystems will be identical to antennas of main interferometric array to extent possible. TP antennas are included as part of the 244 main array.	SCI0104
TP-specific needs	AAC0402	TP antennas will accommodate the specific requirements of TP observing such as rapid, accurate slewing (for OTF) and relatively higher signal stability.	SCI0104

4.5 Site Selection Performance Requirements

Parameter	Req. #	Value	Traceability
Performance up to 3 mm: Opacity	AAC0501	It is desired that all sites have Opacity <10% at 90 GHz for >30% of the year.	SCI0001 SCI0100 SCI0102
Performance up to 3 mm: Phase stability	AAC0502	It is desired that all sites have phase stability that allows for residual rms phase <30 deg using fast switching phase calibration with a 30 sec cycle time at 90 GHz, for >30% of the year.	SCI0001 SCI0100 SCI0102

4.6 Site Selection Regulatory Requirements

Parameter	Req. #	Value	Traceability
Land ownership	AAC0601	It is desired that sites on private and BLM land be prioritized. USFS and Tribal properties shall be avoided when possible.	
Environmental impact	AAC0602	Sites shall be screened for environmental impact, such as overlap with identified endangered species habitat.	

4.7 Site Selection Logistics and Interface Requirements

Parameter	Req. #	Value	Traceability
Station access roads	AAC0701	It is desired that all sites be within 2 km of an existing road or access point.	
Maintenance access	AAC0702	Sites shall have clear access for maintenance at all times. I.e. no predicted access restrictions or seasonal roads.	
Station proximity to power lines	AAC0703	It is desired that all sites be within 2 km of an existing three-phase power line.	
Station proximity to high bandwidth optical fiber	AAC0704	It is desired that all sites be within 2 km of an existing fiber optic network.	
Fiber optic transmission lengths	AAC0705	Sites shall be selected assuming "home run" fibers are required from the site to the correlator. Total fiber transmission distances shall be minimized through shared right-of-way and trenches.	
RFI mitigation	AAC0706	It is desirable that sites limit line of sight to public roads, transmitters, and other known sources of RFI.	
Site safety and security	AAC0707	It is desirable that sites have rural neighbors who may provide indirect site security checks.	

Antenna positions should be such that access is readily available for regular and emergency maintenance visits. Antennas should be located as best as possible away, or terrain-shielded, from significant sources of terrestrial interference, such as cell phone towers, radio transmitters, airport or other radars, and related.

5 Documentation Requirements

5.1 Technical Documentation

All documentation and electronic files related to array configuration shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units or decimal lat/lon.
- The electronic document formats are Microsoft Word and Adobe PDF.

Any deviation from the above shall be agreed to by the ngVLA project office.

5.2 Software and Software Documentation

The primary configuration analysis software will be supported within the CASA package. Deliverables will include:

- Configuration file for the ngVLA interferometric array (244 18m antennas).
- Configuration files for the components of the main array, i.e. core only (94 18m antennas), core + Plains (168 18m antennas).
- Configuration file for the SBA (19 6m antennas).
- Configuration file for the LBA (30 18m antennas).
- Support of the SIMOBSERVE tool, and related tools, to generate simulated observations of relevant astronomical sources.
- Support of the imaging tools in CASA that optimize the array performance (image sensitivity and dynamic range as a function spatial resolution).

6 Open Questions

- Need to better quantify the PSF metric for high fidelity imaging.
- Need further development of imaging and deconvolution algorithms that do not require a Gaussian PSF (i.e. to avoid loss of sensitivity when sculpting the beam).
- Additional performance parameters:
    - Astrometry accuracy: Does other than longest baseline have an impact on it?
    - Pulsar timing: core phasing?
    - Transient searches: non-imaging?
    - May be some relationship between configuration and these capabilities, e.g., the ability to phase the core reasonably, or to perform μas astrometry.

7 Appendix

7.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
BLM	Bureau of Land Management
CDR	Critical Design Review
CoDR	Conceptual Design Review
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic
FDR	Final Design Review
FOV	Field of View
FWHM	Full Width Half Max (of Primary Beam Power)
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goal
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
PSF	Point Spread Function
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SBA	Short Baseline Array
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
TP	Total Power
USFS	United States Forest Service
VLA	Jansky Very Large Array