System Requirements

020.10.15.10.00-0003-REQ

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
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Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	08/10/2016	R. Selina	All	Started first draft. Draws heavily from ALMA Project System Level Technical Requirements, Rev C, dated 2012-12-10.
0.2	08/23/2016	R. Selina	5.1	Updated phase drift analysis after conversation with C. Carilli.
0.3	08/24/2016	R. Selina	6.1, 6.2	Started importing programmatic and functional requirements in to system requirements summary and detail sections.
0.4	08/25/2016	R. Selina	6.3	Started importing performance requirements in to system requirements summary and detail sections.
0.5	10/25/2016	R. Selina	All	Continuing first draft.
0.6	11/21/2016	R. Selina	5.1	Distributed phase/delay error budgets. Calculated coherence table.
0.7	03/10/2017	R. Selina	All	Heavy edit for POP milestone release. Added Key Performance Parameters section.
0.8	03/23/2017	R. Selina	All	Incorporating feedback from E. Murphy and S. Durand. Removed general notes, moved into requirements discussion.
0.9	03/29/2017	R. Selina	5	Incorporating feedback from C. Carilli. Incorporated table from W. Grammer in section 5.11.1. Edits from S. Durand to sections 5.12-5.14.
1.0	03/30/2017	R. Selina	5	Revised imaging dynamic range definition. Added confusion floor requirements. Corrected antenna efficiencies and added secondary operating environment. Refined frequency band definitions.
02	05/08/2018	R. Selina	All	Major update for consistency with latest science requirements, 020.10.15.00.00-0001-REQ, Rev 13 (Draft). Also sync'd with Antenna Specs 020.25.00.00.00-0001-SPE Rev B (Released).
03	05/10/2018	R. Selina	All	Edits throughout before TAC review.
04	11/21/2018	R. Selina	All	Significant edits throughout to incorporate TAC feedback (Lamb, D'Addario, Kantor, Soriano, Weinreb) and RIDs from the IPDSR.
05	12/04/2018	R. Selina	5	Updating traceability to stakeholder requirements now that 020.10.15.01.00-0001-REQ is sufficiently mature. Additional requirements from gap analysis between STK and SYS requirements.

Version	Date	Author	Affected Section(s)	Reason
06	12/05/2018	R. Selina	5, 8	Additional requirements from gap analysis between STK and SYS requirements. Updates to verification table to match.
07	2019-06-01	R. Selina	5.15, 8	Fixed design column in verification table. Corrected mean measure in 5.15.
A	2019-07-22	A. Lear	All	Incorporated minor revisions from M. McKinnon. Prepared PDF for signatures and release.
A.01	2020-03-20	R. Selina	All	Revising for consistency with baselined L0 Stakeholder Requirements. Addressing gap analysis. Integrating calibration requirements, removing conflicting sections. Updated verification to match Requirements Management Plan. Other updates and corrections throughout.
A.02	2020-04-02	R. Selina	All	Completed first pass of gap analysis to Stakeholder Requirements Rev C and sync to Science Requirements Rev B.
A.03	2020-04-15	A. Lear, S. Burleigh	All	Copyedit to ngVLA standards prior to release for Rev B.
A.04	2020-04-16	R. Selina	1, 2.1, 3, 7, 8.	Incorporating feedback from S. Leff. Re-wrote technical measures section for consistency with SEMP. Added new figures by A. Lenox. Updated traceability column relationships. Updated verification tables.
A.05	2020-05-03	R. Selina, M. McKinnon	5, 7, 9	Incorporated clarifications and corrections from MM review.
B	2020-05-04	A. Lear	Tables 8, 18, plus following text; All	Revised band selection from “during slew” to “during settle”; prepared PDF for approvals and signatures.

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1 Introduction

1.1 Purpose

This document and its subsidiaries present the complete set of Level 1 System Requirements that should guide the design of the ngVLA facility. These requirements flow down from the ngVLA Science Requirements documented by Murphy et al. [AD01], and the Stakeholder Requirements [AD02].

The Science Requirements support the Key Science Goals [RD15] defined by the Science Advisory Council (SAC), and were informed by the Science Use Cases [RD16] submitted by the Science Working Groups (SWGs).

The Stakeholder Requirements and its subsidiaries capture programmatic, operational, maintenance, and safety requirements where they drive technical decisions. The Stakeholder requirements also incorporate performance and functional requirements to support non-traditional users such as NASA/JPL and the Near Earth Sensing (NES) community, as well as future commensal data processing systems.

1.2 Scope

The scope of this document is the entire ngVLA facility, from the reception of external signals through to the storage of data products in the archive. The full operational model of the facility is reflected, from the preparation and submission of proposals, to the execution of an observation, and the delivery of data products to users. Necessary features for the maintenance of the facility are also reflected.

Additional system lifecycle requirements, such as technical requirements for features and facilities to enable the integration, verification and commissioning of the system are reflected. However, this document is limited to the technical impact of these requirements on the delivered system – requirements relevant to project scope, schedule, and the conduct of the project are out of scope. For relevant requirements that inform the conduct of the project, please consult the Project Execution Plan [RD20] and its references including AUI/NRAO policies, the NSF Major Facilities Guide [RD21], and the Systems Engineering Management Plan [AD17].

The content of these requirements is at the system level and aims to be implementation agnostic. Some assumptions about the system architecture [AD04] are included here, but only to the degree necessary to unambiguously define the system requirements and enable the derivation of sub-system requirements.

The intended readers of this document are the scientists and engineers who will guide and develop the ngVLA concept. This document is not written in the contractually unambiguous terms necessary for sub-awards and sub-contracts. Rather, the document aims to convey clear intent to the design team, but also notes areas of ambiguity, and stretch goals that improve the overall cost-benefit performance of the system. Lower-level requirements specifications, building upon these system requirements, should select language and structure appropriate for their intended audience.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents apply to this Requirements Specification to the extent specified. In the event of a conflict between the documents referenced herein and the content of this Requirements Specification, the content of the *highest*-level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Reference No.	Document Title	Rev/Doc. No.
AD01	L0 Science Requirements	020.10.15.00.00-0001-REQ
AD02	L0 Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD05	L1 Environmental Specification	020.10.15.10.00-0001-SPE
AD06	L1 System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD07	Requirements Management Plan	020.10.15.00.00-0001-PLA
AD08	Reference Observing Program	020.10.15.05.10-0001-REP
AD09	L0 Safety Requirements	020.10.15.10.00-0004-REQ
AD10	L1 Safety Specification	020.80.00.00.00-0001-REQ
AD11	Calibration Strategy & Requirements	020.22.00.00.00-0001-REQ
AD12	Assembly, Integration and Verification Concept	020.10.05.00.00-0005-PLA
AD13	Commissioning and Science Validation Concept	020.10.05.00.00-0006-PLA
AD14	L1 Security Specification	(In Prep.)
AD15	Observing Mode Framework	020.10.05.05.00-0005-PLA
AD16	Array Configuration Requirements	020.23.00.00.00-0001-REQ
AD17	Systems Engineering Management Plan	020.10.00.00.00-0001-PLA
AD18	Expected Observing Program	(In Prep.)

2.2 Reference Documents

The following documents provide supporting context.

Reference No.	Document Title	Rev/Doc. No.
RD01	EVLA Project Book	
RD02	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo No. 1
RD03	Calibration Strategies for the Next Generation VLA	ngVLA Memo No. 2
RD04	*Interferometry & Synthesis in Radio Astronomy*, Thomson, Moran, Swenson	Second Edition
RD05	Gain Stability: Requirements and Design Considerations	ALMA Memo 466
RD06	Radio Path Length Correction Using Water Vapour Radiometry	R.J Sault, https://arxiv.org/ftp/astro-ph/papers/0701/0701016.pdf
RD07	Convenient Formulas for Quantization Efficiency	A.R. Thompson, *Radio Science*, *42*, RS3022

Reference No.	Document Title	Rev/Doc. No.
RD08	Reliability and MTBF Overview	Vicor Reliability Engineering
RD09	ngVLA Cost Model Memo	V3.0, February 24, 2017
RD10	ngVLA Cost Model Spreadsheet	V3.0, February 24, 2017
RD11	ngVLA Sensitivity	ngVLA Memo #21
RD12	Polarization Calibration with Linearly Polarized Feeds	ngVLA Memo #45
RD13	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106
RD14	RFI Emission Goals on Internally-Coupled Signals	EVLA Memo #104
RD15	Key Science Goals for the ngVLA	ngVLA Memo #19
RD16	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD17	ngVLA Time-domain Correlator Considerations	P. Demorest, 01/05/18.
RD18	ALMA Scientific Specifications and Requirements	ALMA-90.00.00.00-001-B-SPE
RD19	Synthesis Imaging In Radio Astronomy II	ASP Vol 180, 1998.
RD20	ngVLA Project Execution Plan	020.05.00.00.00-0003-PLA
RD21	NSF Major Facilities Guide	NSF 19-68

3 Overview of the System Requirements

This document presents the technical requirements for the ngVLA telescope at the system level. These parameters determine the overall performance of the telescope and the functional requirements necessary to enable the operation and maintenance of the facility.

The Level 1 System Requirements, along with detailed explanatory notes, are found in Section 5. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the verification procedures.

In many cases the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers have a degree of ambiguity or are insufficiently substantiated, this is also documented in the notes. In this way, the trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA concept.

In certain cases parameters are simply noted with a TBD or TBC value. The goal in such cases is to identify parameters that will require definition in future releases of the System Requirements as the associated technical issues are understood.

Section 6 enumerates the Level 2 System Requirements. These requirements are not implementation agnostic and reflect a number of necessary high-level system decisions (such as the number of apertures and their diameters) that impact multiple sub-system requirement derivations. We therefore consider these requirements system-level, but have separately enumerated these requirements and provided traceability to the Level 1 System Requirements. This ensures the integrity of the requirements traceability and enables updates to the associated requirements should these high-level decisions change throughout the design of the facility.

Section 7 identifies performance metrics that will be monitored throughout the conceptual design phase. These are metrics to assist in the trade-off analysis of various concepts, should tensions be identified between requirements.

The following system-level specifications are documented separately and incorporated by reference into this requirements specification:

AD05	*Environmental Specification*	020.10.15.10.00-0001-SPE
AD06	*System EMC and RFI Mitigation Requirements*	020.10.15.10.00-0002-REQ
AD10	*L1 Safety Specification*	020.80.00.00.00-0001-REQ
AD14	*L1 Security Specification*	(In Prep.)

4 Requirements Management

4.1 Requirement Definitions

Consistent with the Requirements Management Plan [AD07], 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)

Requirement Level	Definition
L2	Requirements that define a specification for an element of the system, presuming an architecture (Subsystem Requirements)

4.2 Requirements Flow Down

The Level 1 System Requirements flow from the Level 0 Science Requirements [AD01] and Level 0 Stakeholder Requirements [AD02] for the facility. The relationships between the various requirements documents and contextual "concept" documents are shown in Figure 1.

The Science Use Cases [RD16] were submitted by the Science Working Groups (SWGs) and ranked by the Science Advisory Council to establish a set of Key Science Goals [RD15] for the facility. These Key Science Goals are modeled as a Reference Observing Program and inform the Level 0 Science Requirements.

Experts from throughout the Observatory contributed to the definition of an Operations Concept, defining the desired approach to operating and maintaining the facility. These operational and maintenance requirements, along with programmatic constraints, regulatory requirements and safety requirements are captured in the Level 0 Stakeholder Requirements.

The project-team has defined concepts for the Assembly, Integration and Verification of the facility [AD12], as well as the Commissioning and Science Validation [AD13]. Technical requirements in support of these concepts are captured in these Level 1 System Requirements.

The Science Requirements and Stakeholder Requirements, including its subsidiaries, encapsulate all known Level 0 requirements for the facility. These System Requirements, and subordinates included by reference [AD05, AD06, AD10, AD14], fully encapsulate all known Level 1 requirements.

Individual subsystem specifications (Level 2) flow from the Level 1 System Requirements, and may not always be directly attributable to a single system requirement. For example, phase drift specifications at the system level may be apportioned to multiple subsystems, or a subsystem spec may be in support of multiple higher-level requirements. Completeness of the Level 2 requirements is assessed at the requirements review of each subsystem.

While this is a top-down design process, the process is still iterative rather than a "waterfall" or linear process. The feasibility and cost of requirements implementation lead to trade-offs that feedback to higher-level requirements. The end goal is to build the most generally capable system that will support the KSGs within the programmatic constraints of cost and schedule.

Maintaining enumerated and traceable science requirements, system requirements, and subsystem specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a subsystem specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

The details of the requirements management strategy can be found in [AD07].

4.3 Verb convention

This document uses "shall" to denote a requirement. The verbs "should" and "must" denote desired but not strictly required parameters. "Will" denotes a future happening. Desired but not required features are noted as "desirable" or "goals".

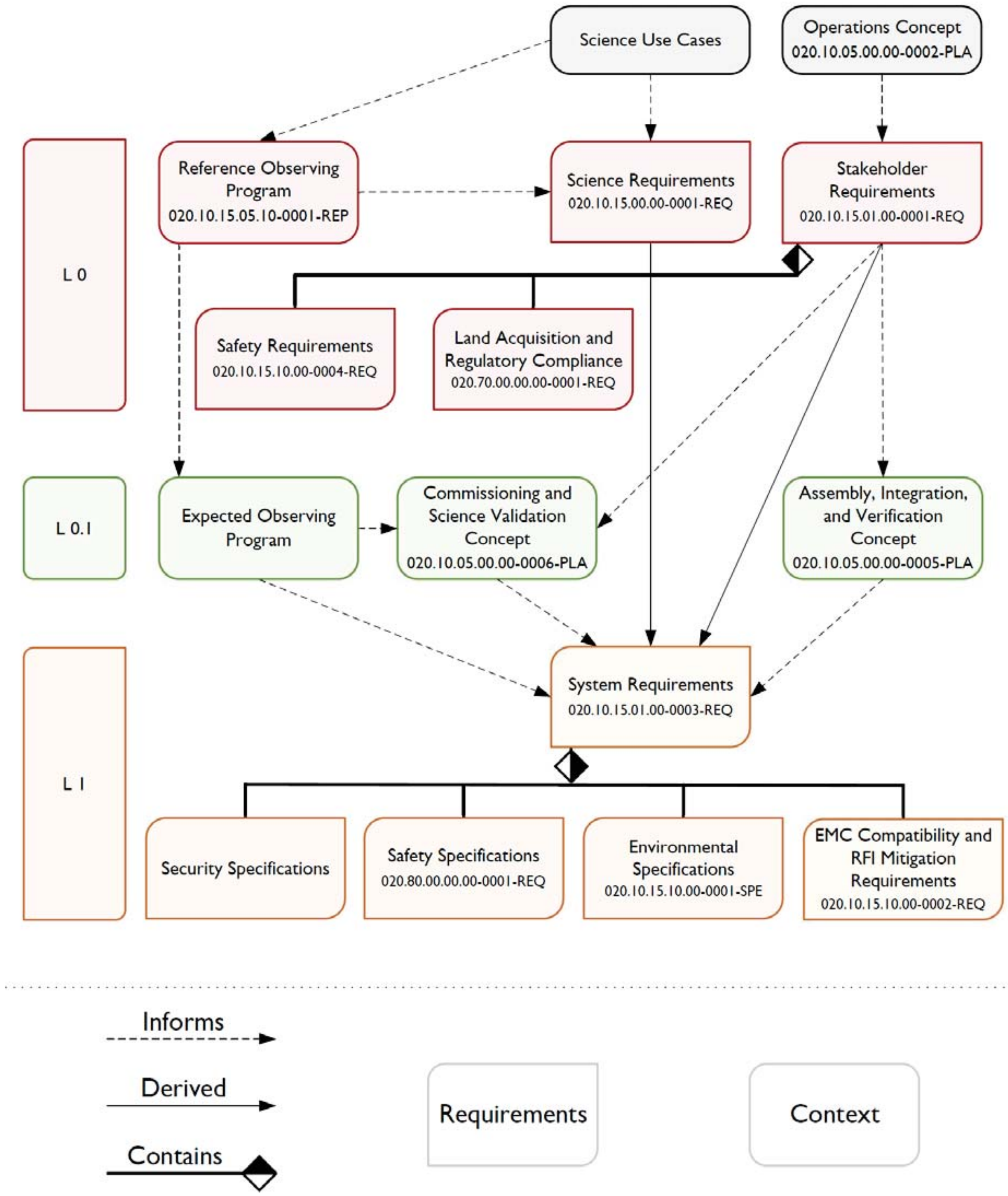

Figure 1 – Requirements flow-down to the ngVLA System Requirements.

5 L1 System Requirements

System-level requirements apply to performance with all operational calibrations applied. The system can be assumed to be fully functioning under the precision environmental conditions (defined in [AD05]) unless explicitly stated otherwise. These requirements are written in an implementation agnostic way to not unduly constrain the conceptual design.

Subsystem requirements apply to performance before operational calibration corrections are applied. The calibration accuracy needed to meet the higher-level system requirements is included in the system requirements notes and is reflected in the functional and performance requirements flow down.

Hardware requirements apply to a properly functioning system under the precision operating environmental conditions. They assume that all system parts that would normally be in place during observations are working within their respective specifications (e.g., HVAC, RTP system).

Requirements traceability is shown to the relevant L0 requirements document, with SCI denoting Requirement IDs in the Science Requirements [AD01] and STK denoting requirements in the Stakeholder Requirements [AD02]. Some requirements are direct pass-through requirements, duplicating high-level requirements that were already adequately detailed. These requirements are noted with the '(copy)' comment in the traceability column.

A limited number of requirements in this document are not implementation agnostic but are consistent with the system architecture and are necessary for requirements derivation and flow-down. These system-level L2 requirements can be found in Section 6.

Note that requirement IDs are static once assigned and therefore not always in sequential order due to subsequent revisions of the associated requirements document.

5.1 Functional Operating Modes

Parameter	Req. #	Value	Traceability
Functional Modes	SYS0001	The system shall provide a set of defined Operating Modes that produce corresponding data products.	[SCI0006, STK0200]
Interferometric Mode	SYS0002	The system shall provide an Interferometric Operating Mode with concurrent computation of cross-correlations and self-correlations for arbitrary numbers of antennas with tunable spectral and time resolution.	[SCI0006]
Phased Array Mode	SYS0003	The system shall provide a Phased Sum Operating Mode that coherently sums the voltage streams from an arbitrary number of antennas and provides a time-tagged voltage data stream with an adjustable phase center on sky.	[SCI0007, SCI0012, SCI0013, STK2801]
Pulsar Timing Mode	SYS0004	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to time a set of dispersed pulse profiles.	[SCI0012]

Parameter	Req. #	Value	Traceability
Pulsar and Transient Search Mode	SYS0005	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to search for dispersed pulse profiles w/o a priori knowledge of their period.	[SCI0013]
VLBI Mode	SYS0006	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is recorded in a VLBI-standard recording format for future processing in a VLBI correlator.	[SCI0017]
Total Power Mode	SYS0007	The system shall provide an Interferometric Operating Mode with computation of self-correlations on-source and off-source to quantify the total power spectral density of a fixed field.	[SCI0104]
On The Fly Mapping Mode	SYS0008	The system shall provide an Interferometric Operating Mode where areas larger than the antenna primary beam are mapped by a continuous scan of the field.	[SCI0004]
Solar Mode	SYS0009	The system shall provide an Interferometric Operating Mode tailored to the observation of sources up to 30dB brighter than the cold sky.	[SCI0016]

5.1.1 Sub-Array Functional Requirements

Parameter	Req. #	Value	Traceability
Sub-Array Capabilities	SYS0601	The system shall be divisible into a minimum of 10 sub-arrays for operation, calibration and maintenance purposes.	[SCI0009]
Phase Preservation	SYS0602	It shall be possible to preserve electronic phase when adding and/or subtracting an element from a sub-array.	[STK1403, STK0902]
Sub-Array Composition	SYS0603	It is desirable that the composition of a sub-array be configurable to any arbitrary combination of antennas from a single antenna to the full array.	[SCI0009]
Sub-Array Operating Modes	SYS0604	It is desirable that any Operating Mode be available in any sub-array.	[SCI0009, SCI0010]
Sub-Array Operating Mode Commensality	SYS0605	The system shall support the commensal sub-array combinations described in Table 1. It is a goal to permit full flexibility in commensal sub-array Operating Modes.	[SCI0010]
Sub-Array Configuration	SYS0606	It is desirable that the configuration of a sub-array be completely independent of all others, permitting different instances and versions of online software between sub-arrays.	[STK1501]
Sub-Array Modification	SYS0607	The system shall permit an Array Operator to add or remove antennas to a sub-array without interrupting an in-progress observation.	[STK0902]

Given the extent of the ngVLA, a significant portion of array observing will likely be conducted in sub-arrays. Many science cases will not require the full angular resolution available, or the weather across the array may be variable. The operations concept also has a continuous maintenance element, so individual elements and sub-arrays will frequently be deployed for testing and/or diagnostic purposes. The atmospheric calibration strategy may also employ sub-arrays. It is therefore critical that adding or subtracting a sub-array element be possible without disturbing the electronic system phase.

As the concept of operation and the calibration strategies are further developed, it is expected that additional sub-array requirements will be identified.

Functional Modes	Interfer.	Phased Array	PA Timing	PA Search	VLBI	TP	OTF	Solar
Interfer. (SYS0002)	Full[1]	Limited[2]	Limited[2]	Limited[2]	Limited[2]	Full[1]	Full[1]	Full[1]
Phased Array (SYS0003)		Full[3]	Full[7]	Full[7]	Full[7]	Limited[2]	Limited[2]	Limited[2]
PA Timing (SYS0004)			Full[4]	Full[7]	Full[7]	Limited[2]	Limited[2]	Limited[2]
PA Search (SYS0005)				Full[5]	Full[7]	Limited[2]	Limited[2]	Limited[2]
VLBI (SYS0006)					Full[6]	Limited[2]	Limited[2]	Limited[2]
TP (SYS0007)						Full[1]	Full[1]	Full[1]
OTF (SYS0008)							Full[1]	Full[1]
Solar (SYS0009)								Full[1]

Table 1 – Required sub-array commensality.

Table 1 Notes:

1. Full flexibility within constraints of the maximum data input to the correlator back-end (Value TBD).
2. Minimum functionality must include full-bandwidth cross-correlation in one sub-array, concurrent with phased array in another. Phased array timing, search, and VLBI capabilities are constrained by SYS0203, SYS0301, SYS0401, and SYS0501.
3. Full flexibility within the constraints imposed by SYS0203.
4. Full flexibility within the constraints imposed by SYS0203 and SYS0301.
5. Full flexibility within the constraints imposed by SYS0203 and SYS0401.
6. Full flexibility within the constraints imposed by SYS0203 and SYS0501.
7. Full flexibility within the constraints imposed by SYS0203, SYS0301, SYS0401, SYS0501.

5.1.2 Interferometric Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Polarization Products	SYS0102	The system shall simultaneously compute both parallel-pol and cross-pol correlations over the full specified bandwidth, and measure all stokes polarization products simultaneously.	[SCI0015]
Autocorrelation Products	SYS0103	It is desirable to provide autocorrelation products for all antennas within the interferometric array concurrent with the cross-correlations.	[SYS3110, SYS3114]
Visibility Weighting	SYS0105	The weight of individual visibilities recorded by the system shall be adjustable before gridding in support of synthesized beam sculpting to the scientific requirements.	[SCI0107]

This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Additional functional and performance requirements follow later in this specification.

5.1.3 Phased Array Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Phased Aperture	SYS0201	The system shall provide phased array capabilities over the full extent of the array (1000km aperture).	[SCI0007]
Concurrent Interferometric Visibilities	SYS0202	The Phased Sum Operating Mode shall support the computation of cross-correlations simultaneous with the phased array capabilities to enable atmospheric calibration. This concurrent interferometric capabilities may have restricted processed bandwidth, spectral and time resolution compared to the mode described in SYS0002.	[SCI0007]
Number of Beams	SYS0203	The system shall support a minimum of 10 beams distributed over 1 to 10 sub-arrays. It is desirable to support 50 beams distributed over 1 to 10 sub-arrays at reduced bandwidth per beam.	[SCI0008, SCI0009]

The need for phased array capability over the full aperture is due to the expected sub-array allocations. E.g., should a subset of stations not be required for an interferometric observation, it may be desirable to phase them for pulsar timing—a mode that is rather indifferent to the shape of the synthesized beam.

5.1.4 Transient (Pulsar) Timing Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Timing Capabilities	SYS0301	The system shall include a back-end timing instrument with a minimum of 5 independent de-dispersion and folding threads. Support for up to 50 de-dispersion and folding threads is desirable.	[SCI0012]
Timing Sys. Bandwidth	SYS0302	The timing system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	[SCI0012]

Parameter	Req. #	Value	Traceability
Timing System Frequency Resolution	SYS0303	The timing system shall support channelization for de-dispersion at a frequency resolution of 1 MHz minimum. Frequency resolution of 50 kHz is desired.	[SCI0012]
Pulse Profile Bins	SYS0304	The timing system shall support a minimum of 2048 pulse profile bins.	[SCI0012]
Polarization	SYS0305	The timing system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations independently and provide full-stokes parameters.	[SCI0012]
Pulse Period	SYS0306	The timing system shall be capable of de-dispersion and folding for pulse periods spanning from 1msec to 30 sec.	[SCI0012]
Dump Rate	SYS0307	The timing system shall record to disk at least every 10 seconds. It is desirable to record to disk every second.	[SCI0012]
Pulse Period Resolution	SYS0308	The time period of the average pulse profile peak (post de-dispersion and folding) shall be reported with an accuracy of 1 usec or smaller.	[SCI0012]

Timing observations refer to observations of sources of known position and pulse period. The array is phased with a beam located at the target source. The signal is processed into the specified frequency resolution, coherently de-dispersed, detected, folded (averaged modulo the known pulse period) into the specified number of pulse phase bins, and recorded at the dump rate.

The target of 50 de-dispersion and folding threads accommodates the most congested fields of view (currently 37 pulsars in a single cluster) and is consistent with the beamforming capabilities expressed in Section 5.1.3. The 8 GHz bandwidth requirement is based on the system's projected band definition. The intent is to ingest the full bandwidth of any receiver operating below 20 GHz.

Additional information supporting these requirement derivations can be found in [RD17].

5.1.5 Transient (Pulsar) Search Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Search Capabilities	SYS0401	The system shall include a back-end search instrument which can process a minimum of 10 beams. It is desirable to process up to 50 beams.	[SCI0013]
Search Sys. Bandwidth	SYS0402	The search system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	[SCI0013]
Search Sys. Frequency Resolution	SYS0403	The timing system shall support channelization for de-dispersion at a frequency resolution better than 1 MHz. Frequency resolution of 100 kHz is desired.	[SCI0013]
Search Sys. Time Resolution	SYS0404	The search system shall have minimum time resolution of 100 µsec. Resolution of 20 µsec is desired.	[SCI0013]

Parameter	Req. #	Value	Traceability
Polarization	SYS0405	The search system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations of each beam independently and provide full-stokes parameters	[SCI0013]

Additional information supporting these requirements can be found in [RD17]. Note that this system doesn't need to include real-time processing capability if the resultant beams can be recorded to disk for post-processing.

5.1.6 VLBI Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
VLBI Recording Capabilities	SYS0501	It shall be possible to record data from a minimum of 3 beams over 1 to 3 sub-arrays in VLBI compliant formats. It is desirable to support this capability for 10 beams distributed over 1 to 10 sub-arrays.	[SCI0017]
eVLBI Capabilities	SYS0502	It is desirable, but not required, to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	[STK2501]

The multi-beam recording capability stems from the projected size of the phased beam. Multiple synthesized beams are required to include both the science target and nearby calibration sources.

This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Additional functional and performance requirements follow later in this specification.

5.1.7 Total Power Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Flux Scale	SYS4401	The autocorrelation products provided in the Total Power Operating Mode shall be linked to a system-provided calibrated flux density reference.	[SCI0104, SCI0110]
Autocorrelation Integration Intervals	SYS4402	The system shall have the capability of bracketing and integrating autocorrelation power around a pointing position at flexible time intervals based on on-source status or a trigger signal (such as a noise diode cycle).	[SCI0104]
PSD Differencing	SYS4403	The system shall be capable of automatically differencing the power spectral density of two pointing positions, or system states, to yield a field power spectral density.	[SCI0104]

This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Additional functional and performance requirements follow later in this specification.

5.1.8 On The Fly Mapping Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Variable Slew Rates	SYS5700	The system shall support using the Interferometric Operating Modes at super-sidereal tracking rates.	[SCI0004]

Parameter	Req. #	Value	Traceability
Phase Center Update Rates	SYS5701	The system shall permit updating the interferometric phase center at a rate of 10 Hz or faster. Goal of 20 Hz.	[SCI0004]

The OTF Mapping operating mode functional requirements also include the Interferometric Operating Mode Functional Requirements listed in Section 5.1.2. This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Additional functional and performance requirements follow later in this specification.

5.1.9 Solar Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Direct Solar Observations	SYS5800	The system shall be capable of safely and directly observing the sun at all frequencies, without the risk of equipment damage.	[SCI0016]

The Solar operating mode functional requirements also include the Interferometric Operating Mode Functional Requirements listed in Section 5.1.2. This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Additional functional and performance requirements follow later in this specification.

5.2 Observing Modes

Parameter	Req. #	Value	Traceability
Standard Observing Modes	SYS3001	Each functional Operating Mode shall have one or more Standard Observing Modes that can generate observing instructions based on PI-defined scientific requirements and produce quality-assured data products.	[STK0700, STK0701]
Number of Standard Observing Modes	SYS3002	Standard Observing Modes shall be developed to execute all planned observations in support of the KSG science use cases, as defined in the Reference Observing Program (AD 08).	[STK0700, STK0701, STK1000]
Non-Standard Observing Modes	SYS3003	Interfaces shall be provided for advanced users to access Non-Standard Observing Modes, to directly generate observing instructions for each functional Operating Mode processed by the system, and to record basic data products.	[STK0702]
Triggered Observations	SYS3004	The system shall include interfaces to receive external (network) triggers to execute previously approved Standard Observing Mode and Non-Standard Observing Mode instructions.	[SCI0005]
Triggered Observation Response	SYS3005	The system shall process a trigger and begin an observation (be configured and on source) in a period not to exceed 10 minutes, with a goal of 3 minutes or less.	[SCI0005]
Trigger Override	SYS3006	The trigger response mechanism shall provide a human Array Operator Override. The Override shall time-out and execute the triggered observation if the observation is not canceled within 60 seconds.	[SCI0005]

The definition of the Standard Observing Modes and the associated requirements for observation execution and data processing will be documented as part of the Observing Mode Framework [AD15] and reflected at a lower level of this requirements hierarchy.

5.3 Data Products

The array will have a progressive series of data products suitable for different user groups. The data products may change based on how well supported an Observing Mode (see SYS0001, SYS3001) is. Common modes should have higher-level data products that add value to the user, while clearly not all permutations can benefit from such a degree of automation.

5.3.1 Low-Level Interferometric Data Product Requirements

Parameter	Req. #	Value	Traceability
Uncalibrated Data	SYS0701	The uncalibrated visibilities, as provided by the online system after required averaging, shall be recorded to disk in a standard format inclusive of meta data necessary for calibration (spec. TBD).	[STK1100]
Flagged Data Table	SYS0702	A flagging table shall be provided along with the visibility data to mark data that is suspected to be corrupted. Causes to be flagged include, but are not limited to, antenna off-source, RFI, or other known issues that would affect data integrity.	[STK1100, STK1102]

This section focuses on data products produced from interferometric observations. These low-level products shall be generated for all observations in the relevant functional Operation Modes defined in Section 5.1.

As with the VLA, the fundamental data product to be archived are uncalibrated visibilities. The online software system shall also produce flags to be applied to the visibilities that would identify known system problems such as antennas being late on source or the presence of RFI. A calibration pipeline should also produce calibration tables that compensate for direction-independent instrumental and atmospheric effects in phase, gain, polarization, bandpass, flux scale, etc., for observations using Standard Observing Modes.

5.3.2 High-Level Interferometric Data Product Requirements

Parameter	Req. #	Value	Traceability
Calibration Pipeline	SYS0703	For Standard Observing Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed that produces a calibration table to apply direction-independent corrections that were supported by the observation, including: delay/phase, gain/amplitude, polarization, and bandpass corrections.	[STK1000]
Imaging Pipeline	SYS0721	For Standard Observing Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed resulting in a calibrated image cube.	[SCI0020, STK0512]

Parameter	Req. #	Value	Traceability
Quick Look Image Pipeline	SYS0722	For triggered observations, there shall be a standard data reduction performed resulting in a continuum image, processed in a time duration equal to or less than the observation duration.	[SCI0020]

To reduce the burden on users, outputs from Standard Observing Modes will offer higher-level data products that users would typically generate today. This will also enable the facility to support a wider user base, possibly catering to astronomers who are not intimately aware of the nuances of radio interferometry, thus facilitating multi-wavelength science.

The high-level data products are difficult to define, and may be different for individual PIs and the data archive. One astronomer may be interested in imaging only a limited field, but the most reusable data product, suitable for the archive, might be a full-field image. In general, the operations concept favors generating high-level data products that are tailored to the archive for Standard Observing Modes.

ngVLA data will be delivered, by default, as Science Ready Data Products (SRDP). The NRAO SRDP Project is presently defining proposal submission criteria, data processing, and archiving structures. Proposals on all NRAO instruments will conform to SRDP requirements to benefit from publication-ready data. These SRDP structures are expected to mature within the VLA and ALMA to the point of routine operations by the time ngVLA is commissioned. Archive requirements that follow will also support SRDP delivery.

5.3.3 Pulsar Timing and Search Data Product Requirements

Parameter	Req. #	Value	Traceability
Pulsar Timing Data Product	SYS0741	For the Standard Observing Modes within the Transient Timing operating mode, dispersion measures, dedispersed pulse profiles and periods shall be generated and recorded in PSRFITS format. (TBC)	[SCI0012]
Pulsar Search Data Product	SYS0742	For the Standard Observing Modes within the Transient Search operating mode, dispersion measures, dedispersed pulse profiles and periods shall be generated and recorded in PSRFITS format. (TBC)	[SCI0013]

5.3.4 Data Archive Requirements

Parameter	Req. #	Value	Traceability
Data Delivery via Observatory Archive	SYS0730	Data products shall be delivered to the Principal Investigators through an Internet-accessible Observatory Science Data Archive.	[STK1106 (copy)]
Archive Period	SYS0731	All low-level data products shall be archived for the life of the facility (as defined in SYS2801).	[STK1106, STK1102]
Archive Products - High-Level	SYS0732	All high-level data products, such as calibration tables and image cubes, shall be archived for the life of the facility (as defined in SYS2801).	[STK1100]

Parameter	Req. #	Value	Traceability
Proprietary Data Rights	SYS0733	The archive shall permit the enforcement of a proprietary period for both low-level and high-level data products, permitting public access only after the proprietary period lapses.	[STK1103]
Archive Batch Reprocessing	SYS0734	The archive shall include an interface for batch re-processing of visibilities and to replace existing low-level and high-level data products.	[STK1102]
Archive Backup	SYS0735	A full backup (two copies total) of all archived data shall be incorporated into the design. The two copies shall not be collocated/co-managed to reduce the risk of simultaneous failures.	[STK1100, STK1106]
Archive User Reprocessing	SYS0736	The system shall include an interface for users to request limited reprocessing of data within supported Standard Observing Modes.	[STK1101, STK1102]
Archive Image Selection	SYS0737	The Archive user interface shall allow users to inspect and select image data for download.	[STK1101 (copy)]
Proprietary Period	SYS0738	The proprietary period shall be tunable on a per-class, per-project and per-scan basis.	[STK1103, STK1105]
Archive Products - Low-Level	SYS0739	All low-level data products, such as visibilities and flagging tables, shall be archived for the life of the facility (as defined in SYS2801).	[STK1100]
External Data Products	SYS0740	The Data Archive shall have provisions for accepting user-produced data products where those products can be quality assured by the Observatory (such as products from Large projects or Legacy projects). In such circumstances the Observatory will approve the user QA process, not the individual products.	[STK1104 (copy)]
Proprietary Period Trigger	SYS0743	The proprietary period counter shall start once the data products have undergone any automated or manual quality inspections and are made available to the principal investigator.	[STK1103]

The data archive has the high-level goal to function as a science multiplier, making data collected by one PI available to another after a proprietary period lapse. Making data available through the archive eliminates duplicate observations and maximizes opportunities for the community to make discoveries from historical observations. It also incentivizes the first PI to publish their work prior to the end of the proprietary period. Both effects boost the array's scientific productivity.

Similar to VLA practice, all low-level data products should be archived for the life of the facility. These fundamental data products can be broadly reused and their storage is consistent with broad archive goals.

The storage requirements for high-level data products are less clear. These may need to be tailored to the individual science case proposed by the PI, which may reduce reuse opportunities. The broad goal is that reusable high-level data products will be archived along with the visibilities, but which products might meet this criteria is not yet defined. High-level data product storage requirements should be revisited after the SRDP project defines their overall requirements.

5.3.5 Data Processing Requirements

Parameter	Req. #	Value	Traceability
Data Processing for Standard Observing Modes	SYS0750	For Standard Observing Modes, data processing shall be executed via an automated pipeline that generates the high-level data products (SRDP) for the given mode.	[STK0512]
Data Processing Resources	SYS0751	The system shall provide data processing resources (both software tools and compute capacity) to generate the high-level data products from Standard Observing Modes.	[STK1000, STK1202, SCI0020, STK0512, STK1001, STK1002]
Throughput & Latency	SYS0752	The data processing capacity for high-level data products shall be designed for 1.2 times the expected average system throughput (defined in the Expected Observing Program), with no additional constraint on latency. The additional 20% is allocated to expected data reprocessing.	[STK1001, STK1002, STK1004]
Heterogeneous Arrays	SYS0753	The data processing system shall support data reduction from heterogeneous arrays.	[STK1002]
Processing Triggers	SYS0754	The system shall provide a mechanism to trigger the immediate processing of an observation.	[SCI0020]
Processing Priorities	SYS0755	The system shall provide a mechanism to set differing processing priorities for the SRDPs associated with a project.	[SCI0020]
Processing in Place	SYS0756	User interface tools to ngVLA data shall permit processing the data in place rather than transferring the data across the Internet for processing and analysis by users.	[STK1005 (copy)]
Support for Legacy Programs	SYS0757	The system shall include interfaces to support generating SRDPs for Large and Legacy scale projects, if the project SRDPs can be generated within available compute resources. Large and Legacy scale projects will identify data processing requirements and resources, and may require additional computing resources to be made available from non-Observatory sources in order to be scheduled.	[STK1004 (copy)]
Interactive Processing	SYS0760	The system shall provide interfaces to, and tools to process, the visibility data outside of the automatic, non-interactive processing model that is needed for Standard Observing Modes in Full Operations.	[STK0523 (copy)]

5.3.6 Data Analysis Requirements

Parameter	Req. #	Value	Traceability
Data Analysis Resources	SYS0761	The system shall provide data analysis resources (both software tools and compute capacity) for users to inspect and analyze the high-level data products from Standard Observing Modes.	[STK1201]
Data Quality Assurance	SYS0762	The system shall include the analysis tools and interfaces to enable Observatory quality assurance inspections of data products prior to delivery to users.	[STK1102, STK1104, STK1200]

5.4 Commensal Data Processing Requirements

Parameter	Req. #	Value	Traceability
Commensal Processing	SYS5600	It is desirable to provide a connection for future commensal processing of visibilities (e.g., transient search) at the native temporal resolution of the observation (prior to any time or frequency averaging).	[SCI0013, STK2901]
Commensal Voltage Streams	SYS5601	It is desirable to provide interfaces to enable commensal processing of the time-voltage stream from each antenna at the granularity of a digitized sub-band or smaller unit of bandwidth.	[STK2901]
Commensal Low-Frequency System	SYS5602	It is desirable to provide physical interfaces, data transmission and correlator bandwidth for a future commensal low-frequency (<1 GHz) front end.	[STK2900]

5.5 Support Datastores

Parameter	Req. #	Value	Traceability
System Calibration Database	SYS3400	A System Calibration database shall be provided to store antenna-based calibration parameters such as gain curves and polarization D-terms.	[STK1150 (copy), STK1300, STK9950]
Astronomical Calibrator Database	SYS3401	An Astronomical Calibrator database shall be provided to store calibrator flux density histories and image models.	[STK9943 (copy), STK9950]
Monitor Database	SYS3402	A monitor database shall be provided to store system status and history for each monitor point in the array.	[STK5002, STK9950]
RFI Database	SYS3403	An RFI database shall be provided to store signal parameters for previously identified interference sources.	[STK2602, STK9950]
Quality Control Database	SYS3404	A quality control database shall be provided to record repairs, test data, and associated information on each LRU.	[STK1900, STK9950]

5.6 Interfaces to External Systems

Parameter	Req. #	Value	Traceability
External eVLBI Elements	SYS5900	It is desirable to provide interfaces to connect up to 10 external eVLBI elements to the real-time ngVLA signal processing system.	[STK2501]
Trigger Subscriptions	SYS5901	The system shall support interfaces to the detection streams from flagship facilities (such as LSST and LIGO) that will generate observation triggers.	[SCI0005]

5.7 Frequency Range and RF Coverage

Parameter	Req. #	Value	Traceability
System Frequency Range	SYS0801	System frequency range shall cover, at a minimum, the 1.2 to 50 GHz and 70-116 GHz windows.	[SCI0001]
Optimized Frequency Range	SYS0802	Sensitivity shall be maximized above 8 GHz.	[SCI0100, SCI0102, STK2801]
Freq. Span A:	SYS0803	1.2-8 GHz.	[SCI0001, SYS0801]
Freq. Span B:	SYS0804	8-50 GHz	[SCI0001, SYS0801]
Freq. Span C:	SYS0805	70-116 GHz	[SCI0001, SYS0801]
Continuity of Frequency Coverage	SYS0806	There shall be no gaps in frequency coverage within frequency spans (A, B, C) listed above. It is a goal that any band edges include at a minimum 1% overlap in bandwidth.	[SCI0001, SCI0002, SCI0003]

While the system shall access all available frequencies in the 1–116 GHz range, the 8–50 GHz range (Frequency Span B) has the most demanding sensitivity requirements (Section 5.9), so system performance should be optimized for these frequencies. Note that these frequency spans are not “bands” and are not meant to imply a specific receiver configuration. The frequency span division is due to atmospheric windows and different priority levels.

Span A is the lowest priority given its overlap with the SKA1 baseline design. However, these low frequencies are still required for KSG4 and KSG5 and must be supported by the ngVLA.

5.8 System Bandwidth and Frequency Tunability

Parameter	Req. #	Value	Traceability
Front End Bandwidth Ratio	SYS0901	A minimum receiver bandwidth ratio of 1.5:1 is required, with a 3:1 goal over Frequency Span A.	[SCI0100, SCI0102]
Instantaneous Digitized Bandwidth	SYS0902	It is desirable for the system to digitize the full bandwidth of each receiver band.	[SCI0003, SCI0100]

Parameter	Req. #	Value	Traceability
Total Instantaneous Processed Bandwidth	SYS0903	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	[SCI0100]
Sub-Bands	SYS0904	If the digitized bandwidth exceeds the instantaneous transmitted and processed bandwidth, the system shall separate the digitized bandwidth into sub-bands for bandwidth selection, transmission and processing.	[SCI0003]
Frequency Tunability	SYS0905	If the front-end bandwidth exceeds the instantaneous transmitted and processed bandwidth, it shall be possible to select discontinuous sub-bands for transmission and processing. For example, transmitting both the top and bottom of the 70-116 GHz band.	[SCI0003]
Fixed Analog Tunings	SYS0906	While supporting the Frequency Tunability requirement (SYS0905), the analog system setup options shall be minimized to facilitate calibration from catalog values.	[STK1403]
Sub-Band Step Size	SYS0907	Sub-band bandwidth selection shall have a granularity of 250 MHz or smaller.	[SCI0003]
Band Switching Time	SYS0908	Switching between any receiver bands shall be achievable within 20 seconds. Goal of less than 10 seconds.	[SCI0018]
Contiguous Bandwidth	SYS0909	Any bandwidth division for transmission and processing shall not create gaps in frequency coverage.	[SCI0003]

The Front End bandwidth ratio is most important at lower frequencies where total instantaneous bandwidth will be limited by the receiver rather than the data transmission system. The 20 GHz/pol instantaneous bandwidth goal is consistent with the expected bandwidth of the highest frequency receiver (Band 5) in Frequency Span B (30–50 GHz). The 14 GHz requirement approximates the expected Band 4 receiver. If the span of these receivers changes, the instantaneous sampled bandwidth requirement and goal should be adjusted to match.

If the full bandwidth of the front end is sampled, any tuning or filtering is expected to be digital only, and implemented to minimize data transmission and processing costs. Tunability within the correlator will be required to trade off bandwidth for spectral resolution. If less than the full receiver bandwidth is sampled, a mechanism must be in place to select any frequency over the observable window (e.g., tuned LOs). Any minimum tuning step size should be restricted by SYS0907.

5.9 Sensitivity Requirements

Parameter	Req. #	Value	Traceability
Effective Area/Tsys Ratio	SYS1001	The effective area/Tsys ratio of the system shall meet or exceed the values given in Figure 1 while operating in the precision environmental conditions defined in 020.10.15.10.00-0001-SPE and assuming 1 mm of PWV. This requirement must be met over 80% of the bandwidth of any given receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106]

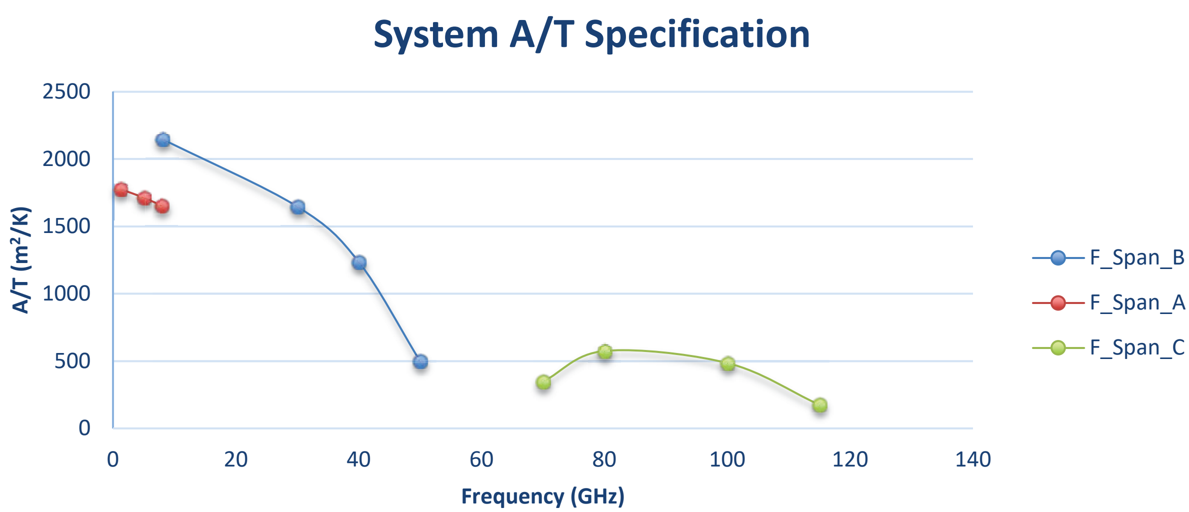

Figure 2 – System A/T specification in m²/K.

Frequency (GHz)	1.2	5	7.9	8	30	40	50	70	80	100	115
Min A/Tsys (m²/K)	1780	1710	1650	2150	1650	1240	500	350	570	490	180

Table 2 – System A/T specification in m²/K

The driving sensitivity requirement is for raw system sensitivity measured in m²/K [SYS0501]. The values in Figure 1 are based in part on expected degradation in aperture efficiency as a function of frequency and achievable system temperatures. Note that deviations at the edges of each receiver band are expected and allowable.

When considering parameters that affect ngVLA antennas' effective collecting area or the overall system temperature, this is the measure that should remain constant and the parameters can be traded against each other (e.g., increasing effective area to accommodate an increase in T_{sys}). In the event that scope contingency is required to fit within cost constraints, this sensitivity requirement may be relaxed.

5.10 System Field of View

Parameter	Req. #	Value	Traceability
Instantaneous Field of View	SYS1101	The system instantaneous FOV (FWHM), when scaled by center frequency, shall be larger than 2 arcmin at 28 GHz.	[SCI0106, SCI0104]
Accessible Field of View	SYS1102	The system shall be capable of observing at elevations of 12° to 89°, relative to the local horizon.	[SCI0019]
Slew Rates	SYS1103	The system shall be capable of slewing to any position within the accessible field of view in less than 2 minutes of time.	[SCI0005]
Tracking Rates	SYS1104	The system shall be capable of tracking objects and mapping an area of sky at 10x sidereal speeds when under 70 degrees in elevation.	[SCI0004]

Based on the system's survey speed requirements and projected sensitivity, the FOV must be greater than 2 arcmins @28 GHz, corresponding to an 18 meter aperture with a taper coefficient of 1.02.

5.11 Dynamic Range

Parameter	Req. #	Value	Traceability
Input Dynamic Range	SYS1201	The analog dynamic range of the receiving electronics shall have a minimum of 30dB of headroom, defined at the 1dB compression point. Goal to achieve spec at 1% compression point.	[SCI0016]
Gain Calibration System Dynamic Range	SYS1202	Any gain and bandpass calibration strategy shall also accommodate a 30dB change in system temperature, so any gain calibration signal injection requires a variable input power range of at least 30dB.	[SCI0016]
Provision of Variable Attenuators	SYS1203	The system shall provide variable attenuators that accommodate the dynamic range specified in SYS1201, while maintaining the minimum number of bits specified in SYS1035.	[SCI0016]
Input Protection	SYS1204	The system shall survive exposure to signals at large as 55 dBm EIRP at a distance of 100m through sidelobes (G=1) with no damage to the receiving elements.	[STK2601]
High-Noise Path	SYS1205	It is desirable to provide a high-noise / low-gain path that permits reception of signals outside the dynamic range requirement specified in SYS1201.	[SCI0016]

The dynamic range requirements flow down from both solar observations and mitigating the impacts of RFI. Dynamic range in this case will be defined as 1 dB compression to the system noise.

Solar requirements depend to some degree on the definition of the sun, given the large differences in output power as a function of solar activity. For the quiet sun at 5780K, and a system temperature of 30K, the implied analog dynamic range is about 23 dB. With an antenna SEFD of 300 Jy and an active sun definition of 10^8 Jy, an analog dynamic range of up to 55 dB could be required for the active sun. For the strongest signals, a high-noise path (bypassing the LNAs) would therefore be desirable.

The Input Protection requirement is based on vehicular radar, which is permitted 55 dBm EIRP over the 76–77 GHz band. It likely represents a worst-case interfering signal in terms of power, other than a cell phone over the horn input during service.

5.12 Spatial Resolution and Spatial Frequency Coverage

Parameter	Req. #	Value	Traceability
Longest Baseline	SYS1301	The longest baseline between antennas in the main array shall be greater than 700 km with extended baselines (VLB) out to 8800 km.	[SCI0103, SCI0118]
Shortest Baseline	SYS1302	The shortest baselines between antennas shall be 22 m or less, with a goal of 10 m.	[SCI0104]
Zero Spacing / Single Dish Total Power	SYS1303	It is a goal that the system measure total power spectral density in the field, with apertures larger than 1.5x the shortest baseline.	[SCI0104]
Integration Time Ratios	SYS1304	If achieving SYS1302 requires multiple array/antenna designs, each array shall sample overlapping spatial scales. The ratio of integration time on one array to the other on these overlapping scales shall not exceed a factor of four, with a goal of matched integration times.	[STK1403]
Fraction of Occupied Cells	SYS1306	The system shall fill at least 50% [TBC] of (u,v)-cells before gridding out to 50 km baselines in a snapshot continuum observation traversing the meridian with a 1,000k x 1,000k pixel grid. Goal to approach this fill ratio out to 700 km scales.	[SCI0106, SCI0108, SCI0109, SCI0107]
Distribution and Weighting of Visibilities	SYS1308	The system shall 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 100 m to 700 km baselines on an 8 hr observation about the meridian. Geometric mean of weights shall also be better than 0.05 at scales corresponding to 8600 km baselines.	[SCI0100, SCI0102, SCI0103, SCI0108, SCI0118, STK2800, SCI0107]
Collecting Area on VLB Baselines	SYS1309	The system shall provide a minimum of 6000 m^2 of collecting area on the VLB-scale baselines.	[SCI0117, STK2800]

Computation for maximum and minimum baseline corresponds to the required resolutions with a taper coefficient of 1.2. The distribution of spatial frequency samples and their associated weights have significant implications for the array's physical configuration and overall system efficiency. The array must be constructed accounting for practical considerations like geological features, land ownership, proximity to population centers, etc. An idealized power-law distribution for an array of 700 km+ in extent is not practical. However, such a distribution is the standard by which the achievable array should be judged and measured, and should be achievable on 36 km scales.

Non-unity weighting of array elements contributes to a loss of observational efficiency. Depending on the angular resolution of interest and the ideal synthesized beam, such non-unity weights will be required. The shortest baseline requirement will most likely require a separate array of smaller apertures in addition to the main array. The single dish provides total power (power spectral density, PSD) measurements that fill in the "zero-spacing" point of the UV plane. The single dish should sample scales smaller than the shortest interferometric baseline to minimize gaps in angular scale, enable relative calibration, and resolve large-scale structures faithfully.

The Fraction of Occupied Cells metric attempts to quantify the snapshot imaging fidelity on scales >100 mas @ 20 GHz (SCI0109). A 50 km baseline accommodates a taper coefficient of 1.2 while achieving the specified resolution. A 100,000 x 100,000 cell grid constrains the pixel size to ~20 m, approximating the antenna diameter. Please consult [RD18] for additional information on this metric.

A full derivation and collection of the array configuration requirements is available in [AD16].

5.13 Spectral Resolution

Parameter	Req. #	Value	Traceability
Highest Spectral Resolution	SYS1401	The available spectral resolution shall be finer than 1 kHz/channel. Goal of 400 Hz/channel.	[SCI0105]
Number of Spectral Channels	SYS1402	A minimum of 240,000 channels shall be supported by the correlator and post processing systems, across all baselines, with four products per baseline (full stokes). Goal of 2,000,000 channels to be supported by the correlator.	[SCI0105]
Flexible Spectral Resolution	SYS1403	The spectral resolution shall be tunable to permit variable resolution across the observed band, increasing the instantaneous processed bandwidth while providing high spectral resolution over defined sub-bands.	[SCI0105, SCI0006]
Doppler Corrections	SYS1404	The system shall include a method to correct/set Doppler corrections to a common reference frame.	[SCI0105]

The spectral resolution requirement defines the minimum channel bandwidth required for spectral line observations.

A spectral resolution of 0.1 km/s at 1.2 GHz is the limiting case from the science requirements (SCI0105) for spectral line resolution, and corresponds to a channel width of about 400 Hz. At 3.2 GHz (the lowest center frequency where 4 GHz of bandwidth could plausibly be sampled), the corresponding channel width is 1 kHz, necessitating about 400k channels to ingest that broad of a bandwidth. Note that this is the goal associated with the science requirement, so a lower number of channels is acceptable.

Time and bandwidth smearing at the longest baselines also set limits, if imaging the full field of view is also required. (While there is no scientific reason to do this, there are calibration cases). For time and bandwidth smearing, the maximum channel width is defined as:

$$\Delta\nu_{channel} = \beta\, \nu_{low}\ D/B_{max}$$

where ν_{low} is the lowest frequency in the band, D is the antenna diameter, and B_{max} is the longest baseline.

The unitless parameter β is used to characterize the acceptable amount of time and bandwidth smearing:

$$\beta = \frac{\Delta\nu}{\nu}\frac{d\theta}{\theta_{beam}} = \delta t \omega_{earth}\frac{d\theta}{\theta_{beam}}$$

Here $\frac{d\theta}{\theta_{beam}}$ is the fraction of the primary beam to be imaged. Actual calculation of the effects of time and bandwidth smearing depend on the source and field structure. A value of β = 0.5 is used as a simple parameterization. A more rigorous quantification of beta should be based on the required imaging fidelity, depending on source and field structure.

For β = 0.5, $\nu_{low} = 1.2\ GHz$, $D = 18\ m$, and $B_{max} = 1000\ km$, the maximum channel width is 10 kHz. Spanning 2.4 GHz of bandwidth would require about 240k channels. This figure will be adopted as the minimum requirement. The goal of 2,000k channels will support imaging at VLB scales over the full field of view ($B_{max} = 8600\ km$), blind spectroscopic surveys over a wider digitized bandwidth, as well as on-the-fly mapping modes. This will provide long-term flexibility and system extensibility.

Doppler setting to a common reference frame is required because the spectral resolution supports velocity resolutions (100 m/s velocity resolution per SCI0105) that are small relative to the motion of local array coordinate frames (i.e. earth rotation and earth orbit).

5.14 Delay and Phase Stability Requirements

Parameter	Req. #	Value	Traceability
Delay/Phase Variations Magnitude	SYS1501	The delay variations caused by the instrument shall be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied.	[STK1402, STK1403, SCI0100]
SNR Loss to Delay/Phase Variations	SYS1502	The instrumental delay/phase noise shall not degrade overall system SNR by more than 1%.	[SCI0100, STK1403]
Phase Noise	SYS1503	Total instrumental integrated phase noise shall not exceed 132 fsec rms.	[SYS1502]
Phase Drift Residual	SYS1504	The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds.	[SCI0111]
Absolute Phase Drift	SYS1505	The absolute phase drift per antenna over 300 seconds shall not exceed 8 psec. Goal to meet this specification over 1000 seconds.	[SCI0111]

Delay and phase stability are closely related. A delay change produces a signal phase change that is proportional to frequency, arising from change in cable length, for example. Alternatively, all frequencies in a bandpass range can be shifted by the same phase if the phase of a local oscillator experiences a phase shift.

In these requirements, the expression "delay/phase" will be used for both situations, a path length or LO change. The time units express delay/phase stability, typically in femto-seconds (fsec; 10^{-15} seconds). The resulting phase change can always be found by multiplying the delay by the appropriate frequency.

Variations in the instrumental delay/phase cause two effects:

- Loss of coherence and thus of sensitivity due to fluctuations faster than the elementary integrating time (**delay noise**), and
- Errors in the phase of the calibrated visibility measurements due to fluctuations on longer time scales (**delay drift**), up to the length of a full calibration cycle, which introduce imaging errors and limit the imaging dynamic range.

For the requirements given here, the time scale division between delay/phase **noise** and delay/phase **drift** is defined as 1 second. Variations in instrumental delay/phase (both noise and drift) arise from changes in the electronic equipment signal path and in various mechanical structures. These can be separated into two types:

- Variations that are a function of time, usually thermally or wind induced, and
- Variations that are a function of antenna pointing angle, usually due to cable movement or twisting, structural deformations under changing gravity vector, or equipment deformation.

Delay/phase variations as a function of antenna pointing angle further separate into systematic and random changes. By definition, random changes will tend to average towards zero with repeated observations, while systematic changes do not decrease, are more damaging, and should have a different constraint level. Different requirements are necessary for small angle changes that impact phase calibration and large angle changes that impact antenna position determination and astrometric observations.

The large angle variations can be estimated from the residual phases after an antenna position determination; however, some systematic instrumental errors may be subsumed into any single antenna position solution. It is assumed that the temporal and antenna pointing angle phase error contributions are independent and therefore RSS additive. If this proves not to be the case, the derivation and allocation of error contributions throughout the system (i.e. the error budget) should be revised.

For both delay/phase changes with angle and with time, the quantity measured is the delay/phase difference of the signals processed through two antenna systems. Making the assumption that the phase variations in the two antennas are uncorrelated and RSS additive, $1/\sqrt{2}$ of the measured delay/phase difference will be taken as the delay/phase variation of each individual antenna. In these requirements, the limits on delay/phase variations always refer to the per antenna variations.

A distinction is made between the *absolute* drift and any *residual* noise after subtraction of a linear fit (removing the known absolute drift via astronomical calibration). The absolute drift specification aims for less than 2π drift over a calibration cycle. The goal of these requirements is to always allow for removal of predictable slow instrumental drifts.

5.14.1 Establishing Temporal Delay/Phase Stability Requirements

The requirements on temporal delay/phase noise and drift, on time scales up to 300 seconds, flow from the two high-level requirements:

1. The delay variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. These natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied.
2. The instrumental delay/phase noise shall not degrade the overall system SNR by more than 1%.

Limiting the phase/delay drift of the instrument in this way ensures that the imaging dynamic range, without the use of self-calibration techniques, is not limited by the instrument systematics. The full imaging dynamic range specified by the science requirements is then reached by self-calibration. These details are further explored in the Calibration Strategy and Requirements [AD11].

Tropospheric fluctuation statistics at the VLA site are available from decades of observations. Simulations, using a range of atmospheric conditions, estimate the effects of rapid phase referencing to a nearby calibrator (fast switching; see [RD02]).

Five observing and phase calibration techniques have been considered for the ngVLA and are documented in [RD03] as well as [AD11]. For the purpose of establishing phase stability requirements, these can be split into three cases:

- Single frequency fast switching: phase calibrator observations are rapidly interspersed with target source observations at cycle time T_1, with both at the same frequency.
- No fast switching with WVR: a phase calibrator is observed at interval T_2, and at the same frequency as the target. Another mechanism such as a WVR is used to correct tropospheric phase perturbations.
- Reference array or paired elements: a phase calibrator is observed at interval T_2, possibly at a different frequency than the target. Separate adjacent antennas observe the science target and a nearby phase calibrator to correct tropospheric phase perturbations on shorter time scales.

These lead to different atmospheric delay/phase residuals and thus different delay/phase stability requirements. The more stringent requirements are then selected to define the system-level requirements.

In Case 1, the requirements are based primarily on simulations with $T_1 \cong 30$ seconds. The fast switching calibrator observation simultaneously removes the tropospheric delay fluctuations and the instrumental phase, so the delay/phase drift is important for intervals T_1 ~30 seconds.

In Case 2, the calibrator observation cannot effectively remove the tropospheric fluctuations and serves mainly to calibrate the instrumental phase. It applies, for example, if the tropospheric effects are negligible or have been corrected by other means (e.g., WVR measurements). Then the instrumental phase drift at the single frequency is important at the calibration interval T_2 ~300 seconds.

ALMA experience shows that for fast fluctuations on time scales $\gtrsim$1 second, corrections based on water vapor radiometry alone produce residuals comparable with fast switching alone, so Case 1 and Case 2 may be equally stringent. Given the increased water vapor at the VLA site, comparable performance of a 22 GHz WVR is optimistic, but this leads to a conservative delay/phase stability specification.

In Case 3, the reference antenna or paired antenna is used to compensate for tropospheric fluctuations by continuously monitoring a phase calibrator. The science antenna observes the phase calibrator at interval T_2 ~300 seconds to calibrate the instrumental phase. The science antenna and the reference antenna may be operating at different frequencies, so drift in the LO system may not be coherent. For paired elements or a reference array, residual phase fluctuations can be estimated based on the anticipated baseline, which we will assume to be around 100 meters in this analysis.

Since the phase stability at 30 seconds will certainly be equal or better than the stability at 300 seconds, the **Case 3** requirements, using the longer time scale of ~300 seconds, are more demanding and should define the instrumental delay/phase drift requirements. The total system allocations are given as the bottom line of Table 1, the "Total Instrumental Error." Proof that Case 3 is most stringent follows below.

The residual phase fluctuations for paired elements or a reference array can be compared as follows. The rms residual atmospheric phase after fast switching phase calibration is given by

$$\sigma_\phi = \sqrt{D_\phi(\frac{v_{atmos} * t_{cycle}}{2} + d)}$$

where D_ϕ is the structure function of the atmospheric phase variations, v_{atmos} is the velocity of the atmosphere at the height of the turbulent layer, t_{cycle} is the switching cycle time, and d is the linear distance between the lines of sight to the target source and the calibrator at the altitude of the turbulent layer.

Typical values for **Case 1** are v_{atmos} = 10 m/s and t_{cycle} = 30 sec; with the target and calibrator separated by 2 degrees, and the height of the turbulent layer 1000 meters above ground, *d* equals about 35 meters. This means the residual atmospheric phase is the root of the phase structure function evaluated at 185 meters. For longer baselines, atmospheric phase errors will be reduced to this level. For shorter baselines, fast switching at this rate will offer no improvement and should be avoided in order to retain observational efficiency.

For Case 3, with continuous phase calibrator monitoring, the residuals are equivalent to the physical baseline (between the science antenna and calibration antenna) plus the separation between the calibrator and source at the height of the turbulent layer. These figures are 100 meters and 35 meters respectively in this comparison, resulting in the phase structure function with the same effective baseline of 135 meters. Therefore, Case 3 is the most stringent.

Note that if the physical baselines between paired elements exceeds 100 meters, this analysis should be revisited.

[RD02] describes a simple model for $\sigma_\phi$that scales with the effective baseline for short baselines:

$$\sigma_\phi \propto (b_{eff})^\beta$$

where β = 5/6. [RD02] also establishes that with 90th percentile conditions, at 100 GHz, σ_ϕ = 7.5 degrees for t_{cycle} = 30 sec, which as described above equals the residual from an effective baseline of 185 meters. Scaling by the power law, we can estimate that for b_{eff} = 135 m , σ_ϕ would be approximately 5.8 degrees. Using this approximation and considering an observation at 120 GHz would yield an allowable phase residual of 135 fsec per baseline, or roughly 95 fsec per antenna ($135/\sqrt{2}$). For simplicity and consistency with the time over which such fluctuations occur, this figure will be used to define the system phase/delay drift residual. Phase noise limits are defined below.

Note: The phase drift specification may need to be more stringent than computed since the instrumental drift-induced error will be at least partially systematic in nature. For this instrumental drift term, only the residual term, after calibration and subtraction of any linear trend, affects eventual performance.

Note: This analysis has not accounted for the impact to imaging dynamic range. Rather, it aims to make the troposphere dominate any post-calibration residual. As the calibration strategy and associated requirements [AD11] are developed and refined, this analysis may be superseded.

5.14.2 Establishing a Phase Noise Requirement

As a first order approximation, we will limit phase noise to reduce system SNR by no more than 1%. The degradation in SNR due to phase variation is estimated in [RD04] as

$$\mathcal{D} = 1 - \frac{1}{2}\langle \varphi_{mn}^2 \rangle$$

where $\mathcal{D}$ is the degradation in SNR for a given phase variation φ on baseline mn, and the phase is in radians. A 1% reduction in SNR is equivalent to a rms phase variation of 8.1 degrees. At our highest observing frequency of 120 GHz, this phase variation equates to 188 femto-seconds. Assuming phase contributions from each antenna in baseline mn are independent processes, the contributions from each antenna sum in quadrature and would therefore be 132 femto-seconds ($188/\sqrt{2}$).

The phase noise specification shall be integrated over the frequency range 1 Hz to 100 kHz.

Note: This analysis should be extended to evaluate the impact on high dynamic range imaging as part of the system calibration strategy.

5.15 Gain & System Temperature Stability Requirements

The noise power delivered to the correlator is the product of the system gain and the system temperature, G * T_{sys}, where $T_{SYS} = T_{ATM} + T_{REC} + T_{SPILL} + T_{CMB} + T_{SRC}$. The requirements discussed here consider only the variations in G, as a function of time and the pointing angle of the antenna.

T_{sys} is expected to range from 18K at 10 GHz to 175K at 120 GHz at zenith, and will vary with atmospheric conditions and pointing elevation. The net system gain is defined [in RD05] as

$$G = P_{dig}/(k\,T_{sys}\,\Delta\nu)$$

where P_{dig} is the input power to the digitizer. If the nominal input level into the digitizer is 1 mW (0 dBm)[1] over an 8 GHz bandwidth, a net gain of 77 dB to 87 dB is required. Gross system gain may be 110 dB to 120 dB, accounting for losses from power division, variable attenuators, padding (for matching), mixer losses, component insertion losses, and connector/cable losses between the first stage and digitizer.

Requirements on system gain stability flow down from the science requirements for

- accuracy of total power observations,
- photometric accuracy required, and
- dynamic range of interferometric observations (both brightness and polarization).

5.15.1 Total Power Observations

Parameter	Req. #	Value	Traceability
TP Antennas: Gain Stability	SYS1601	TP Antenna dG/G shall not exceed 1E-3 over a 60 sec period. Goal to not exceed 1E-4.	[SCI0104]
TP Antennas: Gain Variations with Antenna Pointing Angle	SYS1603	TP Antenna dG/G shall not exceed 1E-2 at 10 GHz over a 4° change in elevation, scaled by frequency (TBC).	[SCI0104, SCI0110]
TP Antennas: System Temperature Stability over Time	SYS1604	TREC shall vary by no more than 0.1% over 60 sec period in the precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	[SCI0104, SCI0110]
TP Antennas: System Temperature Variations with Antenna Pointing Angle	SYS1605	TSPILL and TREC shall vary by no more than 0.1% combined over a 4° change in elevation in the precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	[SCI0104, SCI0110]
TP Antennas: Gain Calibration Reference	SYS1801	The system shall provide a switched flux reference stable to 1E-3 over a 5 minute period. Stability over a 24 hour period shall be better than 1%.	[SCI0104, SCI0110]

Total power observations are based on the difference of auto correlation spectral power (or perhaps analogue total power detector output) between two switched states. For example, these two switched states might be two pointing positions. They also might be the on-source measurements during an OTF scan versus the off-source measurements at the end of the scan. Y-factor measurements to a reference load are another example (see Section 5.15.1.2).

[1] Current technology may require closer to –7 dBm at the input to the digitizer, but 0 dBm is illustrative.

The power spectral density of Gaussian white noise has, by definition, a flat power spectrum, with power level proportional to system bandwidth. In an ideal system, noise will decrease as $1/\sqrt{T}$. Gain variations on time scales shorter than the switching period limit the extent to which the measurement accuracy decreases as $1/\sqrt{T}$. Gain variations on time scales longer than the switching period but shorter than the interval between external calibration impact the calibration accuracy of the total power observation and/or add noise when integrating for longer periods.

The value of the total power gain stability requirements is stated in terms of the two-point Allan standard deviation of the fractional gain variation $\Delta G/G$, as a function of time.

5.15.1.1 Total Power Mode: Gain Stability over Short Time Scales

System gain stability ensures that total power mode sensitivity is not limited by instrumental gain fluctuations. Rather, the limiting factors should be receiver thermal noise and/or atmospheric perturbations. (See [RD05] for further discussion.)

However, gain fluctuations manifest as 1/f noise in the power spectral density of the radiometer output. They add to the PSD at low frequencies and can be a limiting factor in noise dropping by $1/\sqrt{T}$. Over long periods, this may set a floor on system noise, and noise may actually rise due to random walk fluctuations on sufficiently long timescales. The system gain stability should be specified over a gain calibration cycle. For the purpose of this analysis, this is assumed to be about 20 minutes.

At ngVLA operating frequencies, atmospheric-introduced changes in T_{sys} can be quite small. At lower frequencies, T_{atm} is dominated by O_2, which is fairly stable, with relatively small contributions from precipitable water vapor (PWV). So, for a 1 mm change in PWV, T_{atm} at 16 GHz may rise ~0.02K [RD06]. With a system noise temperature of 20K, this equates to a fluctuation (dT_{atm}/T_{sys}) of 1e-3. To make atmospheric changes more dominant at all observed frequencies, gain stability (dG/G) of 1e-3 would be required on antennas operating in a total power mode. This stability is only required on timescales comparable to the switching cycle, which should typically be less than 30 seconds. A 60-second period is chosen as conservative.

Fluctuations in T_{SYS} due to expected changes in T_{REC} or T_{SPILL} have a similar effect on the total power measurements and therefore have comparable restrictions. In practice, they are expected to be larger in magnitude, as are changes in T_{ATM} as a function of elevation. This is especially true for lower elevations.

5.15.1.2 Total Power Mode: Flux Scale Calibration

Should a gain calibration noise source be well characterized in an absolute sense, it may also provide a reference for flux scale calibration. The gain calibration system could be characterized by Y-factor measurements in the lab. Its behavior must be characterized over its entire operating temperature range. Limiting this temperature range simplifies testing/characterization and eventual calibration.

This feature is especially attractive for total power measurements as it can increase the calibration cycle time to an astronomical source. The 1% threshold is selected in accordance with the photometric accuracy science requirement.

5.15.1.3 Total Power Mode: Gain Variations with Antenna Pointing Angle

Gain variations with antenna pointing angle can produce an uncorrectable error over angles comparable to the distance between the source and gain calibrator. These could impact both image fidelity and flux calibration. This parameter will be explored in the future, but the antenna design should aim to limit changes to T_{SPILL} with pointing angle.

5.15.2 Interferometric Observations

Parameter	Req. #	Value	Traceability
Interferometric Antennas: Gain Stability	SYS4601	Antenna dG/G shall not exceed 4E-3 over a 200 sec period at 1 MHz bandwidth resolution. Goal to not exceed 1E-3.	[SCI0113, SCI0114, SCI0119, SCI0115]
Interferometric Antennas: Relative Gain Stability	SYS4602	Relative dG/G between polarization pairs shall not exceed 4E-3 over a 200 sec period.	[SCI0114]
Gain Variations with Antenna Pointing Angle	SYS4603	Antenna dG/G shall not exceed 1E-2 at 8 GHz over a 4° change in elevation, scaled by frequency (TBC).	[SCI0110]
Gain Calibration Reference	SYS4801	The system shall provide a switched flux reference stable to 1E-3 over a 20 minute period.	[SCI0110, SCI0113, SCI0114]

The gain stability requirements constrain system gain variations that would limit interferometry observation and calibration accuracy. Assuming the cross-correlation products are not normalized (as is the case with WIDAR), the cross-correlation power is

$$V_{ij} = \hat{g}_i \; \hat{g}_j^* < v_i \; v_j^* >$$

where v_i is the equivalent voltage at the input to an antenna, $\hat{g}_i = g_i e^{-i\theta_i}$ is the complex voltage gain of that antenna, and V_{ij} is the complex visibility or correlation coefficient of the noise input signals of antennas *i* and *j*. The magnitude of V_{ij} is zero for completely uncorrelated noise signals and is a positive number for correlated noise.

The visibility is closely related to the cross power product of the noise input signals at antennas *i* and *j*, but is scaled by the antennas' complex voltage gain. Therefore, it is essential to quantify the voltage gain and to track gain fluctuations at the antenna, and impose a limit on the residual uncorrected gain variation.

Represented as powers, the desired power product P_{int} represents the cross-power from the astronomical source only,

$$P_{int} = \sqrt{P_{src,i} P_{src,j}}$$

while the correlator output is scaled by root of the products of the two independent gains,

$$P_{corr} = \sqrt{g_i g_j} P_{int}$$

Uncorrected changes in $g_i \, g_j$ will artificially inflate or deflate the flux sensed on the baseline, which introduces ringing and other imaging artifacts that effectively reduce image SNR.

5.15.2.1 Interferometric Mode: Gain Stability on Short Time Scales

System gain stability in interferometric modes supports the imaging and polarization dynamic range requirements. SCI0113 calls for a brightness dynamic range of 45 dB over the field of view at 8 GHz. As laid out in Section 5.15.2, the complex gain term has a phase and amplitude. Both are equally important to meeting the brightness dynamic range requirement, as incorrect placement of flux in the field (due to a phase error) will raise the rms of the emission-free regions. As reported in [RD19] (p. 278), 10% phase errors are comparable to 20% amplitude errors in impact on interferometric dynamic range.

Assume for the moment that self-calibration is available and that the phase errors, after calibration, are negligible for this analysis to put an upper limit on the gain errors that would support the dynamic range requirement. Per [RD19] (p. 279), the relationship of the system dynamic range limit to the typical amplitude error on any antenna is

$$D = \frac{N}{\sqrt{2}\,\varepsilon}$$

where *D* is the dynamic range limit, *N* is the number of array antennas, and ε is the typical amplitude error. Assuming an array of 200 elements, the gain stability (dG/G) of a given antenna, after calibrations are applied, must approximate 4e-3 to support the higher dynamic range requirement. Accounting for imperfect phase calibration, gain amplitude stability of 1e-3 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in section 5.15.3.

5.15.2.2 Interferometric Mode: Gain Stability between Polarization Pairs

Gain stability between polarization pairs in an individual antenna is required to support the polarization dynamic range requirement. SCI0114 calls for a polarization dynamic range of 35 dB at 8 GHz in the center of the field of view. Holding the relative gain stability between polarization pairs within a single antenna to 4e-3 should suffice for this requirement, based on similar arguments to those laid out in section 5.15.2.1.

This requirement will be explored in more detail as part of the calibration strategy and requirements [AD11].

5.15.3 Short Cycle Gain Calibration

The effects of gain fluctuations may be correctible with a sufficiently precise active gain calibration system. This section explores the effect of switched power gain calibration.

For the switched power system to allow effective gain calibrations of dG/G of 1e-3, SNR of 3e3 is required (for a 3 σ detection). With switched power of about 1% of T_{sys}, measuring gain fluctuations of dG/G of 3e-3 requires a noise reduction of 3e5.

$$\sigma \approx {T_{sys}}\Big/{\sqrt{\Delta\nu t}}$$

$$3e5 = \sqrt{\Delta\nu t}$$

Applied over a bandwidth of 1 GHz, the integration time required is about 100 seconds; assuming a duty cycle of 50%, 200 seconds of clock time. Therefore, system gain stability would be required over 200-second periods.

The stability requirement for longer (>200 sec) scales is transferred to the noise diode and its amplification/attenuation stages before coupling into the RF path. Noise diode coupled power fluctuations on time scales shorter than the interval between external calibration (~20 min) impact gain calibration accuracy and add noise. Note that the calibration will allow for subtraction of any linear drift term, so only the residuals (rms) after linear term subtraction will remain.

Passive temperature regulation of the noise diode attenuation/gain stage (if any)—adding significant thermal mass and insulation—may be adequate to meet this requirement.

5.16 Calibration Requirements

The level-1 system calibration requirements are presented in this section. The calibration strategy to meet these requirements, and supporting Level 2 requirement derivations are developed in the Calibration Strategy and Requirements document [AD11].

Parameter	Req. #	Value	Traceability
Calibration Automation	SYS1069	Remeasurement of calibration and related scientific performance characteristics of the array, as required to support the Standard Observing Modes, shall be automated and performed as an Observatory function.	[STK1301 (copy)]
Standard Observing Mode Calibration	SYS4301	A calibration strategy shall be provided for each standard observing mode.	[STK1302, STK0704]
Calibration of Triggered Observations	SYS4302	The system shall include the capability to perform rapid and automated calibration, based on previously obtained and archived system calibration parameters, to support triggered observations.	[SCI0005]
Real Time Atmospheric Delay Calibration	SYS4310	The system shall use contemporaneous cross-correlation visibilities to correct for both electronic and tropospheric delay and amplitude errors (i.e., complex gain errors) in phased array or interferometric functional operating modes in near real time.	[SCI0007]
Standard Calibration Automation	SYS4320	Post-processing calibration for standard observing modes shall be automated via a pipeline.	[STK1301, STK1302]
Storage and Retrieval of Calibration Parameters	SYS4330	Parameters for standard observing modes determined by calibration (such as bandpasses and delays) shall be stored in a calibration database and automatically retrieved and applied.	[STK1300]
Automated Re-Measurement of Parameters	SYS4331	It shall be possible to measure system calibration parameters with both automated and operator-triggered tools, using either the full array or a subarray.	[SYS4330, STK1301]

5.16.1 Calibration Efficiencies

Parameter	Req. #	Value	Traceability
Calibration Efficiency	SYS1061	Overheads for system calibration shall be minimized, with a goal of 90% of time spent on source for Standard Observing Modes.	[SCI0100, SCI0102, SCI0106, STK1403, STK0704]
Calibration Parallelization	SYS1062	Any real-time calibration pipelines shall permit parallelization at the antenna or baseline level.	[STK1403]

Parameter	Req. #	Value	Traceability
Calibration Recall	SYS1063	The system shall remember prior calibration corrections and apply them if their projected accuracy (given time elapsed) still meets the requirements for a given observation; I.e., a scheduling block need not always include its own calibrators.	[STK1403]
Relative Flux Scale Calibration Efficiency	SYS1064	The system shall permit relative flux scale calibration to 5% precision without the need for tipping scans in Standard (Interferometric) Observing Modes.	[STK1403, STK0704]
Polarization Calibration Efficiency	SYS1065	Polarization calibration shall be achievable with a single observation of a compact polarized source of unknown polarization angle for Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]
Bandpass Calibration Efficiency	SYS1066	The system gain stability shall permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]
Gain Calibration Efficiency	SYS1067	System gain calibration shall be achieved with no more than a 2% degradation in system sensitivity as a function of clock time for standard interferometric continuum modes.	[STK1403]
Phase Calibration Efficiency	SYS1068	Phase calibration overheads shall not exceed 100% of on-source time for observations at 116 GHz when operating in the precision operating conditions. It is a goal to reduce tropospheric and electronic phase calibration overheads to less than 10% of on-source time, consistent with SYS1061.	[STK1403]

Total observing efficiency will vary with each observation given its unique calibration needs. The calibration strategy and system design should be carefully designed to minimize systematics, and each design's efficacy should be judged by its impact on observational efficiency. For example, tropospheric phase calibration system improvements that increase operational system efficiency (time on source) can be compared to the cost of added collecting area, greater bit depth, improved antenna surface accuracy, or feed illumination efficiency.

However, hard limits for the observational efficiency are difficult to establish, so these calibration efficiencies are better thought of as technical parameters that should be optimized for general use cases as part of the Observing Modes Framework [AD15]. This is discussed further in Section 7.4.2.

5.17 Polarization Requirements

Parameter	Req. #	Value	Traceability
Full Stokes	SYS1900	The system shall measure the full set of stokes parameters that describe the polarization state of the received and correlated signals.	[SCI0015]
Polarization Purity	SYS1901	The system post-calibration on-axis residual linear pol leakage (amplitude) shall be less than 0.03% at 8 GHz, scaled by observing frequency, where leakage is defined as Stokes Q/I, U/I, or V/I.	[SCI0114]

As stated in requirement SCI0015, the system will measure all polarization (stokes) products simultaneously. Per SCI0114, the system should achieve 35 dB polarization dynamic range at 8 GHz.

This specification is both frequency- and direction-independent and applied only at the center of the field and over 80% of a given receiver's bandwidth. Systematics will increase as the beam's full-width half max is approached due to a degraded off-axis response with offset optical geometries. Band edge response of polarizers is also expected to degrade polarization performance.

How to allocate the error budget among system elements should be determined once a polarization calibration strategy is developed [AD11]. Assumptions about the calibration accuracy and the degree to which antenna based errors are independent will be necessary, and the polarization requirements will be closely tied to gain stability requirements since any gain fluctuations not common to both polarizations will contribute to this error.

5.18 Temporal Requirements

Parameter	Req. #	Value	Traceability
Variable Time Resolution	SYS0104	It is desirable to provide an option to vary the time resolution on a per-baseline basis (i.e., baseline dependent averaging) in order to reduce the total data volumes generated by the correlator.	[CON002]
On-The-Fly Mapping: Data & Control Rates	SYS0106	The system shall support on-the-fly (OTF) mapping rates of 2x sidereal at 28 GHz, with data dump rates and delay update rates <400 msec at the full system bandwidth. Goal to support rates <100 msec at reduced bandwidth or spectral resolution (i.e., fixed data output rate).	[SCI0004, SCI0106]
On-The-Fly Mapping: Antenna Tracking Rate	SYS0107	The antenna and any motion control loops shall support on-the-fly tracking rates of 10x sidereal for elevations below 70° (2.5'/sec).	[SCI0004, SCI0106]
Temporal Resolution	SYS2001	Correlator visibility integration time shall be tunable, with a range of 5 sec to 100 msec (possibly at limited bandwidth) or better. Goal to support integration times as short as 1 msec at limited bandwidth.	[SCI0004, SCI0103]
Temporal Accuracy	SYS2002	Data Product timestamps must be referred to an absolute time standard (e.g., GPS or TAI) with an error of less than 10 ns (goal of 1 ns). This correction may be retroactive (i.e., it is not necessary for it to be known in real time.)	[SCI0112, SCI0012]

System temporal resolution may be set either by the need to prevent imaging time and bandwidth smearing or by the change rate in a time-variable source (such as FRBs). Short integration times are also required for on-the-fly mapping. Note that this requirement presumes that frequency resolution is traded for temporal resolution to keep total data rates practical.

A relationship exists between the maximum integration time and maximum baseline length that is limited by circumferential smearing. To keep the smearing low, a rule of thumb [RD09] is to keep the integration time well below

$$(\omega_e D_\lambda/\theta_f)^{-1}$$

where ω_e is the Earth's rotation angular velocity, D_λ is the baseline length in wavelength units, and θ_f is the angular size of the sky image. For an 18 meter aperture, the maximum image size is about 1,000 km/18 m ≈ 60,000 synthesized beams. A minimum integration time equal to 50% of the above expression is about 100 msec.

Note that on-the-fly mapping at a rate of 10*ω_e at this resolution would require a minimum integration time ten times smaller. However, OTF mapping is not required or expected at this resolution. The OTF rates assume that the interferometric delays (phase center) update as the antenna moves 1/10th of a primary beam, with visibility integrations as required to limit smearing. The 400 msec rate supports 2x sidereal scanning at 28 GHz with the natural beam of the main array, in support of SCI0106, while the 100 msec rate supports 2x sidereal scanning at 116 GHz.

Temporal accuracy is required for astrometric observations and other studies of time-variable phenomena, which depend on absolute knowledge of the event time. This requirement will also support VLBI observations by providing a suitably small fringe search window.

5.19 Radio Frequency Interference Mitigation

These requirements apply to management of externally generated and internally generated/radiated Radio Frequency Interference.

Parameter	Req. #	Value	Traceability
RFI Flagging	SYS4100	The system shall include flagging and excision algorithms to mitigate the impact of ground-based and orbital RFI present over the ngVLA operating frequency range.	[SYS4100, STK2602]

Additional requirements relevant to the mitigation of radio frequency interference are captured in Section 5.11.

5.20 Spurious Signals and Self-Interference Management

These requirements apply to self-generated spurious signals within the array and do not address external Radio Frequency Interference.

Parameter	Req. #	Value	Traceability
Self-Generated Spurious Signal Power Level	SYS2104	Self-generated signals shall not exceed -43dB relative to the system noise level on cold sky over a 1 MHz bandwidth.	[SCI0116, STK2600]
LO Frequency and Sampler Clock Offsets	SYS2105	The system shall include the provisions for frequency offsets and sampler clock offsets at the antenna level to provide additional attenuation of spurious signals.	[SCI0115, SCI0113, SCI0108, SCI0119, STK2600]
Shielding & Emission Limits	SYS2106	System shielding and emission limits shall comply with 020.10.15.10.00-0002-REQ.	[SCI0116, STK2600]

Spurious signals may be coherent or incoherent signals. While both affect system performance, coherent signals are more damaging since they do not average out with more samples over time and need a more stringent specification.

Incoherent and coherent spurious signals could limit the spectral dynamic range. There is a scientific requirement, on spectral dynamic range of 100,000:1, for weak spectral lines in the presence of stronger spectral lines. Flowing down from this are two main technical requirements:

- The bandpass is sufficiently stable in time that it does not give false appearance of weak lines, and
- There should be no self-generated spurious features in the output spectra.

In interferometric modes, spurious signals coherent between antennas can lead to

- Spurious spectral features,
- Closure errors that limit calibration accuracy and thus imaging dynamic range, and
- Image defects, usually broad stripes and ripples throughout the field, which limit the continuum sensitivity.

The relative spurious power in a given spectral bin will be calculated as $(P - N)/N$, where P is the total power in the bin and N is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples.

Adopting the methodology from [RD14], we set the interference to noise ratio to less than 0.1:

$$INR < 0.1$$

Harmful flux density can then be found from SCI0116:

$$S_H < \sigma_{rms} * INR$$

Given as a flux density, the specification can be directly compared to the SEFD to determine the required signal-to-interferer ratio. At 30 GHz, the expected SEFD for the array is of 2.1 Jy:

$$\frac{S}{I}(\Delta\nu) = 10 * \log\left(\frac{9.5\ \mu Jy}{2.1\ Jy}\right)\ dB = -53\ dB$$

Since the power and flux density is proportional, the power of the spurious signal must be no more than –53 dB above the signal level on cold sky over the established channel bandwidth (0.1 km/s = 10 kHz @30 GHz). This specification would apply to total-power measurements but can be relaxed for interferometric measurements by 20 dB due to phase winding/fringe washing (–53 dB + 20 dB = 33 dB/10 kHz). (See [AD06] for supporting derivation of interferometric attenuation factor.)

Extending the bandwidth over which the signal level is measured increases verification measurement fidelity, and a bandwidth of 1 MHz is adopted. The required attenuation will scale by the square root of the bandwidth:

$$\frac{S}{I}(1MHz) = \frac{S}{I}(10kHz) * \sqrt{\frac{1\ MHz}{1\ kHz}}$$

The end result is a spurious signal level of –43 dB/MHz for interferometric antennas. While the derivation above is given at 30 GHz, the requirement is comparable over the given frequency range.

LO-offsetting and 180-degree phase switching (Walsh switching) can be used to further reduce the impact of spurious signal introduced after the first LO. Sampler clock offsets and LO-offsets combined would provide the highest degree of attenuation to self-generated spurious signals.

A more stringent standard is not adopted for total power antennas given that large-scale structure recovery is more applicable on large mosaics with shallower integrations.

5.21 Scientific Operations Requirements

The ngVLA scientific operations requirements are broad, with a scientific operation concept similar to the VLA where observers request time for a specific study and define many of the observation parameters. This is distinct from a survey instrument that has a more rigidly defined operation schedule and data product. This PI-driven model requires a flexible instrument and an observation schedule that maximizes output given system and environmental conditions. The requirements relevant to the scientific operations processes and interfaces to the system are summarized in this section.

Parameter	Req. #	Value	Traceability
Provision of Software Tools	SYS2201	The system shall include tools for the preparation of proposals, preparation of observations, reduction of data products, and analysis of data products.	[STK0801, STK1201, STK1202, STK0805, STK0200]

User interaction with the facility depends on good tools. As with current NRAO facilities, these will include proposal preparation, observation preparation, and data reduction and analysis. Revisions and extension to existing tools from VLA and ALMA, having been updated to incorporate similar SRDP requirements during the ngVLA design phase, are largely expected to be adequate.

One primary difference may be the provision of computing resources. With larger data volumes, the project will provide computing resources for computationally demanding work such as data reduction. This should not require that users set up their own high performance computing (HPC) clusters, though this will not be precluded for the most sophisticated use cases.

Computing resource design, allocation, and location are an example of an area where community engagement may be feasible (see Stakeholder Requirements [AD02]). Computing resources could be hosted at major research universities in a distributed computing model. Community development of software analysis tools, as part of a modular toolkit, may also be practical.

5.21.1 Proposal Submission and Evaluation

Parameter	Req. #	Value	Traceability
Proposal Submission: Standard observing modes	SYS2211	The proposal submission interface shall allow the user to specify their scientific requirements for standard observing modes, without specifying the technical implementation to those requirements.	[STK0801, STK0800, STK0805]
Proposal Submission: Non-standard observing modes.	SYS2212	For non-standard observing modes, it shall be possible for the user to define their technical observation parameters as part of their proposal.	[STK0800, STK0801, STK0702]
Scientific Proposal Evaluation	SYS2213	A tool shall be available for proposal evaluation and ranking, and shall permit the anonymization of proposals during evaluation.	[STK0802, STK0803]

Parameter	Req. #	Value	Traceability
Technical Proposal Evaluation	SYS2214	The proposal evaluation tool shall include technical simulation tools to verify the observing resources required (sub-arrays, time) to support the science requirements.	[STK0802]
Observing Time Calculator	SYS2215	The system shall provide users with a tool to calculate the required science subarrays and associated observing time based on the proposal scientific and/or technical requirements.	[STK0703, STK0805]
Proposal Award Model	SYS2216	The proposal evaluation tools shall support an award model of allocated time by subarray to an observation.	[STK0703]
Subarray Support	SYS2217	The proposal tools and scheduling system shall support, at a minimum, a set of predefined science subarrays.	[STK1401 (copy)]
Proposal Attributes	SYS2218	The system shall support proposal attributes such as regular, triggered, monitoring, large and legacy (see 020.10.05.00.00-0004-PLA), and joint (with other observatories).	[STK0804 (copy)]

5.21.2 Observation Preparation, Execution, and Scheduling

Parameter	Req. #	Value	Traceability
Observation Preparation: Standard Observing Modes	SYS2221	For standard observing modes, the system shall determine the technical configuration of the system and a supporting observation plan that meets the science requirements set by the proposer.	[STK0805, STK0701, STK0704]
Observation Preparation: Non-Standard Observing modes	SYS2222	The system shall include tools and interfaces to generate observation instructions for non-standard modes without the use of the end-to-end software system.	[STK0402, STK0502]
Observation Scheduling GUI	SYS2223	The observation scheduling system shall include a GUI to display completed and scheduled projects to the Operator, and to initiate manual overrides and schedule changes.	[STK0901, STK1502]
Observation Interrupt	SYS2224	It shall be possible to interrupt and cancel an in-progress observation through the observation scheduling system GUI in the Operator Console.	[STK0901, STK1502]
Observation Preparation: Standard Observing Mode Flexibility	SYS2225	For standard observing modes, tools shall support returning the proposed observation plan to the user for review, and to collect user proposed modifications as necessary to support their science requirements.	[STK0705]

Parameter	Req. #	Value	Traceability
Observation Time Model	SYS2226	The observation preparation, execution, and scheduling tools shall support a scientific operations model of allocated time by subarray to an observation.	[STK0703]
Observation Scheduling Criteria	SYS2227	The automatic observation scheduling system shall account for the system status, current and expected weather, project priority and percent complete, and expected RFI when automatically scheduling observations.	[STK0900]
Observation Scheduling	SYS2302	System observations shall be automatically scheduled by an observation scheduling system, although manual over-rides to scheduling shall also be possible.	[STK0901, STK0900, STK0703]

5.21.3 Post-Observation Support

Parameter	Req. #	Value	Traceability
Manual Data Quality Assurance	SYS2205	The system shall include tools and interfaces for manual quality assurance inspections of low-level and high-level data products gathered using non-standard operating modes.	[STK9949]
Quality Assurance Tool Extensibility	SYS2206	The data quality assurance tools shall be extensible to support the inspection of user-generated data products.	[STK1004, STK1104]
Automated QA of Data Products	SYS2207	The system shall include an automated quality control check of low-level and high-level data products generated using standard operating modes.	[STK9948 (copy)]
Quality Assurance Tools for Standard Modes	SYS2208	The system shall include tools for human inspection when the automated QA system identifies faults on data products generated for standard observing modes.	[STK9949]
Data Provenance Tracking	SYS2209	The system shall include all the necessary tools and data stores for scientific operations staff to be able to retroactively associate any recorded data with the full state of the system (inclusive of hardware and software versions across subsystems) used to generate the data set.	[STK9950 (copy)]

This section primarily concerns itself with post-observation user support and quality assurance requirements. The requirements relevant to data products, data processing, and delivery via the Observatory science data archive are described in Section 5.3.

5.21.4 User Interfaces

This section summarizes the user interfaces to the facility.

Parameter	Req. #	Value	Traceability
Proposal Preparation Tool	SYS3500	A tool shall be provided to enable users to prepare and submit their proposals.	[STK1200, STK0801]
Observation Preparation Tool	SYS3501	A tool shall be provided for users to inspect and modify their observation instructions for approved projects.	[STK1200]
Data Quality Inspection Tool	SYS3502	A tool shall be provided for users to inspect the data quality of a performed observation.	[STK1200]
Data Processing Inspection Tool	SYS3503	A tool shall be provided for users to review and modify the post-processing and generation of SRDP for observations using standard observing modes.	[STK1200]
Data Analysis Package	SYS3504	A data analysis tool kit shall be provided for users to analyze the data products generated by the system, applicable to both high and low-level data products generated with either standard or non-standard observing modes.	[STK1200]
User Support Tool	SYS3505	A tool shall be provided for users to request support related to proposing, observing, data quality, processing or analysis of ngVLA data.	[STK1200]
Data Processing Package	SYS3506	A data processing tool kit shall be provided for users to generate high-level data products for non-standard modes using user-provided computational resources.	[STK1202]

5.22 Array Operation Requirements

The PI-driven general purpose and flexible operations model is in tension with the operations cost constraints established in the Stakeholder Requirements [AD02]. This means that the system operation should be automated where possible, enabling systems to self-monitor, self-configure, and self-calibrate to reduce the operations burden and staffing required. This has significant implications for the monitor and control system and supervisory software systems that must be elaborated in those subsystem requirements. Key requirements relevant to the array operations functions are summarized below.

Parameter	Req. #	Value	Traceability
Calibration Automation	SYS2303	The calculation and updating of parametric delay and pointing models shall be automated.	[STK1506]
Self-Calibrating Antenna	SYS2304	It is a goal that the antenna self-configure and self-calibrate (based on catalog values stored in the calibration database) after maintenance or a power interruption, with limited intervention from the operator.	[STK1506]
Single Baseline Data Display	SYS2305	Graphical interfaces shall be provided to display single baseline fringe amplitude and phases in near real-time.	[STK0402, STK0502, STK1502]

Parameter	Req. #	Value	Traceability
Calibration Data Display	SYS2306	Graphical interfaces shall be provided to tabulate and display common antenna calibration coefficients (delays, TSYS, PDIFF, etc.), and flag values that are possible outliers. The threshold for flagging shall be user tunable (e.g., 1-sigma, 3-sigma, etc.)	[SYS3110, STK0402, STK0502, STK1502]
Operator Console	SYS2307	An operator console shall be provided that provides visibility and control of scheduled maintenance and observations, as well as displays of the array configuration, weather, and system status alerts.	[SYS3113, STK1502]
Operator Interface Location	SYS2308	It shall be possible for authorized personnel to access the operator interface software from any approved workstation in the Observatory.	[STK9944 (copy), STK1502]

5.23 Maintenance Operations Requirements

As with the Array Operations requirements, maintenance operations must be streamlined to enable maintenance processes to scale to the larger array while remaining within the operations cost constraints established in [AD02].

Parameter	Req. #	Value	Traceability
Array Element MTBF	SYS2402	The antennas, antenna electronics, array infrastructure, and signal processing systems shall be designed with an expected number of failures to be less than four (4) per array element per year.	[SYS3202]
Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate site maintenance.	[SYS3202, STK1603]
Self-Diagnostic Function	SYS2405	The system shall incorporate self-diagnosis functions to identify faults based on recorded monitor data.	[SYS3203, SYS3112]
Configuration Monitoring	SYS2406	The system shall include monitoring and tracking of the system configuration to the LRU level, including LRUs that are not network-connected for operation (e.g., Refrigerators).	[STK1600]
Engineering Console	SYS2407	The system shall include an engineering console for each subsystem and LRU to communicate system status and assist in real-time diagnosis.	[SYS3110, SYS3112, STK0402, STK0502
Monitor Data Stream	SYS2408	The system shall stream monitor data at variable rates (0.1 sec to 10 min) for automated use by predictive maintenance programs and for direct inspection by engineers and technicians.	[SYS3110, SYS3112, STK0402, STK0502]
Preventive Maintenance Schedules	SYS3200	The system shall be designed with preventive maintenance (PM) interval no shorter than 1 year.	[STK5005]

Parameter	Req. #	Value	Traceability
Maintenance Tiers	SYS3201	Maintenance tasks shall be classified in tiers to assign the level of skill or maintenance visit required. It is a goal that site-based maintenance be limited to lower levels, with high-skill work generally performed at the Repair Center by specialized staff and equipment under a higher degree of environmental and process control.	[STK5005]
Optimization for Maintenance	SYS3202	Tools shall be provided for the organization of the maintenance and repair teams in order to maximize the efficiency of time spent on antenna visits and repair of equipment.	[STK5005, STK5003]
Criteria for Scheduling Maintenance	SYS3203	Tools shall be provided for the automation of preventive and corrective maintenance scheduling, based on a combination of the severity of existing issues, required preventive maintenance, and predictions of pending problems.	[STK5005]
Use of Failure Analysis in Spares Planning	SYS3204	Failure analysis shall be used in the planning of spares inventory. Factors considered shall include the projected availability for spares, the time required to repair the failure, and viability of critical vendors.	[STK5005]
Reporting of Failures and Anomalies	SYS3205	The system shall permit the reporting of failures and anomalies to operators, data analysts, post-processing pipelines, and users. These reports, along with those generated by automated means, shall be tracked in an issue tracking system with a corresponding database.	[STK5005]
Maintenance Metrics Definition	SYS3209	The operations plan shall detail the specific maintenance metrics to be used in the operations phase, such as mean time to repair, resource utilization, and maintenances costs per antenna. A design baseline for each metric shall be provided in the plan.	[STK5005]
Provision of Diagnostic Tools	SYS3220	The system shall include interfaces for engineers and technicians to monitor the health of the system and remotely diagnose failures and behavior anomalies.	[STK5001 (copy)]
Provision of Predictive Tools	SYS3221	The system shall include automated tools to predict the location and nature of failures in support of maintenance scheduling.	[STK5002 (copy)]
Maintenance Scheduling Tools	SYS3222	The maintenance scheduling tool shall include an interface for authorized personnel to reprioritize issues, manipulate the schedule, and ascertain the status of scheduled work.	[STK5003]

To reduce the maintenance burden (and cost), the maintenance interval for the antenna systems must be appreciably longer than the VLA. A preventive maintenance cycle of 1 year is approximately a fourfold improvement.

The MTBF for the associated systems should lead to no more than four failures per array element per year. This equates to an MTBF of around 2,190 hours. This is expressed as

$$MTBF_{sys} = t_{total}/N_{failures} = (N_{elem}\ t)/(4\ N_{elem})$$

The flow-down requirements can be quite stringent. If each array element has the N_{LRU} line replaceable units (LRUs) that are essential to its operation (series analysis), the MTBF can be expressed as:

$$MTBF_{sys} = \sum_{k=1}^{N_{LRU}} \left(\frac{1}{MTBF_k}\right)^{-1}$$

For N_{LRU} = 16, in order to have an MTBF of the system of 2,190 hours, the MTBF per LRU required would be about 35,040 hours (4 years). Apportioning failures throughout the system to have a maintainable array will require further study. Specifying MTTFs rather than MTBFs may be more appropriate, with a goal of harmonizing antenna MTTF and preventative maintenance schedule so that maintenance is more closely tied to the preventive maintenance cycle than responsive to failures.

5.24 System Monitoring Requirements

Parameter	Req. #	Value	Traceability
LRU Monitoring	SYS3101	Each LRU shall provide on-board monitoring and diagnostics to determine the health and status of the unit.	[SYS3203, SYS3112]
LRU Alerts	SYS3102	When an LRU is out of specification, it shall generate a prioritized alert for processing by the operator and maintenance scheduler.	[SYS3203]
Monitor Archive	SYS3103	Monitor data and alerts shall be archived at their generated rate (SYS2408) the full life of the instrument. (SYS2801)	[SYS3110]
Fast Read-Out Modes	SYS3105	Fast-read out modes shall be available for remote engineering diagnostics of all LRUs (i.e., an on-board oscilloscope function)	[SYS3112, STK1506]
Performance Analysis and Automated Maintenance Scheduling	SYS3110	Array software systems shall provide a continual and automated analysis of array status and health, providing the key source of automatically generated maintenance tickets and automated maintenance scheduling.	[STK5005]
Hot Swaps of LRUs	SYS3111	Hardware and software shall be designed to accommodate and recover from hot swaps with minimal interaction required by the maintenance and operations personnel.	[STK5005]
Intelligent LRUs and Subsystems	SYS3112	LRUs and other subsystems shall be smart devices with on-board diagnostics that can be accessed remotely for troubleshooting.	[STK5005]
Operator Interface to System Monitoring Software	SYS3113	The monitoring system shall provide the operator with status and alert screens to indicate array health and system configuration.	[STK5005]

Parameter	Req. #	Value	Traceability
Subsystem Automation	SYS3114	Individual antennas and subsystems within the array shall perform system configuration and monitoring functions without the need for human intervention. It is a goal that each subsystem be capable of reaching an operationally-ready state after a full power cycle without human intervention.	[STK5005]

5.25 Environmental Monitoring Requirements

Parameter	Req. #	Value	Traceability
Weather Monitoring	SYS2501	Parameters that affect system scheduling or are used for calibration (wind speed, temperature, humidity and barometric pressure), shall be measured over the full extent of the array.	[STK0900, SCI0111]
Safety Weather Monitoring	SYS2502	Parameters that affect the health/safety of the array (wind, temperature) shall have redundant monitoring.	[STK0304]
Weather Archive	SYS2503	Weather data from all weather stations shall be recorded at no less than 1 minute periods and archived for the life of the instrument.	[STK1403]

Given the extent of the array, weather monitoring will be required at multiple sites to quantify the environmental conditions over the full extent of the array. All parameters that affect system scheduling or safety should be measured to manage the array operation.

5.26 System Availability

Parameter	Req. #	Value	Traceability
Antenna System Availability	SYS2601	The combined antenna system availability shall be, at a minimum, 90% (goal of 95%) of time available for science operations.	[STK1402]
Centralized Systems Availability	SYS2602	For all centralized systems (e.g., LO distribution, correlator) that are required for data collection, system availability shall be no less than 95%.	[STK1402]

Availability is defined as time available for science operations, accounting for scheduled and unscheduled maintenance downtime.

The availability requirement aims to have 90% of antennas available for science. This is approximately equivalent to the current VLA "three antenna rule," with the goal of allowing for an appropriate amount of downtime to conduct preventative maintenance, repairs, and testing while also maximizing array output.

The availability requirement flow-down needs must be harmonized with the maintenance requirements established in Section 5.26. The mean time to repair (MTTR) must be calculated for common failures to determine downtime for each failure. Time must also be allocated for preventive maintenance and testing, and it must add up to no more than 10% of clock time.

Separate availability requirements are stipulated for the antennas versus the centralized systems, since failures of the latter are expected to preclude system operation. This assumption should be revisited later in the design since modularized architectures may be more flexible in responding to failures than has been assumed.

5.27 Safety and Security

Parameter	Req. #	Value	Traceability
Safety Specification	SYS2700	All designs shall comply with the Level-1 System Safety Specification (020.80.00.00.00-0001-REQ)	[(TBD)]
Subsystem self-monitoring	SYS2701	All subsystems shall monitor system health and prohibit actions likely to cause damage.	[SYS3112]

Parameter	Req. #	Value	Traceability
Security Specification	SYS2703	All designs shall comply with the Level-1 System Security Specification (Doc TBD).	[(TBD)]
Physical Security	SYS2704	Physical security and monitoring shall be considered in the array design.	[STK2201]

The safety requirements fall into two broad categories: protecting the system and protecting personnel.

The system should self-monitor its condition, prohibit actions likely to cause damage, and respond to conditions that indicate imminent failure. An example would be to auto-stow the antenna if operational environment limits are reached and to not permit the operator to switch back to an operational mode until the condition subsides.

Every level of the design must ensure safety of operation and maintenance personnel. Hazard analysis findings for all common services to motion, high-power, high-voltage, or otherwise high-risk systems shall be incorporated into the subsystem requirements and design.

5.28 Cybersecurity

Parameter	Req. #	Value	Traceability
IT Security	SYS2702	The data processing, networking, and data archive systems shall be engineered and deployed in accordance with current best practices in IT Security, as defined by the NSF-funded Center for Trustworthy Scientific Infrastructure and the AUI Cyber Security Policy.	[STK2202]

Given modern threats, the system shall protect against most common hacking attempts. The system should only respond to commands from authorized users and/or sources. Permissive control systems will not meet this standard.

5.29 Logistics Support

Parameter	Req. #	Value	Traceability
Inventory Tracking System	SYS3900	A system shall be provided to electronically track inventory to determine usage rate and location of spare assemblies, component level spares, and consumables.	[STK2100 (copy)]
Shipping and Receiving Logistics	SYS3901	Each facility shall have central shipping and receiving and be integrated with a shipping system between sites.	[STK2102 (copy)]

Parameter	Req. #	Value	Traceability
Tracking of LRUs	SYS3902	Provisions shall be provided for centralized management, testing, and repair of LRUs from the Repair Center. Repaired LRUs may be stored near the point of service at the Maintenance Center and RSS locations.	[STK2103 (copy)]
Observatory-Controlled Logistics	SYS3903	Observatory-controlled shipping resources shall be provided to enable prioritization, possession, and safe-handling of items during transit (i.e., to be used rather than commercial carriers, when practical).	[STK2105 (copy)]
Packaging Used for Shipping	SYS3904	Shipping cases and packaging shall be provided with ESD protection and mechanical shock absorption consistent with the equipment specifications.	[STK2106 (copy)]

5.30 Configuration Management

Parameter	Req. #	Value	Traceability
Identification by Serial Numbers	SYS3600	All configuration items (e.g., all LRUs) shall be uniquely identifiable to facilitate status and location tracking across the Observatory.	[STK1602 (copy)]
Configuration Management Tools	SYS3601	The project shall provide configuration management tools for tracking the design versions of construction deliverables throughout the system life cycle.	[STK1604 (copy), STK1600]
Version Control for Software and Firmware	SYS3602	All custom software and firmware delivered as part of the system shall be version controlled via a configuration management process.	[STK1606, STK1600]
Configuration Retrieval	SYS3603	All configurable LRUs shall retrieve their hardware parameter configuration automatically after replacement, and upon a change in the parameter in the System Calibration database.	[STK9945 (copy), STK1600]

5.31 Quality Assurance and Quality Control

Parameter	Req. #	Value	Traceability
Quality Control Data Access Tool	SYS3700	A quality control data access tool shall provide an interface to the quality control database for authorized personnel to record repairs, test data, and associated information on each LRU.	[STK1900]
Quality Control Data Access Tool Location	SYS3701	The quality control data access tool shall enable authorized personnel to access stored information from any ngVLA location, including antenna sites.	[STK1900]
Quality Control of Deliverables	SYS3702	Stand-alone acceptance testing of software and hardware deliverables (based on a qualification matrix unique to each deliverable) must occur before delivery to, or installation on, the array.	[STK1902 (copy)]

5.32 Facility Requirements

Parameter	Req. #	Value	Traceability
Outfitted Facilities	SYS3800	All facilities shall be outfitted with the furnishings, tools, equipment, computing, and information technology equipment necessary to fulfill the intended function.	[STK2001, STK2002, STK2003, STK2004, STK2005, STK2006, STK2007, STK2008, STK2009, STK2010, STK2011, STK2012]
Facility Sustainability	SYS3801	All new facilities shall be Leadership in Energy and Environmental Design (LEED) certified, with a goal of achieving Gold-level certification or higher, as applicable to new construction as defined in LEED v4.1 or newer.	[STK0302]
Provision of a Visitor Center	SYS3802	An ngVLA Visitor Center shall be provided for public outreach within view of the array, but at a minimum distance of 1 km from the core antennas to mitigate RFI.	[STK2000]
Controlled Visitor Access	SYS3803	Facilities shall be provided for controlled visitor access between the visitor center and array core or nearby antennas.	[STK2000]
Provision of a Maintenance Operations Center	SYS3810	A Maintenance Operations Center shall provide office space and common areas for projected safety, security and maintenance personnel.	[STK2001]
Maintenance Center - Support Equipment	SYS3811	The Maintenance Center shall include space for the requisite tools and equipment to support expected preventive and corrective maintenance activities.	[STK2001]
Maintenance Center - Ready Spares	SYS3812	The Maintenance Center shall include space for the storage and inventory of LRUs.	[STK2001]
Provision of a Warehouse	SYS3820	A central warehouse shall be provided and sized for the central storage and distribution of components, consumables, and critical spares.	[STK2002]
Warehouse Inventory System	SYS3821	The central warehouse shall include provisions for the controlled inventory of all housed components, spares, and consumables.	[STK2002]
Provision of a Repair Center	SYS3830	A Repair Center shall be provided to host staff and equipment necessary for the transfer, diagnosis, repair, and test of electronic LRUs and other equipment.	[STK2003 (copy)]

Parameter	Req. #	Value	Traceability
Provision of an Array Operations Center	SYS3840	An Array Operations Center (AOC) shall provide sufficient space to host off-site array operations and a comparable complement of office space, laboratory space, storage and transfer capabilities, and computing infrastructure as in the existing DSOC.	[STK2004 (copy)]
Provision of a Science Operations Center	SYS3850	A Science Operations Center (SOC) shall be provided to house the scientific operations staff constituted of scientists, data analysts, computing, software, and IT positions, and some administrative and management staff. The facility shall primarily consist of office space and supporting computing infrastructure.	[STK2005 (copy)]
Provision of Remote Support Stations	SYS3860	Remote Support Stations (RSS) shall be provided and located to support operations across the array extent. Each RSS shall have a footprint to support workbenches, organized tools, supplies, and inventory including spare LRUs required for routine maintenance of a group of antennas.	[STK2006 (copy)]
Location of the Maintenance Operations Center	SYS3870	The Maintenance Operations Center shall be located near the array site in order to facilitate logistics, but sufficiently far away to mitigate RFI at the Array Core.	[STK2007 (copy)]
Location of the Array Operations Center	SYS3871	The Array Operations Center shall be located within a two hour drive of the array site in order to facilitate logistics while providing an attractive location to recruit array operations personnel.	[STK2008 (copy)]
Location of the Science Operations Center	SYS3872	The Science Operations Center shall be located at a site that facilitates personnel recruitment, such as an attractive metropolitan area.	[STK2009 (copy)]
Location of the Repair Center	SYS3873	The Repair Center shall be located within a two hour drive of the array site in order to facilitate logistics while providing an attractive location to recruit array operations personnel. It may be co-located with the Array Operations Center.	[STK2010 (copy)]
Location of the Warehouse	SYS3874	The Warehouse shall be located near the array site in order to facilitate logistics, but sufficiently far away to mitigate RFI at the Array Core. It may be co-located with the Maintenance Operations Center.	[STK2011 (copy)]

Parameter	Req. #	Value	Traceability
Provision of a Guard Booth	SYS3880	To maintain site security at the additional buildings near the core of the array, a guard booth shall be provided to support a constant security presence by security staff.	[STK2012 (copy), STK2201]
Provision of Support Buildings	SYS3881	As required, additional buildings near the array core shall provide for the storage and maintenance of heavy equipment that cannot be easily delivered or driven from the nearby Maintenance Center and to support the maintenance and repair staff temporarily on-site.	[STK2013 (copy)]

5.33 Array Infrastructure Requirements

Parameter	Req. #	Value	Traceability
Grassland Impact	SYS4000	The design and construction of utility corridors and roads shall minimize the impact on grasslands and water within the Plains of San Agustin.	[STK2402, STK2400]
Sustainable Roads	SYS4001	Road widths and lengths shall be minimized to reduce the destruction of top soil. The road design shall aim to avoid the collection of water into new ditches or arroyos that will exacerbate soil erosion.	[STK2401 (copy)]
Existing Roads	SYS4002	Existing ranch roads shall be assessed for suitability in both construction and operations. It is a goal to reuse existing roads where possible.	[STK2402 (copy)]
Fences	SYS4003	Any fences shall not impede the flow of cattle and wildlife within and between neighboring ranches, or significantly increase the travel distance to water sources.	[STK2403 (copy)]
Ranching Impact	SYS4004	The project shall aim to reduce the environmental impact to cattle ranching as well as hunting/outfitting, which are both mainstays of local ranches.	[STK2404 (copy)]
Array Core Location	SYS4500	The specific location of the array core shall consider the differences in the quality of lands on the plains for other beneficial uses including ranching.	[STK2405 (copy)]

5.34 Equipment and Vehicle Requirements

Parameter	Req. #	Value	Traceability
Maintenance Personnel Transportation: Array Site	SYS3207	A fleet of maintenance and service vehicles shall be provided to enable staff to reach areas of the array requiring maintenance.	[STK5004]
Maintenance Personnel Transportation: Maintenance Center	SYS3208	Vehicles shall be provided for daily transportation of staff to the Maintenance Center from the Array Operations and Repair Centers.	[STK5004]

Parameter	Req. #	Value	Traceability
Provision of Vehicles and Equipment	SYS3300	Site maintenance vehicles and heavy equipment required for routine operations, preventive maintenance, and corrective maintenance, shall be provided.	[STK5004]
Equipment Screening for RFI	SYS3301	Site maintenance vehicles and heavy equipment operating on the Plains of San Agustin shall be screened for RFI emissions.	[STK2600]
Equipment RFI Standard	SYS3302	Vehicles and Equipment shall not include active emitter systems such as Bluetooth radios or radar that operate in the ngVLA observing bands. Incidental emissions (e.g., radiated emission from spark plugs, engine management systems, etc.) are permitted.	[STK2600]

5.35 System Life Cycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	SYS2801	The system shall be designed for an expected operational life of no less than 20 years, where the operational life is defined to start at the full operations milestone and close-out of the construction project.	[STK0303]
Cost Optimization	SYS2802	The system shall be designed to minimize total life-cycle costs over the projected design life, extending through system decommissioning/ disposal.	[STK0303, STK0600]
Sustainability	SYS2803	Sustainability and long-term environmental impact shall be considered in any material or design trade-study.	[STK0302]
Part Selection for Maintainability	SYS2805	Individual component selection criteria shall include the projected continuity of support for the component or interchangeable equivalents over the system design life.	[STK0310]
Critical Spares	SYS2812	Critical spares shall be identified and provided with sufficient inventory to support the facility for its operational life (SYS2801). Critical spares are defined as parts that are likely to be obsoleted over the operating life, are unlikely to have market substitutes, and cannot be produced/ordered in small volumes.	[STK0403, STK0310]

The system is expected to operate for an initial mission of 20 years. Accounting for the expected time to assembly and commission the instrument, a 30-year design life will be specified for all systems. Extension of the operating period would likely be tied to a renewal project to enable new capabilities to support the extended operating mission. Major infrastructure elements such as the antenna and power distributions system would ideally have longer design lives in anticipation of future re-use, but this goal should not drive system cost or complexity.

The system shall be built with an accounting of the full lifecycle costs, while respecting the constraints for construction and operations cost. Decommissioning costs shall be included as part of this assessment.

Consideration should be given to financial investments that might reduce the array's operational cost while still offering competitive lifecycle cost analysis. Examples might include the use of reusable energy generation, or energy-saving technologies for cryogenic or HVAC systems.

5.35.1 Assembly, Integration, and Verification Requirements

Requirements to support the Assembly, Integration and Verification (AIV) of the system, consistent with the AIV Concept [AD12] include the following:

Parameter	Req. #	Value	Traceability
Test Fixtures	SYS2811	Test fixtures and procedures shall be provided for subsystem level verification.	[STK0400]
System Verification Tools	SYS2813	Tools shall be provided to automate test execution and test reporting as part of array element verification. Such tools shall include near real-time data display for interactive diagnosis by engineers.	[STK0402, STK0400]
Testing of Software and Firmware	SYS2814	All software and firmware developed by the project shall be delivered with automated unit, integration, and regression testing suites.	[STK0427 (copy), STK0400]
AIV Software Tools	SYS2815	Development tools, compilers, source code, and the build system shall be delivered for all project software to enable maintenance over the life of the facility.	[STK0431 (copy), STK0400]
ICD API and software Definition	SYS2816	All Application Program Interfaces (API) or other software interfaces shall be defined in ICDs.	[STK0432 (copy), STK0400]
ICD Automated Conformance Testing	SYS2817	Automated test results demonstrating conformance to API ICDs shall be delivered with the product.	[STK0433 (copy), STK0400]
ICD LRUs	SYS2818	ICDs shall be delivered for each Line Replaceable Unit in the system.	[STK0434 (copy), STK0400]
VLA Interference	SYS2819	It is a goal to minimize interference with VLA operations during the construction/transition phase.	[STK2603 (copy)]
AIV Concept	SYS2820	The system shall provide any ancillary features necessary to conform with the Observatory-approved and released AIV Concept.	[STK0400, STK0536]

5.35.2 Commissioning and Science Validation Requirements

Requirements to support the Commissioning and Science Validation (CSV) of the system, consistent with the CSV Concept [AD13] include the following:

Parameter	Req. #	Value	Traceability
Incremental Delivery to Operations	SYS2830	Operational capabilities and observing modes shall be made available in stages during the transition from construction through to the commencement of full operations.	[STK0511 (copy)]

Parameter	Req. #	Value	Traceability
Delivery with SRDP Pipeline	SYS2831	Delivery of a commissioned standard observing mode shall include an operational SRDP pipeline before it is offered for regular use through PI proposals.	[STK0512 (copy)]
Science Operations API	SYS2832	A science-oriented API (scripting interface) for calling high-level array functions, prior to the widespread use of Scheduling Blocks (SBs), shall be delivered.	[STK0516 (copy)]
Observing Simulator	SYS2833	Simulators to enable the development of observing scripts without the real system shall be delivered.	[STK0517 (copy)]
Interactive Shell Access	SYS2834	The system shall provide interactive shell access to the calibration and imaging software, running on an Observatory-supported OS.	[STK0518 (copy)]
External Calibrator Data Interface	SYS2835	It is a goal for the system to provide interfaces to make use of any contemporaneous flux densities, spectra, and polarization of calibrators in the various ngVLA bands that are already provided by the VLA and/or ALMA.	[STK0520 (copy)]
Availability for Early Science	SYS2836	Proposal-driven observations, or Early Science, shall commence as soon as a commissioned observing mode is available with capabilities in excess of the current VLA.	[STK0501 (copy)]
First Look Science Products	SYS2837	The project shall prepare and release a set of First Look Science Products, obtained as part of Science Validation activities, before the start of proposal-driven observations with the array.	[STK0500 (copy)]
CSV Concept	SYS2838	The system shall provide any ancillary features necessary to conform to the Observatory-approved and released CSV Concept.	[STK0524]

5.36 Documentation Requirements

Parameter	Req. #	Value	Traceability
As-Built Drawings	SYS6001	As-built drawings shall be provided for all custom hardware and facilities delivered as part of the system.	[STK0435]
Operations and Maintenance Manuals	SYS6002	Operations and Maintenance Manuals shall be provided for each LRU in the system.	[STK0435]
Units	SYS6003	Design materials and documentation shall use ISO standards and SI (metric) units. Imperial units may also be shown for clarity.	[STK0435]
Language	SYS6004	The language used for written documentation shall be English.	[STK0435]

Parameter	Req. #	Value	Traceability
Electronic Document Format	SYS6005	Documents and drawings of record shall be delivered in PDF. Native, editable file formats shall also be delivered.	[STK0435]

5.37 Software Development Requirements

Parameter	Req. #	Value	Traceability
SRDP Integration	SYS2401	The ngVLA project should extend and reuse the SRDP Observatory-User interfacing architecture for ngVLA.	[STK2500 (copy)]
Open Source Software	SYS4200	The ngVLA data processing and analysis software shall be developed under an open source license and the source code shall be made available to the community in order to foster community experimentation.	[STK9947 (copy)]
DMS Integration	SYS4201	The ngVLA project shall adopt existing NRAO Data Management & Software (DMS) policies, with facility integration into Observatory infrastructure and standards, in order to promote reuse and maintainability.	[STK2502 (copy)]

6 L2 System Requirements

The following requirements flow from the L1 requirements listed in Section 5. These requirements are not implementation agnostic, but provide necessary and sufficient allocation of L1 requirements to allow derivation of supporting subsystem requirements.

These requirements may move to subsidiary documents in the future.

6.1 System Collecting Area

Parameter	Req. #	Value	Traceability
System Geometric Collecting Area	SYS1021	The system gross geometric collecting area shall be 62,000 m^2 or greater.	[SCI0100, SCI0102, SCI0106]

Note that this requirement would require ~244 18m antennas with unblocked apertures.

6.2 System Temperature

Parameter	Req. #	Value	Traceability
Maximum TSYS in Freq. Span A	SYS1011	TSYS in Frequency Span A shall not exceed values in Table 2, while operating in the precision operating environment, at 45-deg elevation, and 1mm of PWV. This requirement must be met over 80% of the bandwidth of any receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106]
Maximum TSYS in Freq. Span B	SYS1012	TSYS in Frequency Span B shall not exceed values in Table 2, while in the precision operating environment, at 45-deg elevation, and 1 mm of PWV. This requirement must be met over 80% of the bandwidth of any receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106]
Maximum TSYS in Freq. Span C	SYS1013	TSYS in Frequency Span C shall not exceed values in Table 2, while in the precision operating environment, at 45-deg elevation, and 1 mm of PWV. This requirement must be met over 80% of the bandwidth of any receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106]

The system temperature contributes to system sensitivity (SYS0501–SYS0504). Added T_{SYS} can be traded against additional effective collecting area to optimize sensitivity as a function of cost.

The values given in Table 3 are at the point frequency noted and assume the environmental conditions of the precision operating environment [AD05] at an elevation of 45-degrees and assuming 1 mm of PWV.

The system temperature for Frequency Span A accommodates a ~20% degradation from EVLA performance. These figures are supported by developments at CSIRO and Caltech on 3:1 wideband feeds. The goal at low frequencies is to provide improved sensitivity relative to the VLA while not introducing an undue maintenance burden by doubling the antenna receiver complement. Note that when comparing various receiver configurations, the system temperature and the feed illumination efficiency should be equally considered to make fair comparisons. This is discussed further in Section 7.4.1.

System temperatures at Spans B and C (SYS1012, SYS1013) should be as low as practical, consistent with a desire to maximize sensitivity at these frequencies. Reductions in Span A would also be desirable.

Frequency (GHz)	1.2	5	7.9	8	30	40	50	70	80	100	115
Max T_{SYS} (K)	27	28	29	25	31	40	95	120	68	68	150

Table 3 – T_{SYS} over frequency in precision environment.

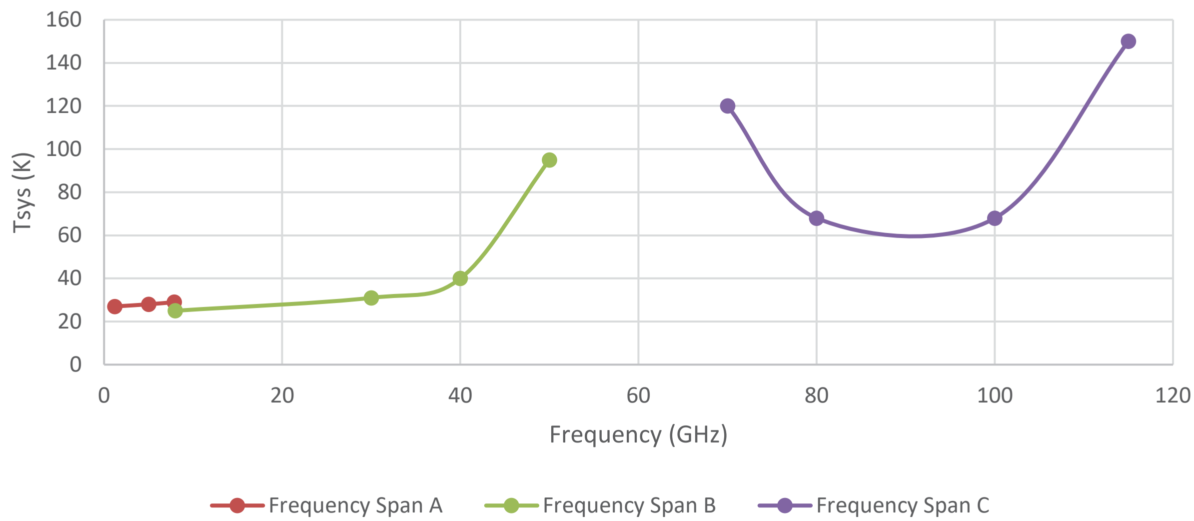

Figure 3 – T_{SYS} over frequency in precision environment.

6.3 *Analog and Digital Efficiency Requirements*

Parameter	Req. #	Value	Traceability
Antenna Efficiency: Precision Environment	SYS1031	The antenna efficiency in the precision operating environment shall exceed the values given in Table 3. This requirement must be met over 80% of the bandwidth of any receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106
Antenna Efficiency: Normal Environment	SYS1032	The antenna efficiency in the normal operating environment shall exceed the values given in Table 4. This requirement must be met over 80% of the bandwidth of any receiver (i.e., band edges are exempted).	[SCI0100, SCI0102, SCI0106]
Minimum Interferometer Digital System Efficiency	SYS1033	The digital system efficiency shall be a minimum of 0.96, including quantization and correlation losses (equiv. to 3.0 effective bits). It is desirable to approach 0.99 efficiency over narrow (<5 GHz) bandwidths for spectral line use cases.	[SCI0100, SCI0102, SCI0106]
Minimum Digital Quantization Levels: Span A, B	SYS1034	The minimum number of digital quantization levels shall be 256 levels (8-bits) for frequency span A and B.	[SYS1033]

Parameter	Req. #	Value	Traceability
Minimum Digital Quantization Levels: Span C	SYS1035	The minimum number of digital quantization levels shall be 16 levels (4-bits) for frequency span C	[SYS1033]
Correlator Precision	SYS1036	The correlator precision shall be 8-bit minimum while ingesting the total instantaneous processed bandwidth specified in SYS0903.	[SYS1033]

Efficiencies associated with calibration and imaging performance are addressed elsewhere in this specification. Antenna efficiency includes antenna reflector/structure losses and feed illumination losses. The antenna efficiency is specified at a single frequency within each Frequency Span (see Section 5.4 for simplicity; elaborated in Section 6.3.1). The digital system efficiency includes quantization efficiency and any losses from requantization at various parts of the digital signal path. With three-bit (eight-level) effective quantization, 0.96 efficiency is achievable [RD07].

6.3.1 Antenna Efficiency Allocations in Precision Environment

Table 4 shows the allocation of antenna efficiency errors. Additional frequencies are included for clarity. The allocation of efficiencies is based on projected taper and spill contributions of candidate feeds with shaped optics. No allocation is included for blockage or polarization, as unblocked apertures are preferred.

The structural contributions include a surface error contribution calculated with the Ruze formula, and a focus efficiency term for defocus as a result of deformations due to gravity. The focus efficiency is the minimum permitted over the full elevation range. Total antenna efficiencies at each frequency appear in the far right column.

	Antenna Efficiencies									
Freq.	Taper	Spill.	Block.	Pol.	**Illum.**	Focus	Surface	Ohmic	**Struct.**	**Total**
GHz	η_T	η_S	η_B	η_X	$\boldsymbol{\eta_T\eta_S\eta_B\eta_X}$	η_F	η_{RUZE}	η_{OHM}	$\boldsymbol{\eta_P\eta_{RUZE}}$	$\boldsymbol{\eta_A}$
2	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
6	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
10	0.95	0.92	1	0.99	**0.87**	1	1	1	**1**	**0.87**
30	0.95	0.92	0.99	0.99	**0.86**	0.99	0.96	1	**0.95**	**0.81**
50	0.95	0.92	0.99	0.99	**0.86**	0.99	0.89	1	**0.88**	**0.75**
80	0.95	0.92	0.99	0.99	**0.86**	0.97	0.75	0.99	**0.73**	**0.62**
100	0.95	0.92	0.99	0.99	**0.86**	0.96	0.64	0.99	**0.61**	**0.53**
120	0.95	0.92	0.99	0.99	**0.86**	0.94	0.52	0.99	**0.49**	**0.42**

Table 4 – Antenna efficiency budget as a function of frequency for precision environment.

6.3.2 Antenna Efficiency Allocations in Normal Environment

	Antenna Efficiencies									
Freq.	Taper	Spill.	Block.	Pol.	**Illum.**	Focus	Surface	Ohmic	**Struct.**	**Total**
GHz	η_T	η_S	η_B	η_X	$\eta_T\eta_S\eta_B\eta_X$	η_F	η_{RUZE}	η_{OHM}	$\eta_P\eta_{RUZE}$	η_A
2	0.95	0.83	1	0.98	**0.77**	1	1	1	**1**	**0.77**
6	0.95	0.83	1	0.98	**0.77**	1	0.99	1	**0.99**	**0.77**
10	0.95	0.92	1	0.99	**0.87**	1	0.98	1	**0.98**	**0.85**
30	0.95	0.92	0.99	0.99	**0.86**	0.99	0.87	1	**0.86**	**0.74**
50	0.95	0.92	0.99	0.99	**0.86**	0.99	0.67	1	**0.66**	**0.57**
80	0.95	0.92	0.99	0.99	**0.86**	0.97	0.36	0.99	**0.35**	**0.30**
100	0.95	0.92	0.99	0.99	**0.86**	0.96	0.21	0.99	**0.20**	**0.17**
120	0.95	0.92	0.99	0.99	**0.86**	0.94	0.1	0.99	**0.09**	**0.08**

Table 5 – Antenna efficiency budget as a function of frequency for normal environment.

Table 5 Notes:

1. The delay/phase drift requirements apply on a time scale up to 300 seconds, which is taken to be the length of a complete instrumental calibration cycle. The drift residual term is an rms residual, after subtraction of any linear trend over the specified time period. It is desirable to meet the drift requirements over longer intervals so as to allow longer calibration cycles; a goal is to meet the delay/phase drift requirement on time scales of 1000 seconds.
2. The phase noise specification should be integrated over the frequency range 1 Hz to 100 kHz.
3. The temporal delay/phase error allocation to "Antenna Structure" refers to the mechanical structure of the antenna, and arises from wind or thermal distortions of the antenna. The delay error is a function of the direction of the incident wave front and direction of the antenna distortion. The drift residual could arise due to non-intersection errors in the antenna, and should constrain any axis non-intersection misalignments.
4. Phase noise is only allocated to the final oscillators in the system that are used for down conversion or data sampling. Note that the digitizer clock stability will scale proportional to the frequency down conversion, so the required stability of the actual digitizer clock for a 7 GHz baseband would be approximately: 76 fsec * 120 GHz/7 GHz = 1.3 psec.
5. It is assumed that the Round Trip Phase (RTP) system will provide slow corrections only, and that the phase noise of the LO distribution system will be largely eliminated by the narrow bandwidth of the PLL for the antenna LO. The antenna structure retains a contribution due to wind induced stochastic oscillations/jitter.
6. Allocations are an arbitrary equal allocation for contributing system elements. This should be revised based on further analysis and technical feasibility.
7. The phase drift specified exceeds the frequency stability of an active hydrogen maser: frequency stability to 10^{-14} equates to phase rms of 3 psec. Providing a coherent frequency reference over the main array scales described in SYS1301 (420 km extent) is required. Sensitivity on the longest baselines must be relaxed to account for separate frequency references at each site. Final specifications for reference generation and distribution outside the 420 km extent is TBD.

The antenna efficiency specification is relaxed in the secondary operating environment (Table 5). The surface efficiency of the reflector is equivalent to a 300 μm rms surface error, reflecting the deformations expected due to differential thermal loading and/or wind loading.

6.4 Allocation of Delay/Phase Noise and Drift Requirements

Parameter	Req. #	Value	Traceability
Allocation of Delay/Phase Noise & Drift	SYS5001	The allocation of instrumental delay/phase errors shall not exceed the values in Table 6.	[SCI0100, SCI0102, SCI0106]

Table 6 shows the temporal delay/phase requirements allocation among the electronics subsystems and mechanical structure. The various quantities are combined in an RSS sense. Initial allocations are equally distributed between systems. This should be revisited as each system's technical feasibility is assessed.

Component	Noise (rms)	Drift Residual (rms) Up to 300 seconds	Absolute Drift Up to 300 seconds
Antenna Structure	76 fsec	42 fsec	4 psec
First LO: FE	76 fsec	42 fsec	0.5 psec
Digitizer Clock: FE	76 fsec	42 fsec	0.5 psec
Antenna RTP System	~0	42 fsec	0.5 psec
LO Distribution System	~0	42 fsec	2.5 psec
LO Reference	~0	TBD	TBD
Total Instrumental Error	**132 fsec**	**95 fsec**	**8 psec**

Table 6 – Allocation of temporal instrumental delay/phase errors (per antenna errors, in fsec).

If the Total Instrumental Error delay/phase noise requirement is met, the expected coherence of an interferometer pair is given in Table 7 at various observing frequencies. Note that these values do not include atmospheric contributions.

Frequency	Coherence
1 GHz	99.99%
10 GHz	99.98%
50 GHz	99.48%
70 GHz	98.98%
120 GHz	97.04%

Table 7 – Expected coherence as a function of frequency.

The coherence is given by $C = e^{-\sigma^2/2}$ where σ is the rms phase error, in radians, of a pair of antennas (i.e. $\sqrt{2}$ times the error contribution of a single antenna). A single antenna's contribution is estimated as the RSS sum of the Phase Noise and Phase Drift Residual.

6.4.1 Calculating Delay/Phase Noise and Drift

When verifying performance to system or subsystem delay/phase noise and drift specifications, the following formalism shall be used. The short period delay/phase **noise** requirement refers to the rms deviation delay/phase from a 10-second average. The requirement applies to the integrated phase noise from the highest significant frequency (~1 MHz) down to 1 Hz.

The delay/phase **drift** requirement refers to the two-point Allan Standard Deviation with a fixed averaging time, τ, of 10 seconds, and intervals, T, between 20 and 300 seconds.

$$\sigma^2(2,T,\tau) = 0.5 * <[\phi_\tau(t+T) - \phi_\tau(t)]^2>$$

ϕ_τ is the average of the absolute or differential phase over time τ = 10 seconds; < … > means the average over the data sample which should extend to 10 or 20 times the largest value of the sampling interval T that is used.

Note that this usage of the name "Allan variance" and other related terms is somewhat nonstandard. Strictly speaking, the Allan variance refers to the two-sample variance of fractional frequency and was introduced by David Allan in his studies of oscillator stability. Here the same formalism is used and the name Allan variance extended to mean the two-sample variance of phase and of gain.

6.5 Allocation of Gain Stability Requirements

Parameter	Req. #	Value	Traceability
LNA Gain Fluctuations w/ Temperature	SYS4901	The gain fluctuations as a function of temperature ((1/G) dG/dT) for cryogenic LNAs shall not exceed 0.03/K.	[SYS1601, SYS4601]
Warm Electronics Gain Fluctuations w/ Temperature	SYS4902	The gain fluctuations as a function of temperature ((1/G) dG/dT) for the warm electronics, from dewar interface to the digitizer, shall not exceed 0.01/K.	[SYS1601, SYS4601]
Dewar Temperature Regulation	SYS4903	The magnitude of temperature variations on the 2nd cryogenic stage (15 K) shall not exceed 0.03K over 200 seconds.	[SYS1601, SYS4601]
Warm Electronics Temperature Regulation	SYS4904	Warm (~300K) electronics temperature variations shall not exceed 0.1K over 200 seconds.	[SYS1601, SYS4601]

As described in Section 5.15, gain stability of 1e-3 is required over short (200-second) timescales (SYS1601, SYS4601).

Typical gain fluctuations as a function of temperature ((1/G) dG/dT) for LNAs are about 0.03/K for cryogenic devices and 0.01/K for warm devices. To achieve dG/G of 1e-3 would require thermal regulation to 0.03K within the Dewar and to 0.1K for warm devices over 200-second scales. These requirements can be traded against each other while still achieving the L1 requirements (SYS1601, SYS4601).

The inclusion of a gain calibration noise source has reduced the period over which this stability is required to 200 seconds, as described in Section 5.15.3. This noise source, and any intervening electronics between the noise source and the coupler, must be stable to 1e-3 over 20-minute periods. This 20-minute period corresponds to the expected gain calibration cycle on astronomical sources.

6.6 Bandpass Requirements

Parameter	Req. #	Value	Traceability
Bandpass Stability	SYS1701	The bandpass amplitude shall be stable to 0.3% over 60 minutes. (TBC)	[SCI0115, SYS1061]
Bandpass Ripple	SYS1702	The bandpass gain across a digitized band shall vary less than 3dB peak to peak over any 100 MHz bandwidth, within the central 80% of the band.	[SYS1033]

Parameter	Req. #	Value	Traceability
Bandpass Flatness	SYS1703	The bandpass of an individual digitized band shall vary by no more than 6 dB peak to peak, measured across the central 80% of the bandwidth.	[SYS1033]
Sideband Separation	SYS1704	The sideband separation in any dual-sideband frequency conversion system shall be better than 30dB. Goal of 40dB separation.	[SCI0115, SCI0113, SCI0116, SYS2104]

The stability requirement is closely related to the spectral line performance as well as the imaging dynamic range. Both specifications require stable gains as a function of time. The bandpass ripple and flatness specifications are constrained to maintain the minimum effective number of sampler bits over the full sampled frequency band.

The sideband separation specification will need to support the spectral dynamic range requirement and imaging fidelity requirement. For spectrally flat sources, the effects would be minimal, but for sources with spectral structure inadequate sideband separation could introduce both bandpass errors and imaging errors. A full 50 dB of separation for spectral line observations is not required since fringe washing will provide ~20 dB of attenuation of emitting sources in the field. LO offsets or sampler clock offsets could provide a further ~20 dB of attenuation.

6.7 *Triggered Observation Requirements*

Parameter	Req. #	Value	Traceability
Trigger Response Time Allocations	SYS5101	The trigger response time allocations for major activities shall not exceed the allocations given in Table 8.	[SYS3005]

The control system will need to have ports to receive and process external triggers to meet the requirements of SYS3004-SYS3005. The response time desired will limit human intervention/ assessment, so it is preferred that the system process them in an automated fashion. Table 8 shows the approximate time budget for response time (typically meeting the three-minute goal of SYS3005).

Action	Time Allocation	Cumulative Time	Notes
Reception of External Trigger	1 sec	1 sec	
Termination of Current Scheduling Block	20 sec	21 sec	
System Setup to New Scheduling Block	20 sec	41 sec	
Antenna Slew to Source	2 min max	161 sec	@90 deg/min Az., 45 deg/min El.; ignores acceleration time
Antenna Settle Time	10 sec max	171 sec	
Receiver Band Selection	20 sec max	181 sec	During settle

Table 8 – Triggered response time budget.

The time budget above imposes the following subsystem requirements:

- Antenna slew rates of 90 deg/min in Azimuth (Az.) and 45 deg/min in elevation (El.);
- Antenna settling time of 10 seconds max;
- Permitting band selection and focus during an antenna settle, which impacts electrical system size; and

- Limiting a scheduling block to 20 seconds, interruptible by the control system.

Note that the term "scheduling block" is not intended to imply a specific structure to an observation. In this context, it is intended to mean the minimum unit of a planned observation that can be executed, completed, and gracefully exited.

7 Technical Metrics

This section provides the Technical Metrics that should be monitored throughout project design and development. These parameters strongly influence the eventual effectiveness of the facility and are useful high-level metrics for trade-off decisions.

These parameters may also be useful for determining the relative priority of the requirements documented in Section 5. This would facilitate the required analysis should tensions be identified between requirements or if capability reductions are required to fit within cost constraints.

7.1 Definitions

The technical metrics below are further described in the Systems Engineering Management Plan [AD17]:

Key Performance Parameters (KPPs): The essential parameters to achieving the key science goals. These are capabilities or characteristics so significant that failure to reach the threshold value of performance can cause the system concept to be reevaluated, or even the program to be reassessed or terminated. Must have a threshold and an objective value. In a trade-off study, everything can be traded off except a KPP. The ngVLA KPPs are tied to a subset of the ngVLA Level-0 Science Requirements [AD01]. An example of a KPP may be continuum sensitivity.

Measures of Effectiveness (MoEs): These are measures closely related to operational achievement and overall success criteria for the project. MOEs reflect overall Observatory and user satisfaction (e.g., performance, safety, reliability, availability, affordability, operability, and maintainability). These metrics can be expressed on a scale with no fixed threshold. The ngVLA MoEs are tied to a subset of the Level-0 Stakeholder Requirements [AD02]. An example of an MoE might be calibration efficiency.

Measures of Performance (MoPs): Measures that are components of, or contribute to, MoEs or KPPs. that characterize physical or functional attributes relating to system operation. MoPs measure attributes considered essential to system capability and capacity to perform its operational objectives. The ngVLA MoPs are tied to a subset of the Level-1 System Requirements. An example of an MoP might be the A/T ratio of the system, supporting the continuum sensitivity KPP.

Technical Performance Measures (TPMs): These are lower level measures, typically aligned with Level-2 subsystem requirements, that support the MoPs. An example might be receiver noise temperature, contributing to the system-level A/T MoP.

The relationships between these various technical metrics and their associated source requirements is summarized in Figure 4.

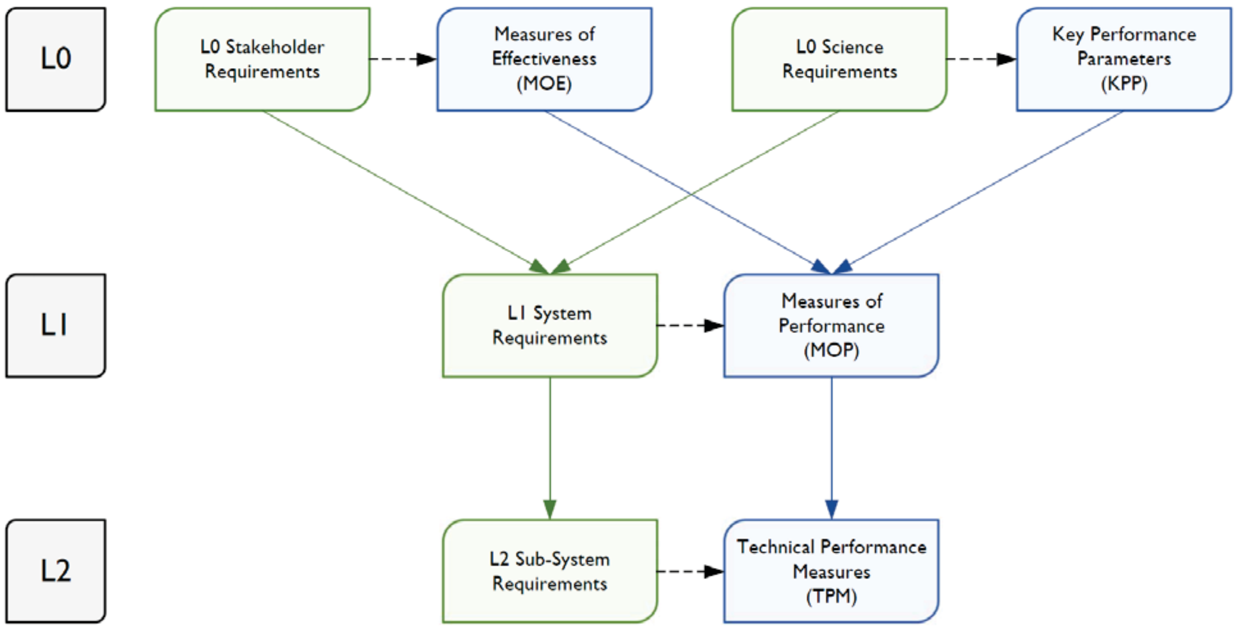

Figure 4 – Relationship of the various technical metrics to the L0 through L2 requirements. The relationships between the various technical metrics are also shown.

7.2 *Key Performance Parameters*

See the ngVLA Science Requirements document [AD01] for the most important metrics associated with each Key Science Goal (KSG). The following are the Key Performance Parameters identified for optimization and monitoring throughout the design phase:

Key Performance Parameters	Req. #
Point Source Sensitivity -Continuum	SCI0100
Point Source Sensitivity - Spectral Line	SCI0102
Surface Brightness Sensitivity - Continuum	SCI0100
Surface Brightness Sensitivity - Spectral Line	SCI0102
Survey Speed	SCI0106
Largest Angular Scale	SCI0104
Maximum Resolution	SCI0103

Table 9 – ngVLA Key Performance Parameters.

The threshold values are defined in the identified science requirement. As estimates of each measure are updated, the impact on the KSGs identified in [AD01] should be assessed.

7.2.1 Point Source Sensitivity: Continuum

Point source sensitivity is the most fundamental measure of system sensitivity, and represents the rms noise of the synthesized beam, measured in units of Janskys/beam. As with other metrics, the rms decreases (improves) as a function of the square root of the number of samples, so a fixed observing time must be given. A one-hour observation will be used.

For the continuum measure, bandwidth will be based on the available instantaneous processed bandwidth of the receiver containing the point frequency in question. It shall be computed at the point frequencies given in the table below.

Point–Source Sensitivity Measure	rms Noise of Synthesized Beam in 1 hr. Integration				
	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
Continuum					
Spectral Line (10 km/s)					

Table 10 – Point Source Sensitivity as a function of frequency. To be determined for the design at key milestones.

7.2.2 Point Source Sensitivity: Spectral Line

Spectral line sensitivity is closely related to continuum sensitivity, but the bandwidth is limited by a given spectral resolution desired. A one-hour integration time and 10 km/s spectral resolution will be used in all cases.

This figure has merit when compared to the point source continuum sensitivity when deciding on the trade-off between various receiver configurations, since the fixed bandwidth makes this measure very sensitive to changes in illumination efficiency, aperture efficiency or system temperature.

7.2.3 Surface Brightness Sensitivity and Resolution: Continuum

Surface brightness sensitivity expresses the array sensitivity scale in terms of the brightness temperature (in K) of an astronomical source that can be detected at a given angular resolution. Surface brightness sensitivity is highest when the aperture fill ratio (ratio of collecting area within a given array extent) is highest, and therefore changes as a function of angular scale.

This parameter can be explored two ways: by fixing the surface brightness of the source and solving for the maximum angular resolution, or by solving for the source brightness that is detectable at a fixed angular scale. The first case is most applicable from the scientific perspective. The distribution of targets in the sky as a function of temperature is relatively well known from surveys, so solving for the angular resolution gives an indication of the imaging performance of the array for the source of interest by defining the angular scale that fully exploits the array sensitivity.

Brightness temperatures should be explored on a logarithmic scale. Point frequency and integration time must be fixed. For this analysis, 1 hour of observing time will be used for all cases, at five frequencies of interest as tabularized below. For continuum cases, the full available instantaneous bandwidth that includes the point frequency shall be used.

Surface Brightness (Tb)	Max. Resolution as a Function of Frequency				
	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
10^{-3} K					
10^{-2} K					
10^{-1} K					
10 K					
10^{2} K					
10^{3} K					
10^{4} K					
10^{5} K					

Table 11 – Example tracking table for Surface Brightness sensitivity. To be determined for the design at key milestones.

7.2.4 Surface Brightness Sensitivity and Resolution: Spectral Line

This metric is the same as continuum surface brightness sensitivity, but at fixed channel bandwidth corresponding to a spectral resolution, expressed as a velocity. This gives an accurate estimate of the angular resolution that can be achieved at a given brightness temperature, spectral resolution, and frequency.

The parameter will be fixed at 10 km/s spectral resolution for an observation of 1 hour.

7.2.5 Continuum Survey Speed

When mapping large areas, the FOV that can be imaged is important along with the continuum sensitivity. Rather than express the FOV, a survey speed is a more relevant parameter for mapping large areas at a given noise level. A 10 μJy continuum sensitivity limit will be used for this measure, expressed in deg^2/hr as a function of observing frequency.

Bandwidth will be based on the available bandwidth of the receiver containing the point frequency in question (most relevant if the center frequencies of the bands are used). It shall be parameterized as a function of frequency but not angular scale, assuming the full array collecting area is used.

MOE	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
Continuum Survey Speed					

Table 12 – Continuum Survey Speed as a function of frequency. To be determined for the design at key milestones.

7.2.6 Largest Angular Scale

Interferometers are insensitive to large-scale structures since they are "resolved out" by the instrument. The largest angular scale that can be detected by the interferometric array is dictated by the shortest baseline. Expressed in arcseconds, this parameter indicates this fundamental limit and the feasibility of combining the collected data with maps from other arrays or single dishes.

Largest angular scale should be expressed as a function of frequency.

MOE	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
Largest Angular Scale					

Table 13 – Largest Angular Scale as a function of frequency. To be determined for the design at key milestones.

7.2.7 Maximum Angular Resolution

The maximum angular resolution that the array can resolve is dictated by the longest baselines present in the array. It will change as a function of frequency.

MOE	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
Maximum Angular Resolution					

Table 14 – Maximum Angular Resolution as a function of frequency. To be determined for the design at key milestones.

7.3 *Measures of Effectiveness*

The following are the Measures of Effectiveness identified for optimization and monitoring throughout the design phase. Note that some of the design constraints identified in AD02 are used to generate these measures when appropriate.

Key Performance Parameters	**Req. #**
Construction Affordability	CON001
Operations Affordability	CON002
Observations Supported by Standard Observing Modes	STK1000
Observational Efficiency	STK1401
Calibration Efficiency	STK1402

Table 15 – ngVLA Measures of Effectiveness. To be determined for the design at key milestones.

Consistent with the definition of these measures, the MoEs can be thought of on a continuum with no clear minimum threshold. Performance to each MoE will be assessed as the design matures and approaches key technical baselines such as the system CoDR, PDR and FDR.

7.3.1 Construction Affordability

A construction project cost cap is provided by CON001. Affordability is a key programmatic metric, so the project construction point estimate will be updated for each revision of the technical baseline, with the goal of reducing the total construction cost.

7.3.2 Operations Affordability

An annual operations cost cap is provided by CON002. Affordability in operations is a key programmatic metric for the NSF AST, so the project annual operations point estimate will be updated for each revision of the technical baseline, with the goal of reducing the projected annual operations cost.

7.3.3 Observations Supported by Standard Observing Modes

ngVLA has a proposal driven operations model, with STK1000 establishing a target of delivering high-level data products to users for 80% of the executed scientific program. Using the Expected Observation Program [AD18] as the reference for the scientific program, the percent of observing time executing standard operating modes will be assessed and reported.

7.3.4 Observational Efficiency

STK1401 establishes minimum thresholds for system availability for science observations, at both the system level and the level of individual array elements. These thresholds are minimums, and improvements in system reliability and availability to improve upon this metric are desired.

7.3.5 Calibration Efficiency

STK1402 establishes goals for calibration efficiency, or the fraction of time spent on the science target. This will be assessed for standard observing modes, providing a measure of the projected calibration overheads in operation for each standard observing model.

7.4 *Measures of Performance*

The Measures of Performance that support the KPPs and MOEs above and have been identified for monitoring are as follows:

Measures of Performance	Req. #
Effective Area/Tsys	SYS1001
Distribution and Weighting of Visibilities	SYS1308
Instantaneous FOV (FWHM)	SYS1101
B_{MIN}	SYS1302
B_{MAX}	SYS1301
Calibration Efficiency	SYS1061
Antenna System Availability	SYS2601
Central System Availability	SYS2602
Array Element MTBF	SYS2402

Table 16 – ngVLA measures of performance.

Interpretation notes for each are enumerated in the subsections below.

7.4.1 Effective Area/System Temperature

This measure indicates array sensitivity independent of angular scale. It is most useful for engineers since it directly relates to the total collecting area, aperture efficiency, digital system efficiency, and system temperature.

All signal path efficiency measures shall be included in determining the effective aperture, including analog and digital system losses. However, calibration system losses will be excluded since they are not as easily quantifiable and are captured separately.

Expressed in m^2/K, this parameter allows for easy trade-offs between efficiencies and noise performance. It is parameterized as a function of frequency.

MOP	2 GHz	10 GHz	30 GHz	80 GHz	100 GHz
Aeff/Tsys					

Table 17 – Effective Area over System Temperature as a Function of Frequency. To be determined for the design at key milestones.

7.4.2 Distribution and Weighting of Visibilities

The distribution and weighting of visibilities dictates the effective array sensitivity after beam sculpting. When combined with the previous sensitivity estimates, the distribution and weighting of visibilities can be used to compute practical imaging sensitivity as a function of time on source.

The weighting of visibilities shall be given over angular scale while supporting the beam quality metric laid out in the Science Requirements document.

7.4.3 Calibration Efficiency

This MOP allows an engineer to estimate the effective array imaging sensitivity as a function of wall clock time, not just time on source. When combined with the raw sensitivity metrics and the distribution and weighting of visibilities, the calibration efficiency permits estimating efficiency in typical observations and the projected scheduling time required for a suite of observations using standard observing modes.

This measure is intended to represent the likely calibration overheads in a standard observing mode. The goal is to reduce the time allocated to calibration while maintaining system performance. While actual observing efficiency will vary on a use case by use case basis, relative improvements in this parameter should broadly improve efficiency for most use cases.

Standard observing modes that should be parameterized for this MOP include full beam, full band, continuum observation at the standard frequencies used for the MOEs (2 GHz, 10 GHz, 30 GHz, 80 GHz, 100 GHz) and employing the full range of resolution of the array.

Total observation time shall be 1 hour to allow for combination of this efficiency factor with other metrics identified in this document.

The following calibration overheads shall be included:

- Phase
- Gain and bandpass
- Relative flux scale

Further assumptions that will be used for this estimation include the following:

- Observation shall traverse the meridian, at a declination of 0 degrees.
- All calibrators shall be 1Jy sources.
- All calibrators shall be 2 degrees from the science target.

A one-hour observation window, allows scope to improve both the time spent on each calibrator and the major cycle time between calibrator visits. Changes in either parameter will be apparent in the observing efficiency.

7.4.4 Antenna System Availability, Central System Availability & Array Element MTBF

These measures all contribute to the Observational Efficiency of the system, and also inform the Operations Affordability MoE. The projected Availability shall account for the MTTR for these respective systems, given the extent of the array and the staffing levels used in the Operations Plan, to ensure that these measures remain internally consistent.

8 Verification

The design may be verified to meet the requirements by analysis (A), inspection (I), a demonstration (D), or a test (T), each defined below.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed system is determined by a simple inspection or measurement.

Verification by Demonstration: The compliance of the developed feature is determined by a demonstration.

Verification by Test: The compliance of the developed system with the specified performance shall be demonstrated by site acceptance tests.

Multiple verification methods are allowed, although the primary (final) verification method is identified below.

8.1 L1 System Requirements

The following table summarizes the expected verification method for each requirement. Separate verification procedures should be developed as part of the assembly, integration and verification plan to elaborate on the verification strategy for each requirement, especially those that require analysis or tests.

The order of requirements in the table corresponds to the order in which they are found in Section 5.

Req. #	Parameter/Requirement	A	I	D	T
SYS0001	Functional Modes		*		
SYS0002	Interferometric Mode			*	
SYS0003	Phased Array Mode			*	
SYS0004	Pulsar Timing Mode			*	
SYS0005	Pulsar and Transient Search Mode			*	
SYS0006	VLBI Mode			*	
SYS0007	Total Power Mode			*	
SYS0008	On the Fly Mapping Mode			*	
SYS0009	Solar Observing Mode			*	
SYS0601	Sub-Array Capabilities			*	
SYS0602	Phase Preservation				*
SYS0603	Sub-Array Composition			*	
SYS0604	Sub-Array Operating Modes		*		
SYS0605	Sub-Array Operating Mode Commensality	*			
SYS0606	Sub-Array Configuration			*	
SYS0607	Sub-Array Modification			*	
SYS0102	Polarization Products			*	
SYS0103	Autocorrelation Products			*	
SYS0105	Visibility Weighting			*	
SYS0201	Phased Aperture				*
SYS0202	Concurrent Interferometric Visibilities			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS0203	Number of Beams			*	
SYS0301	Timing Capabilities		*		
SYS0302	Timing System Bandwidth			*	
SYS0303	Timing System Frequency Resolution			*	
SYS0304	Pulse Profile Bins			*	
SYS0305	Polarization		*		
SYS0306	Pulse Period				*
SYS0307	Dump Rate			*	
SYS0308	Pulse Period Resolution				*
SYS0401	Search Capabilities		*		
SYS0402	Search System Bandwidth			*	
SYS0403	Search System Frequency Resolution			*	
SYS0404	Search System Time Resolution			*	
SYS0405	Polarization			*	
SYS0501	VLBI Recording Capabilities			*	
SYS0502	eVLBI Capabilities	*			
SYS4401	Flux Scale			*	
SYS4402	Autocorrelation Integration Intervals			*	
SYS4403	PSD Differencing			*	
SYS5700	Variable Slew Rates	*			
SYS5701	Phase Center Update Rates				*
SYS5800	Direct Solar Observations	*			
SYS3001	Standard Observing Modes		*		
SYS3002	Number of Standard Observing Modes	*			
SYS3003	Non-Standard Observing Modes			*	
SYS3004	Triggered Observations		*		
SYS3005	Triggered Observation Response	*			
SYS3006	Trigger Time-Out			*	
SYS0701	Uncalibrated Data		*		
SYS0702	Flagged Data Table		*		
SYS0703	Calibrated Data Table		*		
SYS0721	Imaging Pipeline				*
SYS0722	Quick Look Image Pipeline				*
SYS0741	Pulsar Timing Data Product		*		
SYS0742	Pulsar Search Data Product		*		
SYS0730	Data Delivery via Observatory Archive		*		
SYS0731	Archive Period	*			
SYS0732	Archive Products		*		
SYS0733	Proprietary Data Rights		*		
SYS0734	Archive Batch Reprocessing		*		
SYS0735	Archive Backup	*			
SYS0736	Archive User Reprocessing			*	
SYS0737	Archive Image Selection			*	
SYS0738	Proprietary Period		*		
SYS0739	Archive Products – Low Level		*		
SYS0740	External Data Products			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS0743	Proprietary Period Trigger		*		
SYS0750	Data Processing for Standard Observing Modes				*
SYS0751	Data Processing Resources	*			
SYS0752	Throughput & Latency	*			
SYS0753	Heterogeneous Arrays			*	
SYS0754	Processing Triggers			*	
SYS0755	Processing Priorities		*		
SYS0756	Professing in Place		*		
SYS0757	Support for Legacy Programs		*		
SYS0760	Interactive Processing		*		
SYS0761	Data Analysis Resources			*	
SYS0762	Data Quality Assurance		*		
SYS5600	Commensal Processing		*		
SYS5601	Commensal Voltage Streams		*		
SYS5602	Commensal Low-Frequency System		*		
SYS3400	System Calibration Database		*		
SYS3401	Astronomical Calibration Database		*		
SYS3402	Monitor Database		*		
SYS3403	RFI Database		*		
SYS3404	Quality Control Database		*		
SYS5900	External eVLBI Elements		*		
SYS5901	Trigger Subscriptions			*	
SYS0801	System Frequency Range		*		
SYS0802	Optimized Frequency Range		*		
SYS0803	Frequency Span A		*		
SYS0804	Frequency Span B		*		
SYS0805	Frequency Span C		*		
SYS0806	Continuity of Frequency Coverage			*	
SYS0901	Front End Bandwidth Ratio		*		
SYS0902	Instantaneous Digitized Bandwidth		*		
SYS0903	Total Instantaneous Processed Bandwidth				*
SYS0904	Sub-Bands		*		
SYS0905	Frequency Tunability			*	
SYS0906	Fixed Analog Tunings		*		
SYS0907	Sub-Band Step Size		*		
SYS0908	Band Switching Time				*
SYS0909	Contiguous Bandwidth		*		
SYS1001	Effective Area/Tsys Ratio	*			
SYS1101	Instantaneous Field of View		*		
SYS1102	Accessible Field of View	*			
SYS1103	Slew Rates	*			
SYS1104	Tracking Rates	*			
SYS1201	Input Dynamic Range				*
SYS1202	Gain Calibration System Dynamic Range		*		
SYS1203	Provision of Variable Attenuators		*		
SYS1204	Input Protection	*			

Req. #	Parameter/Requirement	A	I	D	T
SYS1205	High-Noise Path		*		
SYS1301	Longest Baseline		*		
SYS1302	Shortest Baseline		*		
SYS1303	Zero Spacing/Single Dish Total Power		*		
SYS1304	Integration Time Ratios	*			
SYS1306	Fraction of Occupied Cells	*			
SYS1308	Distribution and Weighting of Visibilities	*			
SYS1309	Collecting Area on Long Baselines		*		
SYS1401	Highest Spectral Resolution		*		
SYS1402	Number of Spectral Channels		*		
SYS1403	Flexible Spectral Resolution		*		
SYS1404	Doppler Corrections			*	
SYS1501	Delay/Phase Variations Magnitude	*			
SYS1502	SNR Loss to Delay/Phase Variations	*			
SYS1503	Phase Noise				*
SYS1504	Phase Drift Residual				*
SYS1505	Absolute Phase Drift				*
SYS1601	TP Antennas: Gain Stability				*
SYS1603	TP Antennas: Gain Variations w/Antenna Pointing Angle				*
SYS1604	TP Antennas: System Temperature Stability over Time				*
SYS1605	TP Antennas: System Temperature Variations with Antenna Pointing Angle				*
SYS1801	TP Antennas: Gain Calibration Reference				*
SYS4601	Interferometric Antennas: Gain Stability				*
SYS4602	Interferometric Antennas: Relative Gain Stability				*
SYS4603	Gain Variations with Antenna Pointing Angle				*
SYS4801	Gain Calibration Reference				*
SYS1069	Calibration Automation		*		
SYS4301	Standard Observing Mode Calibration	*			
SYS4302	Calibration of Triggered Observations	*			
SYS4310	Real Time Atmospheric Delay Calibration				*
SYS4320	Standard Calibration Automation			*	
SYS4330	Storage and Retrieval of Calibration Parameters		*		
SYS4331	Automated Re-Measurement of Parameters		*		
SYS1061	Calibration Efficiency	*			
SYS1062	Calibration Parallelization		*		
SYS1063	Calibration Recall		*		
SYS1064	Relative Flux Scale Calibration Efficiency				*
SYS1065	Polarization Calibration Efficiency		*		
SYS1066	Bandpass Calibration Efficiency				*
SYS1067	Gain Calibration Efficiency	*			
SYS1068	Phase Calibration Efficiency	*			
SYS1900	Full Stokes			*	
SYS1901	Polarization Purity				*
SYS0104	Variable Time Resolution			*	
SYS0106	On-The-Fly Mapping – Data & Control Rates			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS0107	On-The-Fly Mapping – Antenna Tracking Rates			*	
SYS2001	Temporal Resolution		*		
SYS2002	Temporal Accuracy	*			
SYS4100	RFI Flagging			*	
SYS2104	Self-Generated Spurious Signal Power Level				*
SYS2105	LO Frequency and Sampler Clock Offsets			*	
SYS2106	Shielding & Emission Limits				*
SYS2201	Provision of Software Tools		*		
SYS2211	Proposal Submission – Standard Observing Modes			*	
SYS2212	Proposal Submission – Non-Standard Observing Modes			*	
SYS2213	Scientific Proposal Evaluation			*	
SYS2214	Technical Proposal Evaluation			*	
SYS2215	Observing Time Calculator			*	
SYS2216	Proposal Award Model		*		
SYS2217	Sub-Array Support		*		
SYS2218	Proposal Attributes		*		
SYS2221	Observation Preparation – Standard Observing Modes		*		
SYS2222	Observation Preparation – Non-standard Observing Modes		*		
SYS2223	Observation Scheduling GUI			*	
SYS2224	Observation Interruption			*	
SYS2225	Observation Preparation – Standard Observing Mode Flexibility			*	
SYS2226	Observation Time Model		*		
SYS2227	Observation Scheduling Criteria		*		
SYS2302	Observation Scheduling			*	
SYS2205	Manual Data Quality Assurance			*	
SYS2206	Quality Assurance Tool Extensibility		*		
SYS2207	Automated QA of Data Products			*	
SYS2208	Quality Assurance Tools for Standard Modes			*	
SYS2209	Data Provenance Tracking		*		
SYS3500	Proposal Preparation Tool			*	
SYS3501	Observation Preparation Tool			*	
SYS3502	Data Quality Inspection Tool			*	
SYS3503	Data Processing Inspection Tool			*	
SYS3504	Data Analysis Package			*	
SYS3505	User Support Tool			*	
SYS3506	Data Processing Package			*	
SYS2303	Calibration Automation			*	
SYS2304	Self-Calibrating Antenna			*	
SYS2305	Single Baseline Data Display			*	
SYS2306	Calibration Data Display			*	
SYS2307	Operator Console			*	
SYS2308	Operator Interface Location		*		
SYS2401	SRDP Integration		*		
SYS2402	Antenna MTBF	*			
SYS2403	Modularization		*		
SYS2405	Self-Diagnostic Function			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS2406	Configuration Monitoring		*		
SYS2407	Engineering Console			*	
SYS2408	Monitor Data Stream		*		
SYS3200	Preventive Maintenance Schedules	*			
SYS3201	Maintenance Tiers		*		
SYS3202	Optimization for Maintenance			*	
SYS3203	Criteria for Maintenance Scheduling		*		
SYS3204	Use of Failure Analysis in Spares Planning	*			
SYS3205	Reporting of Failures and Anomalies			*	
SYS3209	Maintenance Metrics Definition		*		
SYS3211	Operations and Maintenance: Transfer of Deliverables		*		
SYS3220	Provision of Diagnostic Tools			*	
SYS3221	Provision of Predictive Tools			*	
SYS3222	Maintenance Scheduling Tools			*	
SYS3101	LRU Monitoring		*		
SYS3102	LRU Alerts		*		
SYS3103	Monitor Archive		*		
SYS3105	Fast Read-Out Modes			*	
SYS3110	Performance Analysis and Automated Maintenance Scheduling			*	
SYS3111	Hot Swaps of LRUs		*		
SYS3112	Intelligent LRUs and Subsystems		*		
SYS3113	Operator Interface to System Monitoring Software			*	
SYS3114	Sub-System Automation			*	
SYS2501	Weather Monitoring		*		
SYS2502	Safety Weather Monitoring		*		
SYS2503	Weather Archive		*		
SYS2504	Atmospheric Phase Monitor			*	
SYS2601	Antenna System Availability	*			
SYS2602	Centralized Systems Availability	*			
SYS2700	Safety Specification		*		
SYS2701	Subsystem Self-Monitoring	*			
SYS2702	IT Security		*		
SYS2703	Security Specification		*		
SYS2704	Physical Security		*		
SYS3900	Inventory Tracking System			*	
SYS3901	Shipping and Receiving Logistics		*		
SYS3902	Tracking of LRUs			*	
SYS3903	Observatory-Controlled Logistics		*		
SYS3904	Packaging Used for Shipping		*		
SYS3910	Logistics Tools and Resources		*		
SYS3911	Issue Tracking-Tool			*	
SYS3912	Packaging - AIV		*		
SYS3600	Identification by Serial Numbers		*		
SYS3601	Configuration Management Tools		*		
SYS3602	Version Control of Software and Firmware		*		
SYS3603	Configuration Retrieval			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS3700	Quality Control Data Access Tool			*	
SYS3701	Quality Control Data Access Tool Location		*		
SYS3702	Quality Control of Deliverables		*		
SYS3800	Outfitted Facilities		*		
SYS3801	Facility Sustainability		*		
SYS3802	Provision of a Visitor Center		*		
SYS3803	Controlled Visitor Access		*		
SYS3810	Provision of a Maintenance Operations Center		*		
SYS3811	Maintenance Center – Support Equipment		*		
SYS3812	Maintenance Center – Ready Spares		*		
SYS3820	Provision of a Warehouse		*		
SYS3821	Warehouse Inventory System			*	
SYS3822	Warehouse Space – AIV		*		
SYS3830	Provision of a Repair Center		*		
SYS3840	Provision of an Array Operations Center		*		
SYS3850	Provision of a Science Operations Center		*		
SYS3860	Provision of Remote Support Stations		*		
SYS3870	Location of the Maintenance Operations Center		*		
SYS3871	Location of the Array Operations Center		*		
SYS3872	Location of the Science Operations Center		*		
SYS3873	Location of the Repair Center		*		
SYS3874	Location of the Warehouse		*		
SYS3880	Provision of a Guard Booth		*		
SYS3881	Provision of Support Buildings		*		
SYS3885	Facility Space - AIV		*		
SYS3886	Data and Voice Services - AIV		*		
SYS3887	Workspace - CSV		*		
SYS3888	Workspace - CSV-Operators		*		
SYS4000	Grassland Impact	*			
SYS4001	Sustainable Roads		*		
SYS4002	Existing Roads		*		
SYS4003	Fences		*		
SYS4004	Ranching Impact	*			
SYS4500	Array Core Location		*		
SYS3207	Maintenance Personnel Transportation: Array Site		*		
SYS3208	Maintenance Personnel Transportation: Maintenance Center		*		
SYS3300	Provision of Vehicles and Equipment		*		
SYS3301	Equipment Screening for RFI			*	
SYS3302	Equipment RFI Standard		*		
SYS2801	Design Life	*			
SYS2802	Cost Optimization	*			
SYS2803	Sustainability		*		
SYS2805	Part Selection for Maintainability		*		
SYS2811	Test Fixtures		*		
SYS2812	Critical Spares		*		
SYS2813	System Verification Tools			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS2814	Testing of Software and Firmware		*		
SYS2815	AIV Software Tools			*	
SYS2816	ICD API and Software Definition		*		
SYS2817	ICD Automated Conformance Testing		*		
SYS2818	ICD LRUs		*		
SYS2819	VLA Interference		*		
SYS2820	AIV Concept		*		
SYS2830	Incremental Delivery to Operations		*		
SYS2831	Delivery with SRDP Pipeline			*	
SYS2832	Science Operations API			*	
SYS2833	Observing Simulator			*	
SYS2834	Interactive Shell Access		*		
SYS2835	External Calibrator Data Interface		*		
SYS2836	Availability for Early Science		*		
SYS2837	First Look Science Products		*		
SYS2838	CSV Concept		*		
SYS6001	As-Built Drawings		*		
SYS6002	Operations and Maintenance Manuals		*		
SYS6003	Units		*		
SYS6004	Language		*		
SYS6005	Electronic Document Format		*		
SYS4200	Open Source Software		*		
SYS4201	DMS Integration		*		

8.2 L2 System Requirements

The following table summarizes the expected verification method for each requirement. Separate verification procedures should be developed as part of the verification plan to elaborate on the verification strategy for each requirement, especially those requiring analysis or tests. The order of requirements in the table corresponds to their order in Section 5.

Req. #	Parameter/Requirement	A	I	D	T
SYS1021	System Geometric Collecting Area	*			
SYS1011	Maximum T_{SYS} in Frequency Span A				*
SYS1012	Maximum T_{SYS} in Frequency Span B				*
SYS1013	Maximum T_{SYS} in Frequency Span C				*
SYS1031	Antenna Efficiency: Precision Environment				*
SYS1032	Antenna Efficiency: Normal Environment				*
SYS1033	Minimum Interferometer Digital System Efficiency	*			
SYS1034	Minimum Digital Quantization Levels: Freq. Span A, B		*		
SYS1035	Minimum Digital Quantization Levels: Freq. Span C		*		
SYS1036	Correlator Precision		*		
SYS5001	Allocation of Delay/Phase Noise & Drift				*
SYS4901	LNA Gain Fluctuations w/ Temperature		*		
SYS4902	Warm Electronics Gain Fluctuations w/ Temperature		*		

Req. #	Parameter/Requirement	A	I	D	T
SYS4903	Dewar Temperature Regulation				*
SYS4904	Warm Electronics Temperature Regulation				*
SYS1701	Bandpass Stability				*
SYS1702	Bandpass Ripple		*		
SYS1703	Bandpass Flatness		*		
SYS1704	Sideband Separation				*
SYS5101	Trigger Response Time Allocations				*

9 Appendix

9.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/submillimeter Array
AST	Division of Astronomical Sciences (NSF)
BW	Bandwidth
CDL	Central Development Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organization
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
ENOB	Effective Number of Bits
FOV	Field of View
FWHM	Full Width Half Max
HPC	High Performance Computing
HVAC	Heating, Ventilation, & Air Conditioning
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goals
LEED	Leadership in Energy and Environmental Design
LO	Local Oscillator
MoE	Measure of Effectiveness
MoP	Measure of Performance
MREFC	Major Research Equipment and Facilities Construction (NSF)
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PLL	Phase Locked Loop
PSD	Power Spectral Density
PWV	Precipitable Water Vapor
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
SEFD	System Equivalent Flux Density
SKA	Square Kilometer Array
SWG	Science Working Group
SNR	Signal to Noise Ratio
SRDP	Science Ready Data Products

TBC	To Be Confirmed
TBD	To Be Determined
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
WVR	Water Vapor Radiometer

9.2 *Derivation Notes from the Level 0 Science Requirements*

Derivations that support the science requirements are aggregated here. Information is duplicated from the main text but reorganized to better show the traceability to individual science requirements. This appendix has been updated for consistency with the Science Requirements Rev B (2020-01-06).

9.2.1 Functional Requirements

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.

This functional requirement translates directly, requiring continuous frequency coverage from 1.2–50 GHz, and from 70–116 GHz. The 50 GHz and 70 GHz boundaries are soft, based on the atmospheric temperature and opacity of the O_2 line. The band edges should be set by receiver design practicalities.

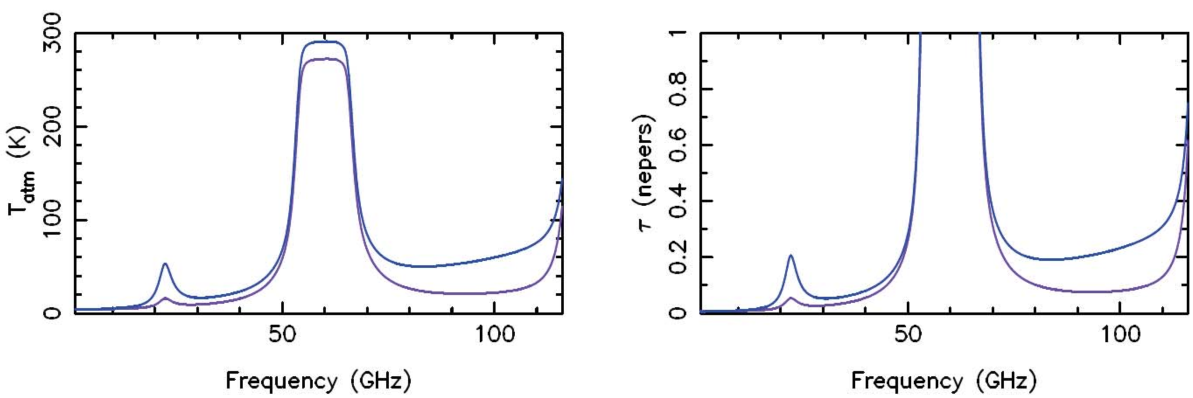

Figure 5 – Atmospheric temperature and opacity for wet (blue) and dry (purple) conditions. [RD11]

Parameter	Req. #	SciCase	Value
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 Sci. Req. Appendix Section for a list of lines). Overlap of 1% in band edges is therefore desirable.

The dominant requirement here is continuous frequency coverage with overlap of 1% at the band edge for all band transitions; i.e. a transition at 3.5 GHz would have a minimum overlap of 35 MHz. Meeting this requirement may require that any direct sampling architectures include variable sample rates to mitigate "dead zones" near the Nyquist zone boundaries.

In avoiding "astronomically interesting" spectral lines at band edges, the design should aim to avoid placing band edges for the receiver at the listed lines. Note that the reference design of the front end system does meet this requirement.

Parameter	Req. #	SciCase	Value
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.

This is interpreted as requiring the capability to digitize and process an arbitrary bandwidth (trade-off with spectral resolution) accessible from the front end. In an architecture that digitizes the full RF bandwidth, this implies bandwidth selection in a digital back end/formatter at the antenna, or in the correlator. Any digital band selection will use selectable, discrete bandwidth steps, which is permissible.

Selection of discontinuous sub-bands for Band 6 (which is wider than 20 GHz) would necessarily be selected before the DTS system, placing part of this bandwidth selection requirement on the digital back end/formatter at the antenna.

Parameter	Req. #	SciCase	Value
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).

Mosaics do not appear to impose any unique requirements upon the system beyond those of discrete pointings. On-the-fly (OTF) mapping may have a number of flow down requirements:

- Tracking rate and pointing error allowed by the ACU at super sidereal rates
- Need for a functional mode for OTF in the ACU
- Delay model management and update rate to support the tracking rate of the antenna
- Minimum dump rate/integration period of the long-term accumulators in the correlator to support the tracking rate of the antenna
- May set a minimum data rate between the correlator and archive (archive ingest rate).

A key requirement for the OTF mode is support for "the full spectral capabilities". This suggests full channelization of the correlator to the spectral resolution requirements, while reducing the integration time to mitigate time/bandwidth smearing.

Of the survey speed cases described in SCI0106, the most demanding is a shallow survey to 10 μJy at 28 GHz. The system must complete a single field of view (primary beam) in approximately 4.3 seconds. The delays must be updated as the antenna traverses 1/10th of a beam, resulting in 400 msec update rates for delays. Visibility data integration/accumulation is limited to the same rate, and a 400 msec rate limits time and bandwidth smearing appropriate for a 300 km aperture, well in excess of natural beam width (equivalent to ~165 km baselines).

At lower frequencies, the antenna scanning rate can become limiting. Supporting 10x sidereal rates on the motion control loop ensure the feasibility of shallow, fast surveys at lower frequencies.

Parameter	Req. #	SciCase	Value
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.

The control system will need ports to receive and process external triggers. The response time required will likely preclude human intervention/assessment, so the system should process them automatically.

The table below provides an approximate time budget for response within the requirement:

Action	Time Allocation	Cumulative Time
Reception of External Trigger	1 sec	1 sec
Termination of Current Scheduling Block	20 sec	21 sec
System Setup to New Scheduling Block	20 sec	41 sec
Slew to Source	2 min max @90 deg/min Az, 45 deg/min El. Ignores acceleration time.	161 sec
Settle Time	10 sec max	171 sec
Band Selection	20 sec max (during settle)	181 sec

Table 18 – Triggered response time budget.

The time budget imposes the following requirements:

- Antenna slew rates of 90 deg/min in Azimuth and 45 deg/min in Elevation
- Antenna settling time of 10 seconds max
- Requirement to permit band selection during an antenna settle; impacts electrical system size
- Limited scheduling block of 20 seconds and/or interruptible by the control system.

Providing the operator with an opportunity to override the trigger is also likely a required functional requirement.

Parameter	Req. #	SciCase	Value
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.

Continuum observations shall have sufficient spectral resolution to mitigate time-bandwidth smearing effects when imaging the full field of view at the lowest operating frequency of the array (1.2 GHz). The acceptable time and bandwidth smearing, β, will be assumed to be 0.5, where

$$\beta = \frac{\Delta\nu}{\nu}\frac{d\theta}{\theta_{beam}} = \delta\omega_{earth}\frac{d\theta}{\theta_{beam}} = 0.5$$

A more rigorous quantification of beta should be based on the required imaging fidelity, depending on source and field structure. Beta of 0.5 is used as a starting point.

With an 18 m aperture and baselines of 1000 km in the main array, at 1.2 GHz, $\Delta\nu$ is approximately 10 kHz. At a bandwidth ratio of 3:1, this would require about 240k channels.

The flexibility goal will be interpreted as a functional requirement for variable channel bandwidth, allowing for high spectral resolution near a spectral line of interest, with coarser spectral resolution over broader bandwidths as required for time and bandwidth smearing.

Parameter	Req. #	SciCase	Value
Phased Array Capability	SCI0007	KSG4-004, KSG5-004	The system shall operate both as an interferometer and phased-array simultaneously.

The commensal phased array and interferometric capabilities are a functional requirement imposed on the central signal processor of the array. Given other parameters of the system, it is assumed to require this capability over the main array aperture diameter (~1000 km), with the phased beam offset from the boresights anywhere within the antenna main beam.

The primary purpose of this requirement is to provide visibilities in the phased array mode to correct for tropospheric and ionospheric delay perturbations from the atmosphere, however, it can also be interpreted as a full commensal capability.

The commensal interferometric capability is understood to be ideally at the full spectral resolution of the correlator. Any channelization of the beamforming mode is assumed to be post beamforming in the commensal mode.

Parameter	Req. #	SciCase	Value
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.

Parameter	Req. #	SciCase	Value
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. It is desirable that all functional capabilities listed above should be available in any combination of sub-arrays.

The combination of SCI008 and SCI009 suggest total beamforming capabilities of at least 10 beams in aggregate, though more would be desirable.

Combinations of functional capabilities between concurrent sub-arrays must be looked at closely. Commensality of modes could be a design complexity/cost driver. A workable interpretation of the desired combination of subarrays is shown in Table 1.

Parameter	Req. #	SciCase	Value
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.

Meeting the full flexibility of SCO0009 could significantly impact the CSP design.

An expected observing program shall be developed showing allowable functional combinations of resources for the central signal processor. This requirement may prove expensive to meet, and may require a high degree of redundant resources within the correlator. Should be reconsidered once the impact is understood.

An attempt has been made to identify required commensal modes, and their expected practical limitations, as shown in Table 1.

Parameter	Req. #	SciCase	Value
Pulsar Timing Capabilities	SCI0012	KSG4-001 KSG4-005, KSG5-004, KSG5-005	Timing multiple pulsars within a single primary beam is required. Support for independent de-dispersion and folding of 5 or more astronomical objects is desired. The system shall provide pulsar timing capabilities with 1 μs resolution.

This imposes a functional requirement for a pulsar timing system that can support de-dispersion and folding for 5 beams over the full receiver bandwidths. This requirement is assumed applicable only to bands below ~20 GHz, limiting the bandwidth processed by this system to 8 GHz.

The pulsar timing system will also need to support the resolution requirement in a coherent timing mode.

Parameter	Req. #	SciCase	Value
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. Interfaces for future high time-resolution imaging capabilities (e.g., FRB localization) are desired.

This requirement is assumed to apply to phased-array modes only and requires a blind/incoherent search capability, with a temporal resolution of 20–100 μs. The system may require this capability over multiple beams. Given SCI0008, SCI0009, and SCI0010, a minimum of 10 beams would have to be recorded or processed in real time. Multi-beam processing in search will be necessary to search a field in a practical time as outlined in [AD11], so processing more beams would be desirable.

Recording or real-time search must process 8 GHz of bandwidth per beam (max front end bandwidth below ~20 GHz), with a goal of processing 20 GHz per beam.

See [AD11] for further elaboration of supporting requirements. The interfaces established for commensal systems enable multiple interface points for future high time-resolution imaging capabilities.

Parameter	Req. #	SciCase	Value
Polarization Products	SCI0015	KSG1-004, KSG3-011	The system shall measure all polarization products simultaneously.

The correlator must process parallel-hands and cross-hands simultaneously to produce the four stokes polarization products. The front end must sample two orthogonal polarizations, but there is no expressed preference for circular vs linear.

Parameter	Req. #	SciCase	Value
Solar Observation Capabilities	SCI0016	N/A	It shall be possible to observe the Sun at all available frequencies.

This functional requirement will depend to some degree on the definition of the sun, given the large differences in output power as a function of solar activity. For the quiet sun at 5780K, and a system temperature of 30K, the implied analog dynamic range is about 23 dB. With an antenna SEFD of 300 Jy, and an active sun definition of 10^8 Jy, a 55 dB analog dynamic range would be required for the active sun. The latter would necessitate a high noise path.

To meet array sensitivity requirements, no additional RF components shall be introduced in front of the first gain stage (LNA). The analog dynamic range of receiving elements shall have at least 30 dB of headroom before compression. This will support observations of the sun under most conditions but would rely on offset antenna pointing for an additional 20 dB of signal attenuation (sun in first side lobe) for active sun scenarios.

Variable attenuation prior to the digitizer shall also have a matching range. Any calibration strategy should also accommodate this change in source flux, so any calibration system injection requires a variable input power of at least 30 dB.

These dynamic range requirements are understood to be most applicable at lower frequency (Bands 1 and 2), with source flux for active sun having a frequency slope that reduces the power at high frequency. These can be most easily estimated by the ratio of the 6000K sun to the noise temperature of the receiver band.

For the 70-116 GHz observing window, mid-band system temperature is approximately 75 K, requiring 19 dB of headroom.

Parameter	**Req. #**	**SciCase**	**Value**
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.

This imposes a functional requirement for bandwidth and bit-rate selection on the phased-array modes, along with recording capabilities.

Given the array size and resultant beam, it is necessary to record a minimum of 3 phased beams within a sub-array, permitting recording of both the science target and two calibrators simultaneously, or phasing up three separate portions of the array and looking at one to three science targets. The recording capabilities must match for all 3 beams (10 desired).

This capability should be viewed concurrently with the pulsar search capability requested in SCI0013. Recording demands for SCI0013 (if implemented as a post-processing capability) are likely more demanding than SCI0017 given expected VLBI observation bandwidths.

Parameter	**Req. #**	**SciCase**	**Value**
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.

This requirement will be met via rapid switching between bands, with a maximum switching time (worst case) of 20 seconds and a goal of typical band switching of 10 seconds or less. Bands can be oriented in the Dewar to place expected multi-frequency complements in adjacent cartridges.

Parameter	**Req. #**	**SciCase**	**Value**
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.

At the latitude of the VLA site (34° North) a declination of -40° is equivalent to a local elevation angle of 16°, where 0° is the local horizon and 90° is the local zenith. This imposes a maximum lower elevation limit for the antenna of 12° to provide a minimal track length during an observation.

Parameter	Req. #	SciCase	Value
Data Delivery Latency	SCI0020	KSG5-008, KSG5-011	The ngVLA shall be capable of delivering “quick-look” continuum images to PI’s within 1 hr of completing (triggered) observations of integration times up to 1 hr to inform/trigger follow-up observations using the ngVLA and/or other telescopes across the electromagnetic spectrum.

If the system is sized for average throughput, observing time and processing time will match for the mean observing scenario. This requirement imposes two additional functional requirements: (1) to be able to trigger the processing of an observation immediately, jumping the processing queue, and (2) to have a separate pipeline to produce the ‘quick look’ images.

9.2.2 Performance Requirements

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.

This requirement bounds a number of system parameters. The ambiguity in allowable time will be resolved via the development of a reference observing program, but rough orders of magnitude will be developed here for context. Cases are shown below.

The System Equivalent Flux Density ($SEFD$) of a single antenna is computed as:

$$SEFD = 2\, k_B\, T_{sys} / (\,\eta_Q \eta_A\, A\,)$$

where k_B is Boltzmann’s constant, η_Q is the digitizer quantization efficiency, η_A is the antenna efficiency, and A is the antenna’s geometric collecting area.

The naturally weighted point source rms sensitivity is computed as:

$$\sigma_{NA} = SEFD / (\,\eta_C \sqrt[2]{N_{pol}\, \Delta\nu\, t\, N_{ant}\, (N_{ant} - 1)}$$

where η_C is the correlator efficiency, N_{pol} is the number of polarizations (2), $\Delta\nu$ is the bandwidth, t is the integration time in seconds, and N_{ant} is the number of antennas (214).

The weighted point source sensitivity is computed as:

$$\sigma_{rms} = \eta_{weight}\, \sigma_{NA}$$

<u>Case A</u>: 0.07 μJy/bm @30 GHz: Assuming 214 18m apertures[2], with 0.81 aperture efficiency, and 13.5 GHz of instantaneous bandwidth, T_{sys} of 31K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 8.8 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to 35 hours.

[2] 214 is chosen intentionally, to represent the main array. The LBA antennas are only used for verification of the long-baseline sensitivity requirements which appear later in the Science Requirements.

Case B: 0.5 μJy/bm @100 GHz: Assuming 214 18m apertures, with 0.60 aperture efficiency, and 14.0 GHz of instantaneous bandwidth, T_{sys} of 68K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 1.9 hours on source.

Assuming η_{weight} of 0.5 increases the integration time on source to about 7.4 hours.

The 30 GHz requirement is appreciably more stringent and will be a limiting continuum sensitivity case for the array. Specifications for instantaneous bandwidth and A/T as a function of frequency can be derived from these two cases.

Instantaneous is set to match the minimum to the available bandwidth with the 30 GHz receiver, which is the driving continuum use case. This suggest a minimum of ~14 GHz of instantaneous processed bandwidth. A goal of 20 GHz of bandwidth should be retained for consistency with previous messaging to the community.

A/T as a function of frequency requires definition of time. We will arbitrarily set the maximum time on source to 100 hours for comparison to other cases. Using these parameters and instantaneous BW of 14 GHz yields A/T values of 842 m^2/K @30 GHz and 116 m^2/K @100 GHz.

Parameter	Req. #	SciCase	Value
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.

The line width is computed as

$$\Delta\nu = \Delta v / c$$

where the velocity resolution, Δv, and speed of light in a vacuum, c, are both in m/s.

Using the same input parameters as **Case A** above, we reduce the bandwidth to 1 km/s resolution at the center of the band (30 GHz). This restricts our channels to 100 kHz. For a naturally weighted beam, the integration time on source is then about 7 hours. Assuming η_{weight} of 0.5 increases the integration time on source to about 26 hours. The most demanding case would be at 10 GHz since the specification is given in km/s, leading to narrow channels at the bottom of the specified range.

Case C: line sensitivity of 30 μJy/bm/km/s at 10 GHz. Centered at 10 GHz, 1 km/s resolution would correspond to 33.3 kHz channels. Assuming 214 18m apertures, with 0.87 aperture efficiency, T_{sys} of 25K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 11 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to about 44 hours. If the integration time is held constant at 100 hours, the required A/T is 1,250 m^2/K.

Brightness temperature, in Kelvin, is computed as

$$\sigma_{T_B} = 1.216\, \sigma_{rms} \,/\, \theta_{1/2}^2 / \,\nu^2$$

where σ_{RMS} is the point source sensitivity in μJy/bm, $\theta_{1/2}$ is the resolution (FWHM) of the synthesized beam in arcseconds, and ν is the center frequency in GHz.

This is a simplification of

$$\sigma_{T_B} = \left({c^2}/{2\, k_B\, \nu^2}\right)\left({\sigma_{rms}}/{\Omega_B}\right)$$

where $\Omega_B = \left({\pi}/{4\ln(2)}\right)\theta_{1/2}^2$ is the beam solid angle.

The band edges are limiting in the 70 to 116 GHz window, as the system temperature rises as we approach the edges of the atmospheric window as can be seen in Figure 3. The lower edge at 70 GHz is the most challenging, as the system temperatures are comparable, but the channel bandwidth is most restricted at this edge.

Case D: Line sensitivity of 1mK at 5" angular resolution and 1 km/s spectral resolution at 70 GHz. Values for efficiency, system temperature, and collecting area are given by the requirements listed in Section 6. At 70 GHz, 1 km/s spectral resolution corresponds to 233 kHz. With 35% of the array contributing on 5" scales (η_{weight} of 0.35) 1mK brightness sensitivity is met with about 44 hours on source.

Case E: Line sensitivity of 750mK at 0.1" angular resolution and 5 km/s spectral resolution at 70 GHz. A 5 km/s spectral resolution increases channel width to 1.16 MHz. With η_{weight} of 0.5, 750mK brightness sensitivity is reached in 48 hours on source.

Since Case E is the most stringent 70 GHz case, we will use this case to define the target A/T of the system at high frequency. With an integration time to 100 hours for this limiting case, the required A/T value is 210 m^2/K at 70 GHz.

Parameter	Req. #	SciCase	Value
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.

The resolution (FWHM) of the longest baseline (B_{max}) is computed as:

$$\theta_{max} = k\lambda/B_{max}$$

If k = 0.6, 5 mas at 30 GHz corresponds to a baseline about 687 km, setting a lower bound on the minimum extent of the array.

Parameter	Req. #	SciCase	Value
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.

Using the FWHM equation given above, 20" at 116 GHz suggests baselines shorter than 26m are required, ideally as short as 16m or less.

Cost modeling suggests the main array aperture should be relatively large (18–25m) to meet sensitivity targets, and minimum spacing requirements are 1.75*D_{ANT} to avoid interference between antennas. This requirement will therefore be met by inclusion of a short baseline array (SBA) in the system architecture.

Note that a total power capability is not strictly required to meet this requirement, but is included in the system requirements set.

Parameter	Req. #	SciCase	Value
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.

A spectral resolution of 0.1 km/s at 1.2 GHz corresponds to a channel width of about 400 Hz. At 3.2 GHz (lowest center frequency where 4 GHz of bandwidth could plausibly be sampled), the corresponding channel width is 1 kHz, necessitating about 400k channels to ingest that broad of a bandwidth.

Time and bandwidth smearing at the longest baselines set a higher channel limit, if imaging the full field of view while processing the full system bandwidth is required. (While there is no scientific reason to do this, there are calibration cases).

Parameter	Req. #	SciCase	Value
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.

The full width half maximum (FWHM) of the antenna beam is calculated assuming a uniform illumination pattern, consistent with the aperture efficiency computation is given by

$$\Theta_{1/2} = 1.02\,\frac{\lambda}{D}$$

The taper coefficient of 1.02 has been verified empirically with the VLA for a shaped system with near uniform aperture illumination. Since the time metric applicable to the survey speed derivations are clock hours, a calibration efficiency term (observational efficiency) must be included. An efficiency of 0.9 will be assumed for both cases below.

Case F: 7 deg^2 @ 1 μJy/bm @ 2.5 GHz, 10 hr epoch. Assuming 214 18 m apertures, with 0.77 aperture efficiency, and 2.3 GHz of instantaneous bandwidth, T_{sys} of 27K, η_Q of 0.96, η_C of 0.99, η_{calib} of 1.0, η_{weight} of 1.0, a single pointing reaches 1 μJy/bm in 13 minutes on source.

The primary beam FWHM is 23.4' wide, for an area of ~ 0.152 deg^2. Such a system would map about 7.2 deg^2 in a 10-hour period. This assumes natural weights and ignores calibration overheads, which will make achieving this requirement difficult in practice.

With the assumed FOV of an 18m unblocked aperture and the 2.3 GHz of instantaneous bandwidth, the A/T required is 1,533 m^2/K at 2.5 GHz. Improvements in aperture efficiency and/or T_{sys} would provide a calibration margin, and an allowance for visibility weighting.

Case G: 10 deg^2 @ 10 μJy/bm @ 28 GHz, 10 hr epoch. Assuming 214 18 meter apertures, with 0.82 aperture efficiency, and 13.5 GHz of instantaneous bandwidth, T_{sys} of 31K, η_Q of 0.93, η_C of 0.98, η_{calib} of 1.0, η_{weight} of 1.0, a single pointing reaches 10 μJy/bm in a mere 2 seconds on source. The rapid scanning of this case drives the on-the-fly mapping mode requirements discussed in Section 9.2.1.

The primary beam FWHM is 2.1' wide, for an area ~ 0.001 deg^2 per pointing. Such a system would map about 23.4 deg^2 in a 10-hour period.

With the assumed FOV of an 18m unblocked aperture and the 13.5 GHz of instantaneous bandwidth, the A/T required is 941 m^2/K at 28 GHz.

Parameter	Req. #	SciCase	Value
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).

An array configuration that inherently (naturally) meets this requirement at all scales and elevation angles is not feasible. Therefore the requirement will be met through beam sculpting and the associated weighting of visibilities.

This is reflected in the η_{weight} of 0.5 in all computations above, and captured in SYS1308. Imaging weighting algorithms and the array configuration therefore must achieve this ratio while producing a sculpted beam with 90% of the power in the main lobe. The array configuration should distribute antennas to meet the beam quality requirement while keeping η_{weight} above 0.5 over the broadest range of scales possible. This likely involves a power-law distribution of antennas from the array vertex.

This requirement needs to be studied in greater detail, with an emphasis on the beam quality metrics and their relationship to other performance parameters. These more detailed derivations will flow into the array configuration and imaging post-processing system requirements.

Parameter	Req. #	SciCase	Value
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.

This requirement needs to be studied in greater detail.

To first order, the constraints on the fraction of occupied cells (SYS1306) and the distribution and weighting of visibilities (SYS1308) both ensure that there are sufficient baselines over the arcmin to mas scales to sculpt a beam to meet the imaging fidelity requirement. However, the algorithmic complexity and sensitivity penalty implied are still being quantified.

Studies of this requirement are closely tied to the work described above for the quality of the synthesized beam.

Parameter	Req. #	SciCase	Value
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.

100 mas at 20 GHz corresponds to baselines about 31–51 km depending on the chosen taper value. Meeting this snapshot imaging performance requirement is feasible with a randomized or even distribution of antennas over an area of ~ 50 km in diameter, and is addressed in the fraction of occupied cells requirement.

The radial extent that is required to support the snapshot imaging fidelity requirement should be verified by simulation. An array with a centrally condensed core will by definition have far more visibilities back to the core, requiring a more even and randomized distribution over the high end of the given range (~50 km).

The values given in SYS1306 are placeholders and need to be determined via simulation. This will be refined in future releases of this document.

Parameter	Req. #	SciCase	Value
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.

This photometric accuracy requirement must be met through flux-scale calibration. The specification implies relative accuracy, using a celestial source for calibration. A stable reference source (such as a temperature stabilized noise diode) must be provided to boot-strap values from known astronomical flux calibrators while monitoring changes in system gain. Changes in atmospheric opacity will also need to be monitored.

At a minimum, the gain stability and stability of the flux reference must be stable to better than 1% over a typical observation cycle of 20 minutes. Ideally the stability would be appreciably better, allocating most of the error to variations in atmospheric opacity and measurement noise.

This requirement should be studied in more detail and evaluated in conjunction with the calibration strategy.

Parameter	Req. #	SciCase	Value
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.

Astrometric accuracy is an RSS summation of the positional uncertainty in the reference frame and the centroid error (proportional to SNR).

With 1000 km baselines, system resolution could be 2.1 mas at 30 GHz. 1% of synthesized beam would therefore correspond to 20 µas. This requirement may have implications for the delay model management, baseline orientation, antenna position errors, pressure and humidity monitoring in the atmosphere, etc.

The functional requirements for environmental monitoring and the delay drift requirements aim to support this requirement, but it should be studied in more detail and evaluated in conjunction with the calibration strategy.

Parameter	Req. #	SciCase	Value
Timing Error	SCI0112	KSG4-003	The system timing error shall be less than 10 ns (1 ns desired) over pulsar periods correctable to a known standard from 30 min to 10 yr.

The 30-minute requirement suggests frequency stability of 3E-12 is required on 30-minute scales. Such a specification is readily achieved with the inclusion of a precision frequency reference such as an active hydrogen maser. The 10-year requirement suggests the system time must be corrected to GPS derived UTC. The corrections should be logged for the life of the instrument to enable post facto corrections of observations.

Parameter	Req. #	SciCase	Value
Brightness Dynamic Range	SCI0113	KSG3-011 KSG3-008	The system brightness dynamic range shall be >45 dB to support deep field studies at 8 GHz and >35 dB to support deep continuum imaging of nearby galaxies at 27 GHz.

The brightness dynamic range is met by controlling the variance in the complex voltage gains of the antenna (including atmospheric effects). Assuming the cross-correlation products are not normalized (as is the case with WIDAR), the cross-correlation power is

$$V_{ij} = \hat{g}_i \ \hat{g}_j^* < v_i \ v_j^* >$$

Where v_i is the equivalent voltage at the input to an antenna, $\hat{g}_i = g_i e^{-i\theta_i}$ is the complex voltage gain of that antenna and V_{ij} is the complex visibility or correlation coefficient of the noise input signals of antennas i and j. The magnitude of V_{ij} is zero for completely uncorrelated noise signals and is a positive number for correlated noise.

The visibility is closely related to the cross power product of the noise input signals at antennas i and j, but is scaled by the complex voltage gain of the antennas. Therefore, it is essential to quantify the voltage gain and to track gain fluctuations at the antenna, and impose a limit on the residual uncorrected gain variation to support the brightness dynamic range required.

Represented as powers, the desired power product P_{int} represents the cross-power from the astronomical source only:

$$P_{int} = \sqrt{P_{src,i} P_{src,j}}$$

while the correlator output is scaled by root of the products of the two independent gains:

$$P_{corr} = \sqrt{g_i g_j} P_{int}$$

Uncorrected changes in $g_i\, g_j$ will artificially inflate or deflate the flux sensed on the baseline, which introduces ringing and other imaging artifacts that effectively reduce image SNR. Both gain and phase are equally important to meeting the brightness dynamic range requirement. As reported in [RD19] (p278), 10% phase errors are comparable to 20% amplitude errors in impact on interferometric dynamic range.

We will assume for the moment that self-calibration is available (a functional requirement) and that the phase errors, after calibration, are negligible for this analysis to put an upper limit of the gain errors that would support the dynamic range requirement. Per [RD19] (p. 279), the relationship of the dynamic range limit of the system scales to the typical amplitude error on any antenna is

$$D = \frac{N}{\sqrt{2}\,\varepsilon}$$

where D is the dynamic range limit, N is the number of antennas in the array, and ε is the typical amplitude error. Assuming an array of 200 elements, the gain stability (dG/G) of a given antenna, after calibrations are applied, must approximate 1e-3 to support the higher dynamic range requirement. Accounting for imperfect phase calibration, gain amplitude stability of 1e-4 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in Section 5.15.3.

This topic will be explored in far more detail in the calibration strategy and requirements document, with an associated flow-down of phase and gain specifications to key subsystems.

Parameter	Req. #	SciCase	Value
Polarization Dynamic Range	SCI0114	KSG3-011	The polarization dynamic range shall be >35 dB at the center of the field of view to support deep field studies at 8 GHz and >25 dB to support deep continuum imaging of nearby galaxies at 27 GHz.

Some possible implications of this requirement include

- Primary beam stability
- Stable polarization angle

- Functional corrections for parallactic angle, full stokes imaging pipeline.
- Relative gain stability between antennas of 10^{-3} (TBC, using analysis for SCI0113)
- Relative gain stability of the two polarizations of 10^{-3} (TBC, using analysis for SCI0113)

This requirement will be studied in more detail as part of the calibration strategy.

Parameter	Req. #	SciCase	Value
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.

This requirement will impose limits on sideband separation and bandpass stability. The later must maintain an amplitude stability of 0.3% (50 dB) after calibration. We will assume a calibration cycle of 1 hour.

The sideband separation specification will need to support the spectral dynamic range requirement and imaging fidelity requirement. For spectrally flat sources, the effects would be minimal, but for sources with spectral structure inadequate sideband separation could introduce both bandpass errors and imaging errors. A full 50 dB of separation for spectral line observations is not required since fringe washing will provide ~20 dB of attenuation of adjacent emitting sources. LO offsets or sampler clock offsets could provide a further ~20 dB of attenuation.

Implementing LO-offsets and/or sampler clock offsets would therefore be highly desirable.

This requirement may also impose channel isolation requirements in the central signal processor, but this has not yet been evaluated. We expect that analog bandpass stability requirements will dominate.

Parameter	Req. #	SciCase	Value
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.

The intent of this requirement is that when system rms noise reaches 95 µJy/bm in a 0.1 km/s channel no system-generated spectral features are visible. The ratio of interfering signal power to the system radiometer noise must be established from this specification.

The relative spurious power in a given spectral bin will be calculated as (P–N)/N, where P is the total power in the bin, and N is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples.

Adopting the methodology from [RD14], we set the interference to noise ratio to less than 0.1.

$$INR < 0.1$$

Harmful flux density can then be found from SCI0116:

$$S_H < \sigma_{rms} * INR$$

Since the specification is given as a flux density, this can be directly compared to the SEFD to determine the required signal-to-interferer ratio. At 30 GHz, the expected SEFD for the array is 2.1 Jy:

$$\frac{S}{I}(\Delta\nu) = 10 * \log\left(\frac{9.5\ \mu Jy}{2.1\ Jy}\right)\ dB = -53\ dB$$

Since the power and flux density is proportional, the power of the spurious signal must be no more than –53 dB above the signal level on cold sky over the established channel bandwidth (0.1 km/s = 10 kHz @30 GHz). This specification will apply to total-power measurements, but can be relaxed for interferometric measurements by 20 dB due to phase winding/fringe washing (–53 dB + 20 dB = 33 dB/10 kHz). (See [AD06] for supporting derivation of interferometric attenuation factor.)

Extending the bandwidth over which the signal level is measured can increase the fidelity of the verification measurement, and a bandwidth of 1 MHz is adopted. The required attenuation will scale by the square root of the bandwidth:

$$\frac{S}{I}(1MHz) = \frac{S}{I}(10kHz) * \sqrt{\frac{1\ MHz}{1\ kHz}}$$

The end result is a spurious signal level of –43 dB/MHz for interferometric antennas. While the derivation above is given at 30 GHz, the requirement is comparable over the given frequency range.

Parameter	Req. #	SciCase	Value
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.

This requirement is similar to the general continuum sensitivity case, but dictates the A/T required on continental-scale (8800 km) baselines.

Assuming a system temperature of 25 K, aperture efficiency of 0.87 (both consistent with Section 6), 5 GHz of bandwidth (consistent with the front end bandwidth ratios above 8 GHz) and an integration time of 100 hrs, the required A/T on these baselines is 211 m^2/K.

This is equivalent to roughly 24 18m antennas providing baselines on these VLB scales. SYS1309 captures this as collecting area, since the aperture size is not constrained at the system level.

Parameter	Req. #	SciCase	Value
VLB Angular Resolution	SCI0118	KSG5-010	A 0.7 mas synthesized beam at 10 GHz is required to support measurement of proper motions for GW events at a distance of 200 Mpc

0.7 mas at 10 GHz requires baselines of 8840 km. We will not apply a correction factor k as was done for the main array, as this is parameter is used to define collecting area on these baselines as a subarray (so it is not centrally condensed like the main array).

Parameter	Req. #	SciCase	Value
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.

The requirements that support the emissive spectral dynamic range are understood to also support the absorptive case, but this topic requires further study.