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.

Version	Date	Author	Affected Section(s)	Reason
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.
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.
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.
B.01	2020-02-09	R. Selina	All	Major revision based on SRR RIDs. See tabulated RIDs for a record of changes.
B.02	2020-02-23	R. Selina	All	90% of RIDs resolved. Uploading intermediate draft to the document management system for broader team use.
B.03	2020-03-01	R. Selina	6,7	95% of RIDs resolved.
B.04	2020-03-15	R. Selina	5, 6.1.1, 6.1.3 – 6.1.6	Updated DR requirements with a table. Phased array mode updates based on OYO and PD. Edits from EJM.
C	2020-03-16	A. Lear	All	Prepared PDF for approvals and release.

Table of Contents

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 [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 the space communications 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 subsystem 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 are applicable 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. Precedence is indicated in the table below as either "This doc", indicating that this document takes precedence, or "Ref doc", in which case the reference document takes precedence.

Reference No.	Document Title	Precedence	Rev/Doc. No.
AD01	L0 Science Requirements	Ref doc	020.10.15.00.00-0001-REQ
AD02	L0 Stakeholder Requirements	Ref doc	020.10.15.01.00-0001-REQ
AD03	Operations Concept	Ref doc	020.10.05.00.00-0002-PLA
AD04	System-Level Architecture Model	This doc	020.10.20.00.00-0002-DWG
AD05	L1 Environmental Specification	This doc	020.10.15.10.00-0001-SPE
AD06	L1 System EMC and RFI Mitigation Requirements	This doc	020.10.15.10.00-0002-REQ
AD07	Requirements Management Plan	Ref doc	020.10.15.00.00-0001-PLA
AD08	Reference Observing Program	Ref doc	020.10.15.05.10-0001-REP
AD09	L0 Safety Requirements	Ref doc	020.10.15.10.00-0004-REQ
AD10	L1 Safety Specification	This doc	020.80.00.00.00-0001-REQ
AD11	Calibration Requirements	This doc	020.22.00.00.00-0001-REQ
AD12	Assembly, Integration and Verification Concept	Ref doc	020.10.05.00.00-0005-PLA
AD13	Commissioning and Science Validation Concept	Ref doc	020.10.05.00.00-0006-PLA
AD14	L1 Security Specification	This doc	020.80.00.00.00-0003-REQ
AD15	Observing Mode Framework	This doc	020.10.05.05.00-0005-PLA
AD16	Array Configuration Requirements	This doc	020.23.00.00.00-0001-REQ
AD17	Systems Engineering Management Plan	Ref doc	020.10.00.00.00-0001-PLA
AD18	Envelope Observing Program	This doc	020.10.15.05.10-0002-REP

2.2 Reference Documents

The following documents are referenced in the text and provide supporting context.

Reference No.	Document Title	Rev/Doc. No.
RD01	EVLA Project Book	V1.00, 2001-06-01
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

Reference No.	Document Title	Rev/Doc. No.
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
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
RD22	Center for Trustworthy Scientific Cyber Infrastructure	https://www.trustedci.org/guide
RD23	AUI/NRAO Cyber Security Policy	NRAO-62-68
RD24	Headroom, Dynamic Range, and Quantization Considerations	ngVLA Electronics Memo #8
RD25	Size of Computing Estimates for the ngVLA	ngVLA Computing Memo #2
RD26	System Availability Budget	020.10.15.00.00-0003-REP
RD27	System Reliability Availability and Maintainability (RAM) Requirements Memo	020.10.50.00.00-0003-MEM
RD28	System Technical Budgets	020.10.25.00.00-0002-DSN
RD29	Legacy Science Program	020.10.05.00.00-0004-PLA

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.

A set of technical constraints, flowing from the programmatic constraints established in the Stakeholder Requirements, is found in Section 5. These constraints document key design decisions and limits on the parameter space available to the system designers. The system requirements must be met while respecting the limits established by these constraints.

The Level 1 System Requirements, along with detailed explanatory notes, are found in Section 6. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements 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 7 enumerates the Level 1.1 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 subsystem 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 phase of the facility.

Section 8 identifies key performance parameters that will be monitored throughout the conceptual design phase. These are requirements highlighted for their importance to the overall effectiveness of the facility, and are useful metrics 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*	020.80.00.00.00-0003-REQ

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)
L1.1	Requirements expressed in technical functional or performance terms, but with necessary assumptions about the system architecture (System Level Requirements)
L2	Requirements that define a specification for an element of the system, presuming an architecture (Subsystem Requirements)

4.2 Requirements Flow Down

The relationships and precedence between the various requirements documents and contextual "concept" documents, leading to the System Requirements, are shown in Figure 1 (next page).

The Science Use Cases [RD16] were submitted by the Science Working Groups (SWGs) and prioritized 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 implementation-agonistic Level 1 requirements.

A subordinate set of Level 1.1 System Requirements extend the system-level requirements while presuming a high-level architecture. Examples include the calibration requirements and array configuration requirements, which depend upon the number and size of apertures in the array. These requirements provide a necessary translation layer before capturing individual subsystem specifications at Level 2. Common system standards are also adopted at this level.

Individual subsystem specifications (Level 2) flow from the Level 1 and Level 1.1 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 feed back 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].

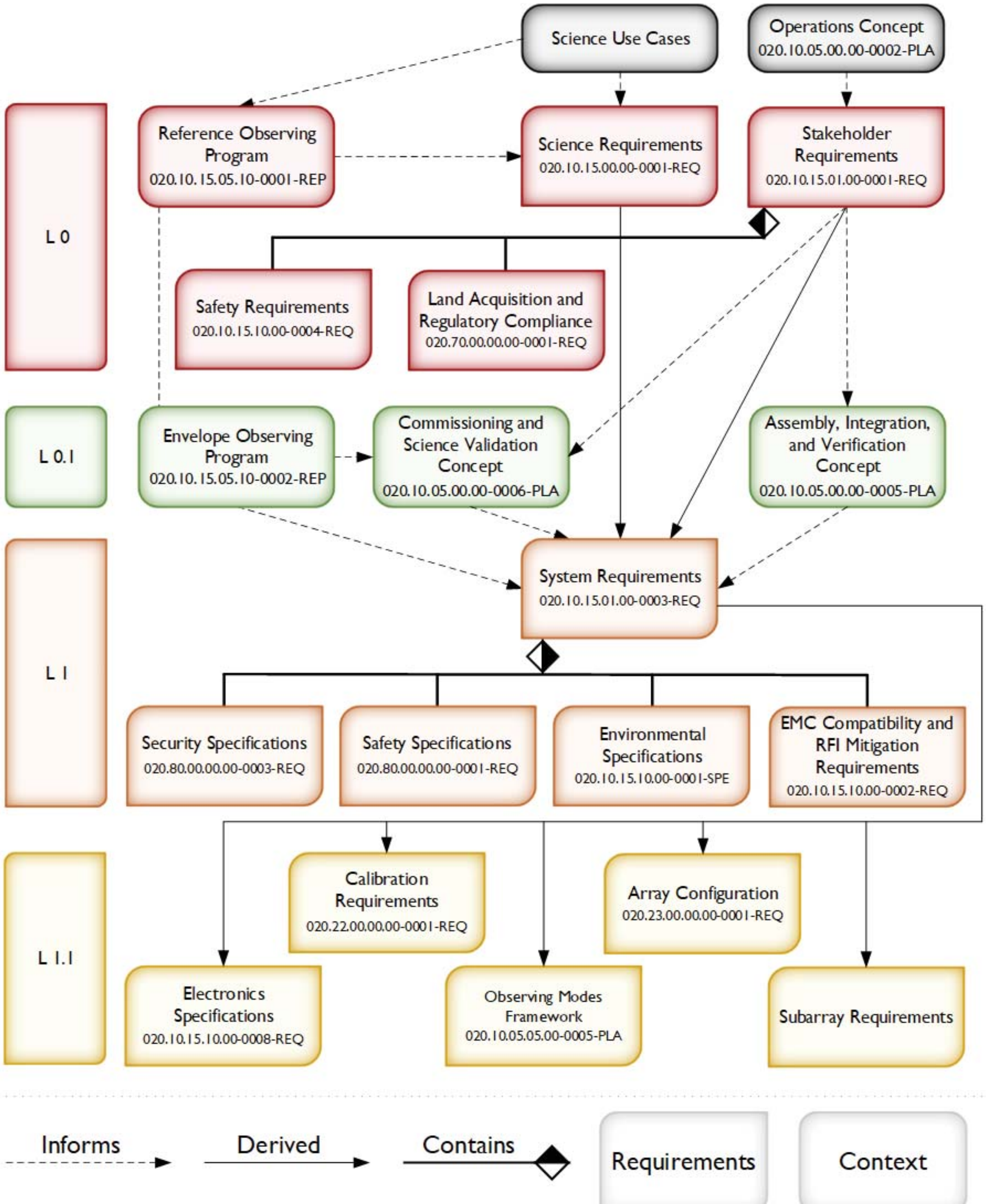

Figure 1 – Requirements flow-down to the ngVLA System Requirements.

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". Designers should strive to satisfy goals on a best-value basis.

5 Constraints

In addition to the Level 0 Requirements, a number of constraints are documented in [AD02]. Respecting these programmatic constraints leads to corresponding technical constraints on the system concept. Additional technical constraints document key decisions from the facility concept development phase. The following constraints are adopted at the system level:

CON101: Single Band Operation: The system shall operate with a single receiver band per subarray at a time (no dual band modes).

CON102: Fixed Antenna Positions: The array configuration shall have fixed antenna positions with no provision for array reconfiguration.

CON103: Alt-Az Mounts: The antennas will be constructed with Altitude-Azimuth mounts, with common limits in both axes.

CON104: Maximum Data Rate: The maximum data rate from the central signal processor shall not exceed 132 GB/sec.

CON105 Average Data Rate: The average data rate from the central signal processor shall not exceed 8 GB/sec. This average is selected as the minimum that supports the Reference Observing Program [AD08].

CON106: Total Processing Capacity: The total data post-processing capacity shall be limited to 60 PFLOP/sec. This total is selected as the minimum that supports the Reference Observing Program and the reprocessing capacity constraint listed below.

CON107: Reprocessing Capacity: The total data processing capacity shall be allocated to retain at least 20% of capacity for reprocessing.

CON108: Real-Time Calibration: Any real-time calibration pipelines shall permit parallelization at the antenna or baseline level.

Constraints 101 through 103 reflect key decisions made as part of the facility concept development, while respecting the programmatic constraint for construction and operations costs. Constraints 104 through 108 flow from a sensitivity analysis of the compute system cost to the use cases and data rates [RD09, RD10, RD25]. The science use cases vary by factors of 10^3 in computational intensity, and designing for pessimistic scenarios (high allocations to computationally intense projects) is not feasible within the cost constraints. Operations will need to treat the compute capacity delivered by the construction project as a fixed resource to be allocated based on scientific priority, and can consider requesting additional computing capacity outside the scope of the construction project.

6 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.

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

6.1 Functional Operating Modes

Parameter	Req. #	Value	Traceability
Functional Modes	SYS0001	The system shall provide a set of defined Functional Operating Modes that encapsulate sets of functional and performance requirements and produce corresponding data products.	[SCI0006, STK0200]
Interferometric Mode	SYS0002	The system shall provide an Interferometric Operating Mode with concurrent computation of cross-correlations (parallel and cross polarization) and auto-correlations (parallel and cross polarization) for all antennas or any subset of the antennas, with tunable spectral and time resolution.	[SCI0006]
Phased Array Mode	SYS0003	The system shall provide a Phased Array Operating Mode that coherently sums the voltage streams from all antennas or any subset of the 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 Array Operating Mode where the time-tagged voltage data stream is processed to time a set of dispersed pulse profiles.	[SCI0012]
Pulsar and Transient Search Mode	SYS0005	The system shall provide a Phased Array Operating Mode where a time-tagged power versus frequency data stream is recorded and processed to search for dispersed pulse profiles without a priori knowledge of their period.	[SCI0013]
VLBI Mode	SYS0006	The system shall provide a Phased Array 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]

Parameter	Req. #	Value	Traceability
Total Power Mode	SYS0007	The system shall provide an Interferometric Operating Mode with computation of auto-correlations binned into on-source and off-source positions 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]
Functional Mode Switching Time	SYS0009	The system shall be able to reconfigure from any Functional Operating Mode to another in 10 seconds or less.	[SCI0006, STK1402, SCI0005]
Standby Mode	SYS0010	The system shall provide a Standby Mode where the system status and health can be monitored, and the system can be commanded to other Functional Operating Modes.	[STK5005]
Default Mode	SYS0011	The system default mode shall be the Standby Mode.	[STK5005]

The system is expected to be divisible into many sub-arrays, with each sub-array operating in a single Functional Operating Mode. Each Functional Operating Mode is expected to have one or more Standard Observing Modes (Section 6.2), which generate quality-assured data products in response to scientific requirements.

All Functional Operating Modes are either interferometric or phased array modes. These two modes are effectively the highest class of modes of the system. All other modes are subclasses with extended, unique attributes. The functional and performance requirements applicable to the interferometric and phased array modes apply to all sub-modes. This is a deliberate arrangement aimed at providing a greater degree of reuse of processing resources and to support the sub-array flexibility requirements in Section 6.1.1.

Total Power (TP) is implemented as a subclass of the interferometric mode. This enables interferometric capabilities like the determination of antenna pointing corrections, even for TP modes, without changing the operating class of the system and the high-level system configuration. Most TP observations will likely be collected as OTF mapping observations, so capabilities developed for one subclass may support another. The inclusion of auto-correlation capabilities concurrent with other interferometric modes are discussed further in Section 6.1.2. The combination of capabilities within each Functional Operating Mode should facilitate routine data processing and concurrent system diagnostics.

The Functional Operating Mode switching time is intended to represent the time from the command being issued to the system being capable of resuming configuration for the planned observation. It does not include allocations for terminating current observations or other overheads. These additional configuration time allocations are considered in Section 7.7.

6.1.1 Sub-Array Functional Requirements

Parameter	Req. #	Value	Traceability
Sub-Array Capabilities	SYS0601	The system shall be divisible into a minimum of 10 sub-arrays.	[SCI0009]

Parameter	Req. #	Value	Traceability
Phase Preservation	SYS0602	It shall be possible to preserve the sub-array phase center when adding and/or subtracting an element from a sub-array.	[STK1403, STK0902]
Sub-Array Composition	SYS0603	The composition of a sub-array shall be configurable to any arbitrary combination of antennas from a single antenna to the full array.	[SCI0009]
Sub-Array Operating Modes	SYS0604	Any Functional Operating Mode shall be available in any sub-array.	[SCI0009, SCI0010]
Sub-Array Operating Mode Commensality	SYS0605	The system shall support a combination of Functional Operating Modes across the set of sub-arrays, with combinations and capabilities equal to or greater than the functionality described in Table 1. It is a goal to permit full flexibility in the functional modes of simultaneous sub-array sets.	[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 in a sub-array without interrupting an in-progress observation.	[STK0902]
Sub-Array Instantiation	SYS0608	The system shall permit an Array Operator to create a sub-array independent of the existence of a scheduled observation.	[STK0902]

Sub-arrays will be required for scientific operation, calibration, and maintenance purposes. 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 system phase center. However, the addition or subtraction of array elements from a sub-array needn't be immediate, and can occur at a natural boundary point such as a scan boundary.

As the calibration and observation strategies are further developed, it is expected that additional sub-array requirements may be identified.

Functional Modes	Interfer.	Phased Array	PA Timing	PA Search	VLBI	TP	OTF
Interfer. (SYS0002)	Full[1]	Limited[2]	Limited[2]	Limited[2]	Limited[2]	Full[1]	Full[1]
Phased Array (SYS0003)	Limited[8]	Full[3]	Full[7]	Full[1,7]	Full[7]	Full[9]	Limited[8]

Functional Modes	Interfer.	Phased Array	PA Timing	PA Search	VLBI	TP	OTF
PA Timing (SYS0004)	Limited[8]	Full[7]	Full[4]	Full[1,7]	Full[7]	Full[9]	Limited[8]
PA Search (SYS0005)	Limited[8]	Full[1,7]	Full[1,7]	Full[1,5]	Full[1,7]	Limited[8]	Limited[8]
VLBI (SYS0006)	Limited[8]	Full[7]	Full[7]	Full[1,7]	Full[6]	Full[9]	Limited[8]
TP (SYS0007)	Full[1]	Full[9]	Full[9]	Limited[2]	Full[9]	Full[1]	Full[1]
OTF (SYS0008)	Full[1]	Limited[2]	Limited[2]	Limited[2]	Full[1]	Full[1]	Full[1]

Table 1 – Required sub-array commensality. The primary or full-featured mode is the Y-axis, with the impact on the secondary mode denoted in each column.

Table 1 Notes:

1. Full flexibility within constraints of the maximum data input to the correlator back-end (CON104).
2. Minimum functionality must include full-bandwidth correlation in one sub-array, concurrent with phased array in another. Phased array timing, search, and VLBI capabilities may have a restricted number of beams or bandwidth beyond the limits of SYS0203, SYS0301, SYS0401, and SYS0501 to fit within the maximum data input constraint to the correlator back-end (CON104).
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.
8. Full flexibility in the phased array mode, with interferometric capabilities (processed bandwidth, time and/or spectral resolution) constrained by the maximum data input to the correlator back-end (CON104).
9. TP data rates are expected to be sufficiently small to support the full number of beams and bandwidth in the phased array, timing, and VLBI modes in the secondary subarrays.

The overarching goal with the capabilities expressed in Table 1 is to enable full flexibility for any combination of subarrays using interferometric-only or phased-array-only sub-classes, with limited functionality accepted for subarray sets that combine the two parent classes.

An operator must be able to create a subarray independent of the observation scheduler in support of engineering and maintenance activities.

6.1.2 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]

Parameter	Req. #	Value	Traceability
Limited Polarization Products	SYS0105	The system shall provide an option to produce only a subset of the correlator products (any combination of the four parallel-pol and cross-pol correlations) within a subarray.	[SCI0015]
Phase Center	SYS0108	The system shall support setting the interferometric phase center off-axis from the antenna pointing direction, out to the 2nd sidelobe of the selected receiver's lower band edge.	[SCI0016]

The autocorrelation products are primarily desired to provide a continuous measure of system temperature (when referenced to a calibrated broadband power source such as a noise diode) to enable system health and RFI environmental monitoring. These data streams are for diagnostic purposes and can be discarded after analysis (retaining only the higher-level diagnostic products). The autocorrelations should not be included in maximum data rate computations (since they can be turned off in the most demanding cases) or archive storage requirements, unless required by the respective Observation Mode.

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.

6.1.3 Interferometric Operating Mode Performance Requirements

Parameter	Req. #	Value	Traceability
Photometric Accuracy	SYS6101	The system shall limit relative photometric error to less than 1% at all frequencies for point sources, in Observing Modes that require accurate photometry.	[SCI0110]
Relative Astrometric Accuracy	SYS6102	The system shall limit astrometric error to <1% of the synthesized beam FWHM, relative to the reference frame, for a bright (SNR≥100) point source.	[SCI0111]
Brightness Dynamic Range	SYS6103	The system brightness dynamic range shall meet or exceed the values listed in Table 2. Values shall be linearly interpolated between the given point frequencies.	[SCI0113]
Polarization Dynamic Range	SYS6104	The system polarization dynamic range shall meet or exceed the values listed in Table 2. Values shall be linearly interpolated between the given point frequencies.	[SCI0114]
Spectral Dynamic Range – Absorptive	SYS6105	The absorptive spectral dynamic range shall be greater than 40 dB.	[SCI0119]
Spectral Dynamic Range – Emissive	SYS6106	The emissive spectral dynamic range shall be greater than 50 dB.	[SCI0115]

Parameter	Req. #	Value	Traceability
Image Fidelity	SYS6107	The system shall produce high fidelity images (>0.9) over the range of scales defined by SYS1301 and SYS1302, at all observed frequencies.	[SCI0108]
Image Fidelity – Snapshot	SYS6108	The system produce high fidelity images (>0.9) for snapshot observations (duration <2sec) of bright (SNR≥100) sources, over scales that correspond to baselines from 22 m to 32 km, at all observed frequencies.	[SCI0109]
No Self-Calibration	SYS6109	It is a goal for the system to support the imaging dynamic range requirements (SYS6103-SYS6106) without requiring the use of self-calibration techniques.	[SCI0102, SCI0100, SCI0113, SCI0114, SCI0115, SCI0119]

The imaging performance requirements flow directly from the science requirements and inform many of the supporting requirements encapsulated in this document.

The photometric accuracy requirement aims to constrain the contribution of the system only, hence it is a relative measure to a given flux density standard. The error in the absolute flux density scale contributed by the celestial reference is not included. This precision is only to be met in operating modes that require such accuracy, with corresponding time allocated for flux scale system calibration.

The system brightness dynamic range in Table 2 approximately scales by a factor of $1/(3f_c)$ above 8 GHz, aiming to match 45dB at 8 GHz and 35dB at 27 GHz, consistent with SCI0114. Polarization dynamic range scales by the same factor. Values at other point frequencies shall be linearly interpolated over the full range of observing frequencies. As noted in SYS6109, it is a goal to achieve these values without the use of self-calibration techniques.

Frequency (GHz)	1.2	8	27	50	70	115
Brightness Dynamic Range (dB)	45	45	35	32	30	28
Polarization Dynamic Range (dB)	35	35	25	22	20	18

Table 2 – Imaging dynamic range performance as a function of frequency.

As these performance requirements apply to the interferometric operating mode, they should also be met in sub-classes of the interferometric operating mode, such as total power and on-the-fly mapping. Exceptions may be developed in future versions of these requirements, reflecting practical differences in the observing mode strategies associated with these functional modes, and resulting limitations on performance.

6.1.4 Phased Array Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Phased Aperture	SYS0201	The system shall provide phased array capabilities over the full extent of the main array as defined in SYS1301 (700 km aperture).	[SCI0007]

Parameter	Req. #	Value	Traceability
Concurrent Interferometric Visibilities	SYS0202	The Phased Array Operating Mode shall support the computation of cross-correlations simultaneous with the phased array capabilities. These 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, with reduced bandwidth if necessary.	[SCI0008, SCI0009]
Open-Loop Calibration	SYS0204	The phasing system shall be capable of applying antenna-based delay/phase corrections based on computed delays from the cross-correlations on a periodic basis (30-300 seconds, matched to the cadence of calibrator observations).	[SCI0007, SCI0008]
Closed-Loop Calibration	SYS0205	The phasing system shall be capable of applying antenna-based delay/phase corrections based on computed delays from the cross-correlations (of a high SNR source anywhere in the primary beam) and/or the WVR system on a 1 to 30 second cadence.	[SCI0007, SCI0008]
Beamforming	SYS0206	The phasing system shall permit beamforming, with time-dependent complex array element weights, and the capability of implementing nulling directions and control of side lobe gain.	[SCI0008]
Polarization Correction	SYS0207	The phasing system shall correct for differences in polarization angle prior to combining signals from each antenna, using a common basis for both polarizations.	[SCI0015]
Beamforming Efficiency	SYS0208	The phasing system shall have a signal-to-noise performance better than 95% of that achievable by an ideal signal chain, given the same inputs and instrumental calibration residuals.	[SCI0008]
Concurrent Visibility Spectral Resolution	SYS0209	The concurrently generated cross-correlations shall have a settable center frequency and spectral resolution that may differ from the beamformed output.	[SCI0007]

The need for phased array capability over the full main array 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. The use of the main array aperture size in this definition is not intended to preclude using the extended baselines (as defined in SYS1301) in the phased array mode, so long as the phased sub-array does not exceed 700 km in extent.

The concurrent interferometric capabilities support atmospheric calibration and some science use cases. Limitations in the configuration of the concurrent visibilities are expected. Enabling different spectral resolution for phased array and interferometric visibilities is desirable, but the center frequency of the interferometric visibilities is restricted to lie within the beamformed band. Concurrent operation could be relaxed to a time multiplexed mode, should concurrent operation drive the design of the central signal processing system.

The ngVLA must enable phasing over the full range of frequencies (up to 116 GHz). This will likely require use of the WVR data in the sum, as well as real-time use of the cross-correlations in a non-reversible way. It is necessary to have this capability in a closed-loop mode (when there is a high SNR source in the antenna primary beam) or an open-loop mode (when a high SNR calibrator is observed periodically). Beamforming array element weights would be updated at the cadence of the closed-loop mode.

Another important use of the concurrent cross-correlation data will be polarization calibration. The extent of the array, and the likely use of linearly polarized feeds, will necessitate that both orthogonal polarizations be corrected to a common basis before being combined in the beamformer. The accuracy of this process should meet the requirements in Section 6.16.

The beamforming efficiency requirement is presently a placeholder. This value aims to be achievable, given the realizable quantization efficiencies and an allocation to phasing system errors. This requirement should be considered in more detail as part of a detailed assessment of the phased array mode use cases.

6.1.5 Transient (Pulsar) Timing Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Timing Capabilities	SYS0301	The system shall include a pulsar timing capability to process (de-disperse and fold) a minimum of 5 beams. It is desirable to process all available beams from the beamformer system (SYS0203), at reduced total bandwidth if necessary.	[SCI0012]
Timing System Bandwidth	SYS0302	The timing system shall process 8 GHz of bandwidth or the full instantaneous bandwidth of the band in use, whichever is less. Processing the full instantaneous bandwidth available in each band below 20 GHz is desirable.	[SCI0012]
Timing System Frequency Resolution	SYS0303	The timing system shall support channelization at a frequency resolution of 1 MHz minimum. Frequency resolution of 50 kHz is desired, at reduced total bandwidth if necessary.	[SCI0012]
Pulse Profile Bins	SYS0304	The timing system shall support a minimum of 2048 pulse profile bins.	[SCI0012]
Polarization	SYS0305	The timing system shall process both polarizations and provide full-stokes profiles.	[SCI0012]
Pulse Period	SYS0306	The timing system shall be capable of folding for pulse periods spanning from 1 msec to 30 sec.	[SCI0012]
Dispersion Measure Range	SYS0308	The system shall coherently de-disperse data within frequency channels for dispersion measures up to 3000 pc/cm^3.	[SCI0012]

Parameter	Req. #	Value	Traceability
Timing System SNR	SYS0309	The timing system shall have a signal-to-noise performance better than 95% of that achievable by an ideal signal chain, given the same configuration, inputs and instrumental calibration residuals.	[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 time resolution achievable in an individual observation is a function of the number of pulse profile bins and the pulse period. Frequency channelization may constrain the achieved time resolution, as channel bandwidth and time resolution are inversely proportional and can be traded against each other in an individual system configuration. No oversampling is expected or required to enhance time resolution beyond what his naturally provided by a Nyquist-sampled frequency channel.

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

6.1.6 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 all available beams from the beamformer system (SYS0203), at reduced total bandwidth if necessary.	[SCI0013]
Search System Bandwidth	SYS0402	The search system shall process 8 GHz of bandwidth or the full instantaneous bandwidth of the band in use, whichever is less. Processing the full instantaneous bandwidth available in each band below 20 GHz is desirable.	[SCI0013]
Search System Frequency Resolution	SYS0403	The search system shall support channelization at a frequency resolution better than 1 MHz. Frequency resolution of 100 kHz is desired.	[SCI0013]
Search System Time Resolution	SYS0404	The search system shall have minimum time resolution of 100 μsec. Resolution of 20 μsec is desired.	[SCI0013]
Polarization	SYS0405	The search system shall process both polarizations and provide full-stokes profiles.	[SCI0013]
Search System SNR	SYS0406	The search system shall have a signal-to-noise performance better than 95% of that achievable by an ideal signal chain, given the same configuration, inputs and instrumental calibration residuals.	[SCI0013]
Periodicity	SYS0407	The search system shall support the search for either periodic or aperiodic signals, as commanded in an individual system configuration.	[SCI0013]

Additional information supporting these requirements can be found in [RD17]. At a minimum, the system must include the capability to record the power vs time/frequency data stream, as expressed in SYS0005.

While processing is included in this present requirements set, the post-processing capacity could be deferred if necessary to fit within programmatic constraints.

The number of beams, frequency resolution, and time resolution in individual system configurations using this mode must can be tailored to the requirements of the specific observation, but must respect the constraint of the maximum data input to the correlator back-end (CON104). Frequency channelization may also constrain the achieved time resolution, as channel bandwidth and time resolution are inversely proportional and must be traded against each other in an individual system configuration.

6.1.7 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 a VLBI standard format. It is desirable to support this capability for 10 beams distributed over 1 to 10 sub-arrays.	[SCI0017]
VLBI Bandwidth Setting	SYS0503	The recorded bandwidth per VLBI beam shall be setable in increments consistent with the selected VLBI standard format (e.g., 1MHz * 2^N for present standards.) The total requested bandwidth may be recorded as multiple sub-band streams.	[SCI0017]
VLBI Quantization Setting	SYS0504	The recorded bandwidth per VLBI beam shall have setable quantization in increments consistent with the selected VLBI standard format (e.g., 2^N, for N between 1 and 8).	[SCI0017]
VLBI Recorded Bandwidth	SYS0505	The system shall include a total recording capacity of at least 8 GHz. Goal to record the full bandwidth of a selected receiver up to the limits on total processed bandwidth (SYS0903).	[SCI0017]

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.

The total data rate to be recorded is not yet established, and will depend upon evolving recorder standards. The central signal processor output should be capable of transmitting the full processed bandwidth of the system, at the native bit rate, should a suitable recorder be present.

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.

6.1.8 Total Power Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Power Spectral Density Scale	SYS4401	The system shall generate autocorrelation products at a period synchronized to twice the switched power reference trigger signal.	[SCI0104, SCI0110]
Autocorrelation Integration Intervals	SYS4402	The system shall have the capability of bracketing and integrating autocorrelation power around a pointing position, at time intervals spanning from 0.1 to 10 sec, based on on-source status and the switched power trigger signal.	[SCI0104]

Parameter	Req. #	Value	Traceability
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 set of requirements aims to enable a Total Power mode as a variant of the interferometric mode using position-switching.

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.

The total power operating mode presently has the lowest level of definition in these requirements. Additional functional and performance requirements associated with this mode are anticipated in future versions of these system requirements.

6.1.9 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]
Scanning Patterns	SYS5702	The system shall support a set of configurable scan patterns and antenna trajectories in support of the defined Standard Observing Modes. The minimum patterns to be supported are continuous raster scans, spirograph or daisy scans, and billiard ball patterns.	[SCI0004]

The OTF Mapping operating mode functional requirements also include the Interferometric Operating Mode Functional Requirements listed in Section 6.1.2. This list of functional requirements is not exhaustive, but instead aims to list the few requirements that are unique to this operating mode. Requirements related to tracking rates for OTF Mapping and other modes are described in Section 6.17.

6.1.10 Standby Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Electrical Power Conservation	SYS9990	It is a goal to reduce system electrical power consumption in the standby mode, while retaining the capability to transition to other Functional Modes at full specification.	[STK0303, STK1402]

The standby mode should fully support the safety and security (Section 6.26), environmental monitoring (Section 6.23), and monitor and control requirements (Section 6.24). Maintenance Operations (Section 6.22) and configuration management functions (Section 6.29) shall also remain operational during this state.

6.2 *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 support interfaces to the detection streams from flagship facilities (such as LSST and LIGO) with filters to generate observation triggers for previously approved projects using both 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 20 seconds.	[SCI0005]

The relationship between Standard Observing Modes and the Functional Operating Modes is described in Section 6.1. 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.

6.3 *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 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.

6.3.1 Low-Level Interferometric and Total Power 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 in a standard format inclusive of meta data necessary for calibration (spec. TBD).	[STK1100]

Parameter	Req. #	Value	Traceability
Online Flagged Data Table	SYS0702	A flagging table shall be provided along with the visibility data to mark data that is suspected to be corrupted based on online system flags. 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]
Online Flagged Data Table Metadata	SYS0705	The flagging table shall include metadata indicating the reasons or causes particular integrations were flagged.	[STK1100, STK1102]

This section focuses on data products produced from interferometric and total power observations. These low-level products shall be generated for all observations in the relevant functional Operation Modes defined in Section 6.1.

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. This flagging table is distinct from the one generated by an offline pipeline. A calibration pipeline will also produce calibration tables (as a high-level data product) that compensate for instrumental and atmospheric effects in phase, gain, polarization, bandpass, flux scale, etc., for observations using Standard Observing Modes.

6.3.2 High-Level Interferometric and Total Power Data Product Requirements

Parameter	Req. #	Value	Traceability
Calibration Coefficients Table	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 corrections that were supported by the observation, including delay/phase, gain/amplitude, polarization, and bandpass corrections.	[STK1000]
Offline Flagged Data Table	SYS0704	For Standard Observing Modes within the Interferometric Operating Mode, the standard data reduction shall produce an online flagged data table to mark data that appear to be outliers and should be ignored in future processing steps. These flags may be generated before and after application of the calibration coefficients.	[STK1000]
Imaging Pipeline Products	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]
Quick Look Image Pipeline Products	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, with data product extension beyond PI-requirements to make the products more suitable for reuse across projects, for Standard Observing Modes.

ngVLA data will be delivered, by default, as high-level data products. The NRAO Science Ready Data Products (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.

Known high-level data products include a flagged data table and calibration coefficient table generated by a calibration pipeline. The calibration pipeline will correct for direction-independent instrumental and atmospheric effects in phase, amplitude, polarization, bandpass, and flux scale, for observations using Standard Observing Modes. Outliers may be flagged before or after the application of these calibration coefficients.

The quick look imaging pipeline may impose functional requirements upon the correlator back end, or other parts of the online system. E.g. it may be necessary to produce a continuum channel in the CBE for rapid processing. Such considerations should be evaluated in the requirements flow down.

6.3.3 Low-Level Phased Array Data Product Requirements

Parameter	Req. #	Value	Traceability
Phased Sum Voltage Stream	SYS0745	The system shall generate phased sum timestamped voltage stream of selectable bandwidth. The data stream shall include metadata to establish data provenance.	[SYS0746, SCI0015, SCI0013, SCI0012]
VLBI Data Stream	SYS0746	The phased sum voltage streams shall be encoded in a VLBI-compliant format (TBD), inclusive of required metadata.	[SCI0017]

These low-level products shall be generated for all observations in the relevant functional Operation Modes defined in Section 6.1.

The encoding format for the phased array data streams has not yet been established, and will be selected to conform to common standards used in VLB observations.

6.3.4 Pulsar Timing and Search Data Product Requirements

Parameter	Req. #	Value	Traceability
Pulsar Timing Data Product	SYS0741	For the Standard Observing Modes within the Pulsar Timing operating mode, de-dispersed pulse profiles shall be generated and recorded in PSRFITS format. (TBC)	[SCI0012]

Parameter	Req. #	Value	Traceability
Pulsar Search Data Product	SYS0742	For the Standard Observing Modes within the Pulsar and Transient Search operating mode, power versus time, frequency and polarization shall be recorded in PSRFITS format. (TBC)	[SCI0013]

These high-level products shall be generated for all observations in the relevant functional Operation Modes defined in Section 6.1. PSRFITS is the present standard for recording pulse profiles and power versus time, frequency, and polarization series data for search system post-processing. This standard is adopted assuming continued support and development of the format.

6.3.5 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]
Archive Products – Low-Level	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 (TBC), shall be archived for the life of the facility (as defined in SYS2801).	[STK1100]
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 to replace or add high-level data products.	[STK1102]
Archive Backup	SYS0735	A full backup (a minimum of two copies) of all archived data shall be incorporated into the design. The copies shall not be collocated/co-managed to reduce the risk of simultaneous failures, and individual archive copies shall have internal redundancy to survive multiple disk errors.	[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 settable on a per-class, per-project and per-scan basis.	[STK1103, STK1105]

Parameter	Req. #	Value	Traceability
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 lapses. 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. When data is reprocessed, saving prior high-level data products may not be necessary if the new products obsolete the former. 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.

Project classes shall be extensible, with a minimum set of Normal, Large, and Legacy, consistent with AD02.

6.3.6 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 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 at least 1.2 times the expected average system throughput (defined in the Reference Observing Program), with no additional constraint on latency. The additional 20% is allocated to expected data reprocessing.	[STK1001, STK1002, STK1004]

Parameter	Req. #	Value	Traceability
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 queue an observation for priority data transfer and data processing.	[SCI0020]
Processing Priorities	SYS0755	The system shall provide a mechanism to set differing processing priorities for the high-level data products associated with a project.	[SCI0020]
Processing in Place	SYS0756	User interface tools for ngVLA data analysis and processing shall permit processing the data in place.	[STK1005 (copy)]
Support for Large and Legacy Programs	SYS0757	The system shall include interfaces to support generating high-level data products for Large and Legacy scale projects, if the project data products 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]
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)]

The requirement to process data in place (SYS0756) will require the definition of practical constraints on the quantity of data that may be processed in this fashion. Interactive tools may be limited in terms of in-memory data sets or other implementation constraints. These constraints and any limits on data transfer and remote processing shall be considered after the Observing Mode and corresponding data product definitions mature.

The interactive processing requirement (SYS0760) is intended to support non-standard modes, and the commissioning of new standard observing modes.

6.3.7 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]

The data analysis tools are expected to be the primary user tools to interface with, and manipulate, high level data products. This interface, and other user interfaces, are further described in Section 6.20.1.

6.4 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]
System Configuration Database	SYS3405	A system configuration database shall be provided to record the configuration of the system at the LRU level and higher, tracking the location of each serialized device and the versions of software deployed.	[STK1600]

The support datastores capture all known ancillary data repositories necessary for the operation, calibration, and maintenance of the system. Calibration, logistics, maintenance, scientific operations, and support functions that interface with these data stores are described in Sections 6.15, 6.18, 6.20, 6.22, 6.28, 6.29, and 6.30.

6.5 Commensal Capability Requirements

Parameter	Req. #	Value	Traceability
eVLBI Capabilities	SYS0502	It is desirable to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	[STK2501]
Commensal Processing	SYS5600	The system shall 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 (<1.2 GHz) front end.	[STK2900]

Parameter	Req. #	Value	Traceability
Commensal Metadata	SYS5603	The system shall provide interfaces to the metadata streams from each antenna and each subarray for commensal processing system use.	[STK2901]

The goal of interfacing with external network-connected VLBI stations in real-time is aimed at including other flagship facilities that can appreciably add to system sensitivity or spatial resolution. A minimum capability would provide the requisite delay buffers to accommodate the projected network delays to the GBT. A more capable implementation would have delay buffers to interface with Effelsberg and phased ALMA.

6.6 *Frequency Range*

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]
Freq. Span A:	SYS0803	1.2–8 GHz	
Freq. Span B:	SYS0804	8–50 GHz	
Freq. Span C:	SYS0805	70–116 GHz	
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 minimum 1% overlap in bandwidth.	[SCI0001, SCI0002, SCI0003]

While the system shall access all available frequencies in the 1.2–116 GHz range, the 8–50 GHz range (Frequency Span B) has the most demanding sensitivity requirements (Section 6.8), 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 band edge ratio and sensitivity requirements across each frequency span.

The telescope is expected to observe in one receiver band at a time. Each Frequency Span may be broken into bands, and the intention in the following sections is to specify constraints on how the band partitioning is done without specifying each band specifically. This is done to leave any available trade-space and design decisions to the respective design engineers.

6.7 *System Bandwidth and Frequency Tunability*

Parameter	Req. #	Value	Traceability
Front End Band Edge Ratio	SYS0901	A minimum receiver band edge ratio of 1.5:1 is required, with a 3:1 goal over Frequency Span A.	[SCI0100, SCI0102]
Total Instantaneous Processed Bandwidth	SYS0903	The system shall process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	[SCI0100]
Frequency Selection	SYS0905	If the receiver bandwidth exceeds the instantaneous 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]

Parameter	Req. #	Value	Traceability
Fixed Analog Tunings	SYS0906	While supporting the Frequency Selection requirement (SYS0905), the analog system shall provide a set of fixed tunings to facilitate calibration from catalog values. It is a goal to minimize the number of fixed tunings.	[STK1403]
Sub-Band Step Size	SYS0907	Sub-band center frequency 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]

The front end band edge ratio (f_{LOW}/f_{HIGH}) 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 in Frequency Span B (8–50 GHz). The 14 GHz requirement approximates the expected bandwidth of a mid-band receiver in Frequency Span B. The instantaneous sampled bandwidth requirement and goal should be adjusted to match the selected receiver implementation post CoDR.

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. This tuning step requirement may be relaxed in Frequency Span C should a best-value solution be identified with more restricted tuning steps.

6.8 Sensitivity Requirements

Parameter	Req. #	Value	Traceability
Effective Area to Noise Temperature Ratio	SYS1001	The effective area to noise temperature ratio of the system shall meet or exceed the values given in Table 3, with linear interpolation between columns, while operating in the precision environmental conditions defined in 020.10.15.10.00-0001-SPE [AD05] and assuming 1 mm of PWV, at an elevation of 45 degrees. This requirement must be met over 80% of the bandwidth of any given receiver. Band edges shall degrade to no less than 70% of spec.	[SCI0100, SCI0102, SCI0106]

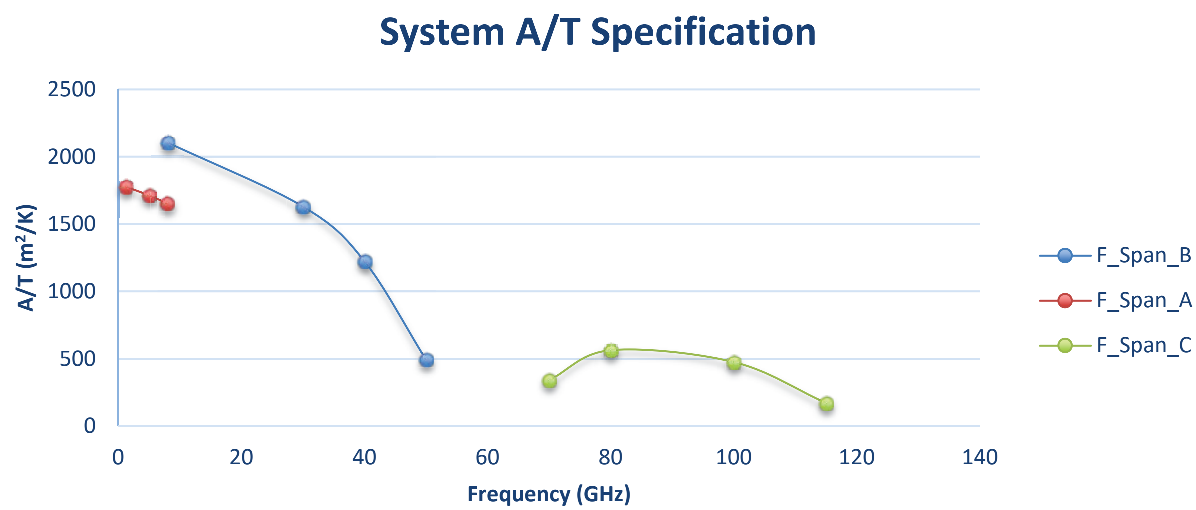

Figure 2 – System A/T specification in m²/K.

Frequency (GHz)	**1.2**	**5**	**7.9**	**8**	**30**	**40**	**50**	**70**	**80**	**100**	**115**
Min A/Tsys (m²/K)	1780	1710	1650	2110	1630	1220	490	340	560	480	170

Table 3 – System A/T specification in m²/K

The values in Figure 1 and Table 3 are based in part on expected degradation in aperture efficiency as a function of frequency and achievable system temperatures. Deviations at the edges of each receiver band are expected and allowable. Values between the listed frequency points in Table 3 shall be linearly interpolated.

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}).

6.9 *System Field of View*

Parameter	Req. #	Value	Traceability
Instantaneous Field of View	SYS1101	The system instantaneous FOV (FWHM) shall be larger than 2 arcmin at 28 GHz, and shall scale proportionally to wavelength at all other observed frequencies (SYS0801).	[SCI0106, SCI0104]
Accessible Field of View	SYS1102	The array elements shall each be capable of observing at elevations of 12° to 88°, relative to the local horizon, and at all Azimuth angles.	[SCI0019]

Parameter	Req. #	Value	Traceability
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]
Azimuth Wrap	SYS1105	The system azimuth range shall be no less than 540 degrees, providing a +/-90 degree range of overlap about true north.	[SCI0019, SCI0005, STK1402]

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. SYS1103's requirement for a 2 minute response time may presume that the antenna does not need to "unwrap" in Azimuth. I.e., this requirement shall be compliant when achieved for a 180° slew in Azimuth.

6.10 Input Dynamic Range and Headroom

Parameter	Req. #	Value	Traceability
Instantaneous Dynamic Range	SYS1201	The instantaneous dynamic range of the system shall meet or exceed the values in Table 4. Values in Freq. Span B shall be interpolated.	[SCI0016, STK2602]
Input Dynamic Range Across Setups	SYS1203	The input dynamic range of the system, across all system configurations, shall exceed the values in Table 5. Values in Freq. Span B shall be interpolated.	[SCI0016]
Input Protection	SYS1204	The system shall survive exposure to input signal power of up to 10 dBm, integrated over the receiver bandwidth, with no damage to the receiving elements.	[STK2601]
IP3 Headroom	SYS1206	The system headroom on cold sky, measured to the 3rd order intercept point (IP3), shall meet or exceed the values in Table 5. Values in Freq. Span B shall be interpolated.	[SCI0105, SCI0116]

The input dynamic range requirements flow down from both solar observations and mitigating the impacts RFI. These requirements are explored in detail in RD24. Instantaneous dynamic range is the range of input powers that shall be accommodated in a single system setup. The dynamic range across setups permits the reconfiguration or adjustment of the system (e.g., the tuning of step attenuators).

Dynamic range will be defined between the system noise on cold sky and the 1 dB compression point, assuming a broadband input signal. The 1% value is informational only. Headroom to the IP3 point ensures the desired system linearity and the suppression of unwanted intermodulation products and harmonics in the presence of strong RFI.

Frequency Range	Inst. Dynamic Range Required over 2 GHz	Inst. Dynamic Range Required, at specified quantization efficiency, over full receiver band	Inst. Dynamic Range Required, at lower quantization efficiency, over full receiver band
Freq. Span A	26dB	26dB	30dB
Freq. Span B (8GHz)	29dB	23dB	30dB
Freq. Span B (50 GHz)	29dB	20dB	30dB
Freq. Span C	15dB	6dB (20dB desired)	11dB (30dB desired)

Table 4 – Instantaneous dynamic range requirements for the ngVLA front ends.

Frequency Range (Band)	Dynamic Range Across Setups, dB (1% Compression)	Dynamic Range Across Setups, dB (1dB Compression)	System Headroom to IIP3, dB (on cold sky)
Freq. Span A	34	46	56
Freq. Span B (8 GHz)	30	42	52
Freq. Span (50 GHz)	21 (30 Desired)	33 (42 Desired)	43
Freq. Span C	19 (30 Desired)	31 (42 Desired)	41

Table 5 – Dynamic range and linearity requirements.

6.11 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	The system shall measure total power spectral density in a field, with apertures larger than 1.5x the period of the spatial frequency measured by the shortest interferometric baseline.	[SCI0104]
Integration Time Ratios	SYS1304	If achieving SYS1302 requires multiple array/antenna designs, each array shall sample overlapping spatial scales. The ratio of time required in each array to achieve matching sensitivity on overlapping scales shall not exceed a factor of four, with a goal of one.	[STK1403]
Baseline Distribution	SYS1306	The distribution of baselines in a single integration snapshot at zenith with the ngVLA main array shall meet the requirements in Table 6, where A1 is the geometric collecting area of a single antenna in the array and N(b; b1 < b < b2) is the number of baselines between baseline lengths b1 and b2.	[SCI0106, SCI0108, SCI0109, SCI0107]
Collecting Area on VLB Baselines	SYS1309	A minimum of 10% of the system A/T required in SYS1001 shall be placed on the extended (VLB-scale) baselines between 700 km and 8600 km from the array center.	[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 a main 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.

The shortest baseline requirement will most likely require a separate array of smaller apertures in addition to the main array. The single dish requirement (SYS1303) will provide 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.

Recovering the power spectral density in a field (where the field size is set by the single dish aperture) will require on-off switching and data binning, as specified by SYS0007. Many antennas may be engaged in total power measurements in order to match the sensitivity of the interferometric array on overlapping scales, consistent with the ratios established in SYS1304.

The distribution of collecting area in the array determines both the spatial resolution and the sensitivity as a function of resolution. It can also impact the achieved imaging fidelity.

Baseline Span: b_1, b_2	Collecting Area: $A_1\sqrt{N(b: b_1 < b < b_2)}$
35 m, 100 m	> 2,500 m^2
100 m, 1 km	> 17,400 m^2
1 km, 20 km	> 24,200 m^2
20 km, 500 km	> 22,900 m^2
500 km+	> 7,200 m^2

Table 6 – Radial distribution of system sensitivity in the main array.

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

The term Main Array in this document will refer to the connected element array that provides baselines out to 700km, consistent with SYS1301. The terms VLB or Extended baselines will refer to array elements that extend beyond the Main Array, and which are expected to have differing technical solutions for reference signal distribution and other practical constraints. These terms are not intended to define scientific sub-arrays used for observations.

6.12 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, beamformer, and post processing systems, across all baselines. Goal of 2,000,000 channels to be supported by the correlator and beamformer.	[SCI0105]
Variable Spectral Resolution	SYS1403	The spectral resolution shall be variable across the observed band (within the constraints set by SYS1401 and SYS1402).	[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 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 ratio of the angular offset to be imaged to the size of the synthesized beam. 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 $B_{max} = 1000\ km$[1], the maximum channel width is 10 kHz. Spanning 2.4 GHz of bandwidth would require about 240k channels, so we will adopt 240k channels as the minimum requirement. The goal of 2,000k channels would 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. Note that the goal is solely for the correlator-beamformer to support this degree of channelization. The constraints (Section 5) on the data post-processing system will preclude processing the resultant data rates.

To provide an indication of the achievable limits on bandwidth smearing, β is calculated in Table 7 for a range of maximum baselines and lower frequency points. 240k total channels are assumed, each 10kHz wide. Beta will scale linearly for other channel widths. E.g, reducing the channel width to 1kHz would reduce beta from 0.463 to 0.046 for $\nu_{low} = 1.2\ GHz$ and $B_{max} = 1000\ km$.

B_{max} (km)		**1**	**10**	**100**	**1,000**	**10,000**
ν_{low} (GHz)	**1.2**	5.E-04	0.005	0.046	0.463	4.630
	8	7.E-05	0.001	0.007	0.069	0.694
	30	2.E-05	2.E-04	0.002	0.019	0.185
	70	8.E-06	8.E-05	0.001	0.008	0.079
	100	6.E-06	6.E-05	0.001	0.006	0.056

Table 7 – Achievable beta with 240k channels, 10kHz wide, as a function of maximum baseline.

Flexibility is part of the rationale for tunable spectral resolution across the band. The goal of SYS1403 to increase the instantaneous processed bandwidth while providing high spectral resolution over defined sub-bands. Such a capability is relevant to observations that have the need for continuum sensitivity along with spectral resolution around a line. Accommodating both needs in a single system setup increases overall observational efficiency, while respecting data rate limits.

[1] This derivation would also support a lower beta when a B_{MAX} of 700 km is used, consistent with the spatial resolution requirements.

Doppler setting to a common reference frame (i.e., shared by all baselines) 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). We use the terms "correct/set" to denote corrections made post-facto, and fixed across the observation. This is distinct from Doppler tracking, which is dynamic, and not required.

Note that the processed bandwidth, number of channels, and channel resolution are all given as limits. Any individual system configuration would need to be set within these limits, while respecting the data rate constraints established in CON104 and CON105.

6.13 Delay and Phase Stability Requirements

Parameter	Req. #	Value	Traceability
Amplitude and Delay/Phase Variations Magnitude	SYS1501	The amplitude and delay variations caused by the instrument, over the main array extent required in SYS1301 (700 km), 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 amplitude and delay fluctuations of the atmosphere after all available corrections (e.g., fast switching, WVR, etc.) have been applied. It is a goal to achieve this performance for the extended baselines.	[STK1402, STK1403, SCI0100]
SNR Loss to Delay/Phase Variations	SYS1502	The instrumental delay/phase noise, over the main array extent required in SYS1301 (700 km), shall not degrade overall system SNR by more than 1%. It is a goal to achieve this performance for the extended baselines.	[SCI0100, STK1403]
Phase Noise	SYS1503	Total instrumental integrated phase noise shall not exceed 132 fsec rms.	
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 4 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 delay/phase changes both 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 π drift over a calibration cycle. The goal of these requirements is to always allow for removal of predictable slow instrumental drifts.

Note: The phase drift and noise specifications given here do not account for the impact to imaging dynamic range (SYS6103). Rather, the drift specification aims to make the troposphere dominate any post-calibration residual. These requirements are a floor, and may be superseded by more stringent needs identified as part of the calibration requirements [AD11].

6.14 Gain and 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 noise contributions from

- the column of atmosphere in the main beam (ATM),
- the receiver and electronics (REC),
- the spillover (SPILL), which is the atmosphere and ground outside the main beam,
- the cosmic microwave background (CMB), and
- the astronomical sources in the field (SRC), respectively.

The requirements discussed here consider the variations in G, as a function of time and the pointing angle of the antenna. Some constraints on changes in the system temperature components are also given.

T_{SYS} is expected to range from 25K at 8 GHz to 150K at 115 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)[2] over an 8 GHz bandwidth, a net gain of 77 dB to 87 dB is required. Gross system gain may be 100 dB or more, 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

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

6.14.1 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 [AD05]. (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 [AD05]. (TBC)	[SCI0104, SCI0110]
TP Antennas: Gain Calibration Reference Short Term	SYS1801	The system shall provide a switched power reference stable to 1E-3 over a 5 minute period.	[SCI0104, SCI0110]

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

Parameter	Req. #	Value	Traceability
TP Antennas: Gain Calibration Reference Long-Term	SYS1802	The switched power reference shall be stable to better than 1% over a 24 hour period.	[SCI0110, SCI0104]

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 6.14.1.2).

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.

6.14.1.1 Total Power Mode: Gain Stability over Short Time Scales

The system gain stability aims to ensure that the sensitivity of spectral line observations in the total power mode 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.

6.14.1.2 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.

6.14.1.3 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.

6.14.2 Interferometric Observations

Parameter	Req. #	Value	Traceability
Interferometric Antennas: Gain Stability – Precision Environment	SYS4601	Antenna dG/G shall not exceed 4E-3 over a 200 sec period at 1 MHz bandwidth resolution in the precision operating conditions defined in 020.10.15.10.00-0001-SPE [AD05].	[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). This gain variation is defined as a residual after any corrections for elevation angle are applied.	[SCI0110]
Interferometric Antennas: Gain Stability – Normal Environment	SYS4604	Antenna dG/G shall not exceed 8E-3 over a 200 sec period at 1 MHz bandwidth resolution in the normal operating conditions defined in 020.10.15.10.00-0001-SPE [AD05]. Goal to not exceed 4E-3 over a 200 sec period at 1 MHz bandwidth resolution.	[SCI0113, SCI0115, SCI0119, SCI0114]
Gain Calibration Reference	SYS4801	The system shall provide a switched power reference stable to 4E-3 over a 20 minute period in both the precision and normal operating conditions defined in 020.10.15.10.00-0001-SPE [AD05].	[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.

These requirements will be explored in more detail as part of the calibration requirements [AD11].

6.14.2.1 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 6.14.2, 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. In practice, this value could be treated as an rms value since it is typically bracketed by astronomical calibrations. This could restrict the calibration cycle period though, so a linear drift term is more conservative.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~5–20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in Section 6.14.3.

This requirement is relaxed by a factor of two in the normal environment (SYS4604) to account for thermal heating in the daytime. The goal associated with this requirement would maintain this level of stability in support of high dynamic range imaging during the daytime.

These requirements will be explored in more detail as part of the calibration requirements [AD11].

6.14.2.2 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 6.14.2.1.

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

6.14.3 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.

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

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

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.

6.15 Atmospheric and Instrumental Calibration

The Level-1 (implementation agnostic) system calibration requirements are presented in this section. The supporting Level 1.1 requirements, presuming an architecture, are developed in the Calibration Requirements document [AD11].

Parameter	Req. #	Value	Traceability
Standard Observing Mode Calibration	SYS4301	A calibration strategy shall be provided for each standard observing mode, and the adopted strategy shall be enumerated in the data model.	[STK1302, STK0704]
Real Time Amplitude and Delay Calibration	SYS4310	The system shall use contemporaneous cross-correlation visibilities to correct for both electronic and atmospheric delay/phase and amplitude errors (i.e., complex gain errors) in phased array or interferometric functional operating modes in near real time.	[SCI0007]
Antenna Pointing Calibration	SYS4311	The system shall enable the use of contemporaneous cross-correlation visibilities to determine and apply antenna pointing corrections.	[SCI0113, SCI0114, STK1301]

Parameter	Req. #	Value	Traceability
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 bandpass coefficients and delays) shall be stored in a calibration database and automatically retrieved and applied.	[STK1300]
Automated and Triggered Re-Measurement of Parameters in Subarrays	SYS4331	It shall be possible to initiate the measurement of system calibration parameters with both automated and operator-triggered tools, using either the full array or a subarray.	[SYS4330, STK1301]

These functional calibration requirements aim to support the science operations concept. The measurement of calibration characteristics of the array, in support of the Standard Observing Modes, should be automated and performed by the observatory rather than the observer, with a standardized pipeline and quality assured data products.

Enumeration of the calibration strategy in the data model aims to capture how calibration data or database entries maps to targets. This information can be updated with new values prior to the default processing step, if necessary. This traceability also ensures that experimental methods that deviate from the default processing can still be attempted at a later time.

6.15.1 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 Recall	SYS1063	The system shall store and recall 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 permit the use of cataloged solutions (e.g. leakages) where these meet the requirements of the mode. It is a goal that cataloged solutions support the polarization calibration requirements for all Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]

Parameter	Req. #	Value	Traceability
Bandpass Calibration Efficiency	SYS1066	The system gain stability shall permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]
Amplitude Calibration Efficiency	SYS1067	The integrated noise over the full duty cycle of the switched amplitude calibration source shall not exceed 2% of System Temperature.	[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 8.3.2.

6.16 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 signals.	[SCI0015]
Polarization Correction	SYS1902	Any necessary transformation of the polarized signals received by each array element to a common basis shall support the polarization dynamic range established in SYS6104.	[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 of view and over 80% of a given receiver's bandwidth. The center of field of view is assumed to be both the primary beam center and interferometric phase center.

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.

6.17 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.	[STK0303]
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 <50 msec at reduced bandwidth or spectral resolution (i.e., fixed data output rate).	[SCI0004, SCI0106]
Tracking Rates	SYS0107	The antenna and any motion control loops shall support tracking rates of 10x sidereal for elevations below 70° (2.5'/sec), with rates scaling by cos(El) to 1x sidereal (0.25'/sec) at 88°.	[SCI0004, SCI0106]
Near-Field Delay Corrections	SYS0109	The system shall apply near-field corrections to visibilities measured towards targets whose distance presents phase errors on the longest baseline, due to wavefront curvature, of more than 9 degrees.	[STK2800]
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).	[SCI0112, SCI0012]
Timestamp Corrections	SYS2003	Timestamps may be applied or corrected retroactively (i.e., it is not necessary for it to be known in real time.) Any timestamp corrections shall be made through a metadata table that is incorporated into the data model.	[STK9950, SCI0012, SCI0112]
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]

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. The goals for temporal resolution may preclude the implementation of Walsh functions or other LO switching solutions.

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 50 msec rate is consistent with the maximum phase center update rate called for in SYS5701, and would support 10x sidereal scanning rates at 50 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.

The inclusion of near-field phase corrections aims to support non-traditional use cases like radar illumination of near-Earth objects. The 9-degree limit is arbitrary, but aims to constrain resulting gain errors to 1%. This requirement could be reviewed if associated near-field use cases are developed.

6.18 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]
Standard Mode RFI Mitigation	SYS4101	The RFI flagging and excision algorithms shall be configured to match to the requirements of each Standard Observing Mode.	[STK2602]
Non-Standard Mode RFI Mitigation	SYS4102	It shall be possible to turn off any/all of the RFI flagging and excision algorithms when observing with non-standard observing modes.	[STK2602]

Additional requirements relevant to the mitigation of radio frequency interference are captured in Section 6.10. Requirements for the avoidance of self-interference follow in Section 6.19.

6.19 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]
Shielding & Emission Limits	SYS2106	System shielding and emission limits shall comply with 020.10.15.10.00-0002-REQ [AD06].	[SCI0116, STK2600]
Electromagnetic Compatibility	SYS2107	All ngVLA equipment shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility). Prevention of electromagnetic interference (EMI) between subsystems (inter-system electromagnetic compatibility) is also required.	[STK0304]

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 is defined as:

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

Where σ_{rms} is given by SCI0116 to be 95 μ Jy/bm, limiting S_H to less than 9.5 μ Jy/bm. This 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. The total power requirements should be considered in more detail in future versions of this requirements document.

6.20 Scientific Operations Requirements

The ngVLA scientific operations requirements are broad, with a scientific operation concept similar to the VLA and ALMA 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 expected to be a suitable solution.

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.

6.20.1 User Interfaces

This section summarizes the user interfaces to the facility.

Parameter	Req. #	Value	Traceability
Proposal Preparation Tool	SYS3500	A proposal preparation tool shall be provided to enable users to prepare and submit their proposals.	[STK1200, STK0801]
Observation Preparation Tool	SYS3501	An observation preparation tool shall be provided for users to inspect and modify their observation instructions for approved projects.	[STK1200]
Data Quality Inspection Tool	SYS3502	A data quality inspection tool shall be provided for users to inspect the data quality of a performed observation.	[STK1200]
Data Processing Inspection Tool	SYS3503	A data processing inspection tool shall be provided for users to review and modify the post-processing and generation of high-level data products 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 user support 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 computing resources that conform to observatory-defined standards.	[STK1202]

6.20.2 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	The proposal submission interface shall allow the user to define their technical observation parameters when requesting Non-Standard Observing Modes.	[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]
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]

Parameter	Req. #	Value	Traceability
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]
Proposal Attributes	SYS2218	The system shall support an extensible list of proposal attributes such as regular, triggered, monitoring, sponsored, large and legacy (see 020.10.05.00.00-0004-PLA), and joint (with other observatories).	[STK0804]

The proposal attributes list (SYS2218) should be extensible, as these project classes will define proprietary periods (SYS0738) and other aspects of the observation execution and data delivery. Known classes include

- Regular: the default class, applicable to projects accepted through the time allocation process that are self-contained and executable based on observation scheduler priority criteria.
- Triggered: projects that are not dynamically scheduled, and instead rely on external data streams to trigger the immediate execution of the observation.
- Monitoring: projects with routinely observe a time-varying field, and may have limits on periodicity or system configuration.
- Sponsored: sponsored projects which have a different scheduling priority than regular observations.
- Large and Legacy: As defined in Legacy Science Program [RD29], and may have unique data processing requirements or proprietary periods.
- Joint: observations performed concurrently with other observatories, typically with fixed execution times.

6.20.3 Observation Preparation, Execution, and Scheduling

Parameter	Req. #	Value	Traceability
Observation Preparation – Standard Observing Modes	SYS2221	For standard observing modes, the observation preparation tool 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 – Shared Risk Observing Modes	SYS2222	The observation preparation tool shall include functionality and interfaces to generate observation instructions for Shared Risk Observing Modes without the use of the end-to-end software system.	[STK0402, STK0502]

Parameter	Req. #	Value	Traceability
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]
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, expected RFI, hour angle and frequency equity, source position limits, stringency of scientific observation requirements, and cadence (for recurring observations), when automatically scheduling observations.	[STK0900]
Observation Scheduling Priority	SYS2228	The automatic scheduling system shall prioritize scheduling based on (1) scientific ranking priority, (2) band availability, (3) subarray extent, and (4) project completion percentage.	[STK0900]
Observation Scheduling	SYS2302	System observations shall be automatically scheduled by an observation scheduling system, though manual over-rides to scheduling shall also be possible.	[STK0901, STK0900, STK0703]
Observation Execution Logs	SYS2310	The system shall automatically generate execution logs, including the issuance of commands associated with an observation, to provide a record of system actions and to enable system debugging.	[STK0502]
Simulated Observation Execution	SYS2311	The system shall simulate the execution of observation instructions when commanded, and shall generate the associated execution logs for verification.	[STK0502]

The observation preparation tool must support two distinct set of use cases. The first employs the end-to-end software system, starting with proposal submission, as would typically be employed for standard observing modes during routine operations. The second set of use cases pertain to commissioning of modes. In this later case, the generation and execution of observation instructions should be performed outside of the end-to-end software system, with significant intervention from system scientists.

6.20.4 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]
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]
Observation Monitor Data Query Tool	SYS2210	A tool shall be provided to link any observation to the monitor database and retrieve alerts and specified monitor points over the observation execution time period.	[STK9949]

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 6.3.

6.21 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 and self-configure 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]

Parameter	Req. #	Value	Traceability
Self-Calibrating Antenna	SYS2304	It is a goal that individual array elements (inclusive of all housed subsystems) perform a sequential safe startup and self-configure (based on values stored in the system configuration and 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]
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.	[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, STK1502]
Safe Restart	SYS2309	All subsystems shall restore the Standby (Default) Mode in the event of network or power outages.	[STK1506]
Operator Log Interface	SYS2312	An interface shall be provided for an Operator to append information to the automatically generated system execution logs (SYS2310).	[STK1502]

6.22 *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
Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate site maintenance.	[STK1603]
Self-Diagnostic Function	SYS2405	The system shall incorporate self-diagnosis functions to identify faults based on recorded monitor data.	[SYS3203]
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, STK0402, STK0502]

Parameter	Req. #	Value	Traceability
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, STK0402, STK0502, STK5001]
Variable Monitor Data Rates	SYS2409	The system shall be capable of varying the data rate for a monitor point, or set of monitor points, when a defined condition (defined by any monitor point) is met.	[STK5001]
Preventive Maintenance Schedules	SYS3200	The array elements shall be designed with preventive maintenance (PM) interval no shorter than 1 year.	[STK5005]
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]
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 the viability of critical vendors.	[STK5005]
Manual Reporting of Failures and Anomalies	SYS3205	The system shall permit the reporting of failures and anomalies by operators, data analysts, post-processing pipelines, and users, to a centralized issue tracking system and 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]
Operations and Maintenance: Transfer of Deliverables	SYS3211	All procedures, test equipment, and test software shall be delivered to the Operations and Maintenance staff prior to full operations.	[STK5004, STK5005]
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)]

Parameter	Req. #	Value	Traceability
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]
Remote Updates	SYS3223	The system shall permit the update of individual LRU firmware and software to be performed remotely via a network connection.	[STK1506]
Local Control	SYS3224	Local control of an antenna and housed subsystems shall not depend on the availability of remotely accessed networked systems.	[STK5005]
Automated Reporting of Failures and Anomalies	SYS3225	The Self-Diagnostic Function (SYS2405) shall automatically log issues to the issue tracking database.	[STK5005, STK5002]
Antenna Maintenance Personnel	SYS3230	Regular antenna maintenance shall be achievable by two technicians with standardized maintenance vehicle.	[STK5004]
Field Maintenance LRU	SYS3231	Field maintenance shall be achieved through replacement of LRUs as far as possible and should require minimum labor and equipment.	[STK1603]
LRU Interchangeability	SYS3232	LRUs should be interchangeable with no on-site calibration, tuning or alignment.	[STK1603]
Electronic Identification	SYS3233	All maintenance significant items, shall have electronically identifiable (Bar Code, RFID tag or similar) Part Marking as defined in the Configuration Management Plan.	[STK1602]
Identify Failures Physically	SYS3234	Maintenance significant items, where possible, shall identify a failed state via physical display (e.g. LED).	[STK5001]
Report Failure Information	SYS3235	Maintenance significant items shall report failures and failure isolation information and configuration information, via the M&C system.	[STK5001]
Report Predicted Failures	SYS3236	Maintenance significant items, where possible, shall report fault prediction sensor data via the M&C system.	[STK5001, STK5002]
Failure Information Source	SYS3237	Maintenance significant items shall report failure information in line with failure isolation as identified in a FMECA analysis.	[STK5001, STK5002]
Record Failures	SYS3238	All failure data shall be recorded in a FRACAS system.	[STK5002]

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. This requirement must be met while also supporting the MTBM and MTBF requirements listed in Section 6.25.

6.23 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]
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)	[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]
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 the operationally-ready Standby state after a full power cycle without human intervention.	[STK5005]

This section primarily focuses on the monitor and control functions embedded into the system. The associated monitor and control data stores are described in Section 6.4. Array operations and maintenance system and staff interfaces to the monitor and control system are described in Sections 6.21 and 6.22.

6.24 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 added to the monitor data stream (SYS2408) and archived for the life of the instrument.	[STK1403]

Parameter	Req. #	Value	Traceability
Atmospheric Phase Monitor	SYS2504	An atmospheric phase monitor (APM) at the Central Cluster shall be available, and shall interface with the scheduling system.	[STK1402]

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.

6.25 System Availability and Reliability

Parameter	Req. #	Value	Traceability
System Operational Availability	SYS2601	System Availability for Science Operations shall be greater than 80% of time, with more than 90% of antennas available in each band.	[STK1402]
Subarray Operational Availability	SYS2602	It is a goal to achieve a sub-array level system availability of 95% of time, with at least 70% of antennas available for science operations.	[STK1402]
Preventive Critical Maintenance	SYS2603	The system shall enable preventive maintenance on availability-critical items without interrupting observing operations.	[STK1402]
Data Loss from RFI Saturation	SYS2604	The system shall not lose more than 1% of observing time due to RFI saturation, averaged across all bands.	[STK1402]
Telescope Inherent Availability	SYS2605	The ngVLA Telescope shall have an inherent availability of more than 95%. It is a goal that the ngVLA Telescope should have an inherent availability of more than 98%.	[STK1402]
Support System Availability Contribution	SYS2606	The ngVLA Support System shall contribute less than 1% to critical system failure downtime. It is a goal that the ngVLA Support System should contribute less than 0.5% to critical system failure downtime.	[STK1402]
Power Quality Failure Immunity	SYS2607	The System shall prevent the loss of power to all availability-critical components, for power supply quality levels as defined in the system EMC specification (020.10.15.10.00-0002-REQ, AD06).	[STK1402]
Array Element MTBM	SYS2610	The Array Elements shall have a Mean Time Between Maintenance (MTBM) of more than 1500 hours.	[STK1402]
Array Element MTTR	SYS2611	The Array Elements shall have a Mean Time to Repair (MTTR) of less than 3 hours.	[STK1402]

Operational availability is defined as time available for science operations, accounting for scheduled and unscheduled maintenance downtime, engineering/upgrades and RFI saturation, but not accounting for downtime due to weather outside of safe operating limits (as defined RD26 and RD27). Science operations time includes all time required to calibrate the instrument and individual observations.

System availability of 80% is a significant improvement over current VLA operations (70-75% availability), but is consistent with the operations concept for the facility. The availability requirement aims to have 90% of antennas available during routine operations. This is the threshold that is adopted to define a fully operational steady state, and is approximately equivalent to the current VLA "three antenna rule." The aim of the 90% threshold is to allow for an appropriate amount of downtime to conduct preventive maintenance, repairs, and testing while still maximizing system scientific output. Antenna availability shall be determined on a per-receiver band basis, and achieved at all bands.

The goal of 95% system availability at the sub-array level is tied back to the stakeholder requirements to conduct commissioning and maintenance activities in sub-arrays. Central systems should exhibit reliability in support of this threshold, with maintenance preferentially conducted on subarrays rather than the full array. The 70% antenna availability tied to this requirement aims to limit the total array capabilities that are allocated to maintenance at any given point in time.

Future refinements of these requirements may establish performance limits on other parameters, such as processed bandwidth, in support of key Observation Modes.

The Support System is the collection of maintenance and logistics functions that maintain the array. These include all ancillary systems that are not directly engaged in the execution of end-to-end observations activities. This system includes the maintenance team that service the array, and the allocation in the availability budget includes service response times.

Due to the inherent redundancy of the array, the reliability specification of the array elements is not primarily driven by availability requirements, but rather by the maintenance budget. The large number of dishes and geographical distribution will require multiple repair crews, which contribute significantly to the operational budget. The reliability of the ngVLA antennas will have to be improved by at least a factor of 3 compared to EVLA antennas, to achieve the operational cost targets. The MTBF and MTBM are specified for the array elements, which includes both preventive and corrective maintenance. The specification values are derived in RD27.

6.26 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, [AD10]).	[SAF0034]
Subsystem self-monitoring	SYS2701	All subsystems shall monitor system health.	[SAF0042]
Safety Interlocks	SYS2705	The system shall include interlocks so that no computer command may result in human safety issues or equipment damage.	[SAF0031]

Parameter	Req. #	Value	Traceability
Security Specification	SYS2703	All designs shall comply with the Level-1 System Security Specification (020.80.00.00.00-0003-REQ, AD14).	[STK2201]
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.

6.27 Cybersecurity

Parameter	Req. #	Value	Traceability
IT Security	SYS2702	All network-connected 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.

The cybersecurity requirements reflect the minimum standards for an NSF astronomical facility [RD22] operated by AUI/NRAO [RD23]. These requirements may be extended in the future given international partner requirements and the developing concept for distributed operations responsibilities and infrastructure.

6.28 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)]
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 – ESD Protection	SYS3904	Shipping cases and packaging shall be provided with ESD protection consistent with the equipment specifications.	[STK2106]
Packaging – Mechanical Protection	SYS3905	Shipping cases and packaging shall provide mechanical shock absorption consistent with the equipment specifications. Cases housing sensitive equipment shall have identified locations for shock indicators.	[STK2106]

Parameter	Req. #	Value	Traceability
Logistics Tools and Resources	SYS3910	Logistics tools and resources (physical and human) shall be in place to support efficient product flow from suppliers to antenna sites prior to the start of AIV activities.	[STK2102]
Issue Tracking-Tool	SYS3911	Prior to the start of system-level AIV and site deployments, the project shall have in place an issue tracking tool that tracks open action items/punch list for site activities.	[STK5005]
Packaging – AIV	SYS3912	Packaging for delivered hardware shall ensure the safe storage of equipment in nominal warehouse conditions.	[STK0536]

Given the constraints on the operations cost of the system (Section 5), along with the distributed nature of the array, a robust logistics support system will be required to coordinate array maintenance and support activities. The datastores associated with these logistics systems are described in Section 6.4.

6.29 Configuration Management

Parameter	Req. #	Value	Traceability
Identification by Serial Numbers	SYS3600	All configuration items (e.g., LRUs, sub-assemblies) shall be uniquely identifiable to facilitate status and location tracking across the Observatory. Identification for LRUs shall be both visible and electronic.	[STK1602]
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 installation.	[STK9945 (copy), STK1600]
Configuration Monitoring	SYS3604	All configurable LRUs shall periodically monitor the System Calibration database for changes, and shall update their configuration based upon a change in relevant parameters.	[STK1150, STK9945]

Data provenance is a critical feature of a complex scientific instrument. Tracking changes in the system configuration and the associated impact on observations is necessary for quality assurance of the data products. Such functions also facilitate array operation and maintenance. The datastores associated with the configuration management system are described in Section 6.4.

6.30 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) shall occur before delivery to, or installation on, the array.	[STK1902 (copy)]

This section pertains to the quality assurance functions necessary to support array operations. The datastores associated with these quality assurance tools are described in Section 6.4. Quality assurance of the data products is described in Section 6.20.4.

6.31 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]

Parameter	Req. #	Value	Traceability
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]
Warehouse Space – AIV	SYS3822	The project shall deliver warehouse capabilities needed to store electronics and other assemblies delivered by the IPTs that require safe keeping prior to antenna integration.	[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)]
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 main array and extended baselines.	[STK2006 (copy)]
Remote Support Station Sizing	SYS3861	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]
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)]

Parameter	Req. #	Value	Traceability
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)]
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)]
Facility Space – AIV	SYS3885	The project shall provide adequate space needed for pre-deployment activities, equipment maintenance and storage, and AIV staff office space.	[STK0400]
Data and Voice Services – AIV	SYS3886	It is a goal to deliver data and voice service at each antenna site at the start of civil construction.	[STK0400]
Workspace – CSV	SYS3887	Dedicated workspace shall be provided in the local control room at the array site for CSV activities.	[STK0502]
Workspace – CSV-Operators	SYS3888	The remote control room needed for CSV activities shall contain a sufficient number of IT-supported workstations, in addition to the main multi-monitor control console needed by an operator.	[STK0502]

This list of facility requirements is not exhaustive, since additional facilities may be required depending on system architecture decisions (e.g., a Data Center, Correlator, and Central Electronics Buildings, etc.). Facility requirements at Level-2 shall reflect these interface-driven requirements.

6.32 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)]

This list of array infrastructure requirements is not exhaustive, but captures the requirements relevant to the array infrastructure that flow from the stakeholder requirements. Many array infrastructure requirements will be interface-driven and will depend on system architecture decisions and design elaboration of interfacing systems. Infrastructure requirements at Level-2 shall reflect these interface-driven requirements.

6.33 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	Site 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]

Additional requirements for equipment and vehicles are anticipated as part of the logistics support design of the facility, and will be developed to support the operations and maintenance plan.

6.34 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]
Projected Environment & Risk Exposure	SYS2821	The system shall be designed to survive the environmental conditions expected over the Design Life of the instrument, and shall survive 50-year events (extreme weather, seismic, etc.) without damage in excess of 1% of construction cost.	[STK0304 (copy)]

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.

6.34.1 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 (<10 sec. lag) 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, 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 and transition phase.	[STK2603 (copy)]
AIV Concept	SYS2820	The system shall provide any ancillary features necessary to conform to the Observatory-approved and released AIV Concept.	[STK0400, STK0536]

6.34.2 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)]
Delivery with High-Level Data Product Pipeline	SYS2831	Delivery of a commissioned standard observing mode shall include an operational high-level data product 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]
CSV Concept	SYS2838	The system shall provide any ancillary features necessary to conform to the Observatory-approved and released CSV Concept.	[STK0524]

6.35 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]

Parameter	Req. #	Value	Traceability
Units	SYS6003	Design materials and documentation shall use SI (metric) units. Imperial units may also be shown for clarity.	[STK0435]
Language	SYS6004	The language used for written documentation shall be English.	[STK0435]
Electronic Document Format	SYS6005	Documents and drawings of record shall be delivered in PDF. Native, editable file formats shall also be delivered.	[STK0435]

6.36 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 ngVLA facility integration into Observatory infrastructure and standards, in order to promote reuse and maintainability.	[STK2502 (copy)]

7 L1.1 System Requirements

The following requirements flow from the L1 requirements listed in Section 5. These requirements are not implementation agnostic, but are consistent with the System Architecture [AD04] and provide necessary and sufficient allocation of L1 requirements to allow derivation of supporting L2 subsystem requirements.

Additional allocations of L1 requirements to multiple subsystems can be found in the System Technical Budgets [RD28].

7.1 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.	[SYS1001]

The system effective area to system temperature ratio (SYS1001) has been decomposed into effective area and temperature components. The effective area has then been decomposed into a set of efficiency figures and geometric collecting area. The resulting collecting area is reflected in the table above, with system temperature and efficiency factors in the following sections.

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

7.2 System Temperature

Parameter	Req. #	Value	Traceability
Maximum TSYS in Freq. Span A	SYS1011	TSYS in Frequency Span A shall not exceed values in Table 8, 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. Band edges shall degrade to no less than 70% of spec.	[SYS1001]
Maximum TSYS in Freq. Span B	SYS1012	TSYS in Frequency Span B shall not exceed values in Table 8, 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. Band edges shall degrade to no less than 70% of spec.	[SYS1001]
Maximum TSYS in Freq. Span C	SYS1013	TSYS in Frequency Span C shall not exceed values in Table 8, 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. Band edges shall degrade to no less than 70% of spec.	[SYS1001]

As described above, the system effective area to system temperature ratio (SYS1001) has been decomposed into effective area and temperature components. As the design matures, T_{SYS} can be traded against additional effective collecting area, if necessary to optimize sensitivity as a function of cost.

The values given in Table 8 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 8.3.1.

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 8 – T_{SYS} over frequency in precision environment.

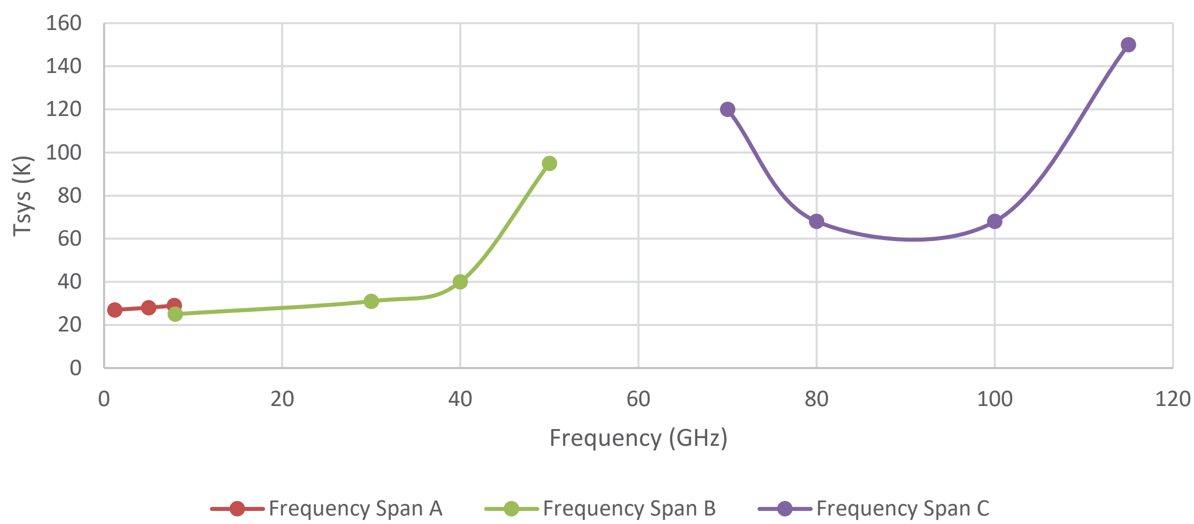

Figure 3 – T_{SYS} over frequency in precision environment.

7.3 *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 9. This requirement must be met over 80% of the bandwidth of any receiver. Band edges shall degrade to no less than 70% of spec.	[SYS1001]

Parameter	Req. #	Value	Traceability
Antenna Efficiency – Normal Environment	SYS1032	The antenna efficiency in the normal operating environment shall exceed the values given in Table 10. This requirement must be met over 80% of the bandwidth of any receiver. Band edges shall degrade to no less than 70% of spec.	[SYS1001]
Minimum Interferometer Digital System Efficiency	SYS1033	The digital system efficiency shall be a minimum of 0.95, including quantization and correlation losses. Goal to achieve 0.98 efficiency over 80% of each digitized band.	[SYS1001]
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, with an ENOB of at least 7.35.	[SYS1001]
Minimum Digital Quantization Levels – Span C	SYS1035	The minimum number of digital quantization levels shall be 64 levels (6-bits) for frequency span C, with an ENOB of at least 5.2.	[SYS1001]

Efficiencies associated with calibration and imaging performance are addressed elsewhere in this specification.

Antenna efficiency includes antenna reflector/structure losses and feed illumination losses. While the antenna efficiency is specified at point frequencies, values should be linearly interpreted between these points.

The digital system efficiency includes quantization efficiency, any losses from requantization at various parts of the digital signal path, and the cross-correlator efficiency. The associated number of levels and effective number of bits (ENOB) account for the required signal to noise ratio in the presence of RFI, while accounting for permitted slope and ripple across the band. These requirements are consistent with the headroom and dynamic range requirements given in Section 6.10, and the supporting derivations can be found in ngVLA Electronics Memo #8 [RD24].

7.3.1 Antenna Efficiency Allocations in Precision Environment

Table 9 shows the allocation of antenna efficiency errors as a function of efficiency. Values between the point frequencies should be linearly interpolated. The allocation of efficiencies is based on projected taper and spill contributions of candidate feeds with shaped optics. The allocation for blockage is intended to account for panel gaps only, 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, but adjustment of the focus axis is permitted. 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	$\eta_T\eta_S\eta_B\eta_X$	η_F	η_{RUZE}	η_{OHM}	$\eta_P\eta_{RUZE}$	η_A
1.2	0.95	0.83	0.99	0.99	**0.77**	1	1	1	**1**	**0.77**
5	0.95	0.83	0.99	0.99	**0.77**	1	1	1	**1**	**0.77**
7.9	0.95	0.83	0.99	0.99	**0.77**	1	1	1	**1**	**0.77**
8	0.95	0.92	0.99	0.99	**0.86**	1	0.99	1	**0.99**	**0.85**
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	**0.72**	**0.62**
100	0.95	0.92	0.99	0.99	**0.86**	0.96	0.64	0.99	**0.61**	**0.52**
115	0.95	0.92	0.99	0.99	**0.86**	0.94	0.55	0.99	**0.51**	**0.44**

Table 9 – Antenna efficiency budget as a function of frequency for precision environment.

7.3.2 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
1.2	0.95	0.83	0.99	0.99	**0.77**	1	1	1	**1**	**0.77**
5	0.95	0.83	0.99	0.99	**0.77**	1	0.99	1	**0.99**	**0.76**
7.9	0.95	0.83	0.99	0.99	**0.77**	1	0.99	1	**0.99**	**0.76**
8	0.95	0.92	0.99	0.99	**0.86**	1	0.98	1	**0.98**	**0.84**
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**
115	0.95	0.92	0.99	0.99	**0.86**	0.94	0.13	0.99	**0.12**	**0.10**

Table 10 – Antenna efficiency budget as a function of frequency for normal environment.

The antenna efficiency specification is relaxed in the secondary operating environment (Table 10). Values between the point frequencies should be linearly interpolated. 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.

7.4 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 11.	[SYS1501, SYS1502]

Table 11 shows the temporal delay/phase requirements allocation among the electronics subsystems and mechanical structure, applicable over the extent of the Main Array (SYS1301). The various quantities are combined in an RSS sense.

Initial allocations are equally distributed between systems, and this may be revisited as each system's technical feasibility is assessed. Stricter limits may be applied to components based on the Calibration Requirements [AD11] and/or System Technical Budgets [RD28].

Component	Noise (rms)	Drift Residual (rms) Up to 300 seconds	Absolute Drift Up to 300 seconds
Antenna Structure	76 fsec	42 fsec	2 psec
First LO: FE	76 fsec	42 fsec	0.25 psec
Digitizer Clock: FE	76 fsec	42 fsec	0.25 psec
Antenna RTP System	~0	42 fsec	0.25 psec
LO Distribution System	~0	42 fsec	1.25 psec
LO Reference	~0	TBD	TBD
Total Instrumental Error	**132 fsec**	**95 fsec**	**4 psec**

Table 11 – Allocation of temporal instrumental delay/phase errors (per antenna errors, in fsec).

Table 11 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 is applicable for integration from 1 Hz to the highest offset frequency that contributes significantly (1% level) to overall phase noise. Phase noise of high-performance oscillators typically rolls off steeply above 1 MHz. However, this should not be assumed, as a system with wideband down conversion and high speed digitizers would be sensitive to jitter well above 1 MHz if it were it to occur.
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. We assume that reference and distribution oscillator noise will largely be filtered out by the relevant phased-lock loops. 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 delay/phase drift specified exceeds the frequency stability of an active hydrogen maser. Providing a coherent frequency reference over the main array scales described in SYS1301 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 SYS1301 extent is TBD.

If the Total Instrumental Error delay/phase noise requirement is met, the expected coherence of an interferometer pair is given in Table 12 at various observing frequencies. Note that these values do not include atmospheric contributions.

Frequency	Coherence
1.2 GHz	99.99%
10 GHz	99.98%
50 GHz	99.48%
70 GHz	98.98%
115 GHz	97.28%

Table 12 – 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.

7.4.1 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.

7.5 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.	[SYS1501, SYS4602, 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.	[SYS1501, SYS4602, SYS4601]
Dewar Temperature Regulation – Precision Environment	SYS4903	The magnitude of temperature variations on the 2nd cryogenic stage (15 K) shall not exceed 0.12K over 200 seconds in the Precision Operating Conditions (020.10.15.10.00-0001-SPE, AD05).	[SYS1501, SYS4602, SYS4601]
Warm Electronics Temperature Regulation – Precision Environment	SYS4904	Warm (~300K) electronics temperature variations shall not exceed 0.4K over 200 seconds in the Precision Operating Conditions (020.10.15.10.00-0001-SPE, AD05).	[SYS1501, SYS4602, SYS4601]
Dewar Temperature Regulation – Normal Environment	SYS4905	The magnitude of temperature variations on the 2nd cryogenic stage (15 K) shall not exceed 0.12K over 200 seconds in the Normal Operating Conditions (020.10.15.10.00-0001-SPE, AD05).	[SYS1501, SYS4604]
Warm Electronics Temperature Regulation – Normal Environment	SYS4906	Warm (~300K) electronics temperature variations shall not exceed 0.4K over 200 seconds in the Normal Operating Conditions (020.10.15.10.00-0001-SPE, AD05).	[SYS1501, SYS4604]

As described in Section 6.14, gain stability of 4e-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 4e-3 would require thermal regulation to 0.12K within the Dewar and to 0.4K for warm devices over 200-second scales. These requirements can be traded against each other while still achieving the L1 requirements (SYS1601, SYS4601).

Note that while the emphasis here is on gain amplitude, temperature fluctuations of the LNAs can also introduce phase delays, so careful consideration of the contributions to the phase drift budget (Table 11) must also be considered.

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 6.14.3. This noise source, and any intervening electronics between the noise source and the coupler, must be stable to 4e-3 over 20-minute periods. This 20-minute period corresponds to the expected gain calibration cycle on astronomical sources.

SYS4903-4904 reflect the expected performance in the precision environment. Performance in the normal environment is presently set to the same level in SYS4905-4906 in order to support high dynamic range observations below 50 GHz during the daytime, supporting the goal of SYS4604. However, this normal environment requirements could be relaxed, within the constraints set by SYS4604, if proven infeasible.

These requirements should be considered the floor on required performance. Stricter limits may be applied to components based on the Calibration Requirements [AD11] and/or System Technical Budgets [RD28].

7.6 Bandpass Requirements

Parameter	Req. #	Value	Traceability
Bandpass Stability	SYS1701	The bandpass amplitude shall be stable to 0.3% over 60 minutes. (TBC)	[SYS6105, SYS6106]
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.	[SYS6105, SYS6106, SYS1001]
Bandpass Flatness	SYS1703	The bandpass of an individual digitized band shall vary by no more than 8 dB peak to peak, measured across the central 80% of the bandwidth. Goal of less than 6 dB peak to peak.	[SYS6105, SYS6106, SYS1001]
Sideband Separation	SYS1704	The sideband separation in any dual-sideband frequency conversion system shall be better than 30dB. Goal of 40dB separation.	[SYS6105, SYS6106]
LO Frequency and Sampler Clock Offsets	SYS2105	The system shall include the provisions for frequency offsets at the antenna level to provide additional attenuation of spurious signals. It is desirable to also enable digitizer clock offsets.	[SYS6105, SYS6106]

The bandpass 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. A supporting SNR budget is given in [RD24].

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 and sampler clock offsets, required by SYS2105, may provide additional attenuation of the unwanted sideband power and enable the specification to be supported in total power observations. The total power requirements are still under development and should be refined in future releases of these requirements.

7.7 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 13.	[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 13 shows the approximate time budget for response time (typically meeting the three-minute goal of SYS3005, depending on slew distance).

Action	Time Allocation	Cumulative Time	Notes
Reception of External Trigger	1 sec	1 sec	
Operator Override Period	20 sec	21 sec	
Termination of Current Scheduling Block	30 sec	31 sec	Concurrent with Operator Trigger Override period.
System Setup to New Scheduling Block	20 sec	51 sec	Must include time necessary to switch between Functional Operating Modes.
Antenna Slew to Source	2 min, max	171 sec	@90-deg/min Az., 45 deg/min El.; ignores acceleration time.
Antenna Settle Time	10 sec	181 sec	
Receiver Band Selection	20 sec, max	191 sec	Concurrent with settle time.

Table 13 – 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 during an antenna slew, which impacts electrical system size; and
- Limiting a scheduling block to 20 seconds, interruptible by the control system.

The rapid termination of a scheduling block may have implications for pipeline heuristics. E.g., the observation may not terminate with a bracketed phase/gain calibrator observation. Consultation with stakeholders suggests that rapid termination is preferred, and that strategies to extrapolate gain/phase exist and should be implemented.

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.

8 Key Performance Parameters

This section provides the Key Performance Parameters (KPPs) 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.

Key Performance Parameters have been identified below in the Science and Stakeholder requirements sets, which have been traced to corresponding System Requirements.

8.1 L0 Science KPPs

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:

L0 Science 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 14 – 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.

8.1.1 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 Table 15.

8.1.2 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.

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

8.1.3 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 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) Continuum	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 16 – Example tracking table for Surface Brightness sensitivity. To be determined for the design at key milestones.

8.1.4 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.

Surface Brightness (Tb) Spectral Line	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 17 – Example tracking table for Surface Brightness sensitivity. To be determined for the design at key milestones.

8.1.5 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.

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

Table 18 – Continuum Survey Speed as a function of frequency. To be determined for the design at key milestones.

8.1.6 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.

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

Table 19 – Largest Angular Scale as a function of frequency. To be determined for the design at key milestones.

8.1.7 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.

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

Table 20 – Maximum Angular Resolution as a function of frequency. To be determined for the design at key milestones.

8.2 L0 Stakeholder KPPs

The following are the KPPs from the Stakeholder Requirements 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, as these programmatic constraints represent foundational stakeholder needs.

L0 Stakeholder Key Performance Parameters	Req. #
Construction Affordability	CON001
Operations Affordability	CON002
Observations Supported by Standard Observing Modes	STK1000
Observational Efficiency	STK1401
Calibration Efficiency	STK1402

Table 21 – ngVLA Stakeholder KPPs.

Performance to each Stakeholder KPP will be assessed as the design matures and approaches key technical baselines such as the system CoDR, PDR and FDR.

8.2.1 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.

8.2.2 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.

8.2.3 Observations Supported by Standard Observing Modes

The 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.

8.2.4 Observational Availability

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.

Availability for Science Operations shall be computed accounting for the following sources of downtime:

1. Planned downtime of the system for engineering upgrades.
2. Planned downtime of the system to maintain critical parts.
3. Unplanned downtime due to failure of critical system parts.
4. Time lost due to logistical delays in the support system (e.g. response time).

8.2.5 Calibration Efficiency

STK1402 establishes goals for calibration efficiency, or the fraction of time spent on the science target.

Time spent on calibration shall be assessed for each standard observing mode, providing a measure of the projected calibration overheads in operation for each standard observing model, using the assumptions and metrics established in Section 8.3.5.

8.3 L1 System KPPs

The L1 System KPPs that support the L0 KPPs and have been identified for monitoring are as follows:

L1 System Key Performance Parameters	Req. #	Traces to
Effective Area/Tsys	SYS1001	SCI0100, SCI0102
Baseline Distribution	SYS1306	SCI0100, SCI0102
Instantaneous FOV (FWHM)	SYS1101	SCI0106
B_{MIN}	SYS1302	SCI0104
B_{MAX}	SYS1301	SCI0103
Calibration Efficiency	SYS1061	STK1402
System Availability	SYS2601	STK1401
Subarray Availability	SYS2602	STK1401
Number of Standard Observing Modes	SYS3002	STK1000

Table 22 – ngVLA measures of performance.

Interpretation notes for each are enumerated in the subsections below.

8.3.1 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.

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

Table 23 – Effective Area over System Temperature as a Function of Frequency. To be determined for the design at key milestones.

8.3.2 Distribution of Baselines

The distribution of baselines dictates the effective array sensitivity after beam sculpting. When combined with the previous sensitivity estimates, the distribution baselines can be used to compute practical imaging sensitivity as a function of time on source. The distribution of baselines will be reported for the bin sizes in Table 6.

8.3.3 Instantaneous Field of View

The instantaneous field of view of the system is set by the primary beam (FWHM) of the limiting (largest) antenna in a subarray. Larger fields of view increase the number of observations which can be accomplished with a single antenna pointing (vs a mosaic or on-the-fly map), contributing to the overall observational efficiency.

8.3.4 B_{MIN} and B_{MAX}

B_{MIN} and B_{MAX} are coarse analogs for the largest angular scale and smallest angular scale (i.e. maximum resolution) that can be resolved by the array. They should be measured for a source at zenith on a given baseline.

8.3.5 Calibration Efficiency

This KPP 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 of baselines, 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 measure include full beam, full band, continuum observations at the standard frequencies used for the L0 KPPs (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 at a minimum, with this list extended to match the requirements of the observing mode:

- Gain (Phase & Amplitude)
- Bandpass
- Relative Flux scale

Further simplifying 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 100mJy 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.

8.3.6 System Availability & Subarray Availability

These measures both contribute to the Observational Efficiency of the system, and also inform the Operations Affordability KPP. 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.

Total System Availability shall include the losses associated with the Availability for Science Operations (Section 8.2.4) and shall also account for these additional factors:

1. Time lost due to weather outside the operating condition limits [AD05].
2. Time lost due to expected RFI saturation.
3. Time lost due to failure of external systems on which the system is dependent (e.g. grid power supply failure or network failure).

Availability shall be reported for both the full array and a subarray, accounting for the two conditions given in SYS2601 and SYS2602. Availability shall also be estimated on a per-band basis.

8.3.7 Number of Standard Observing Modes

Tracking the number of Standard Observing Modes implemented in the design and commissioning plan, and the eventual delivery of those modes, supports the cross-comparison to the available modes to either the Reference Observing Program (and the eventual satisfaction of the KSGs) or the Envelope Observing Program as part of the L0 KPPs.

9 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.

9.1 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 groupings in Section 6.

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	Functional Mode Switching Time			*	
SYS0010	Standby Mode			*	
SYS0011	Default 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			*	
SYS0608	Sub-Array Instantiation			*	
SYS0102	Polarization Products			*	
SYS0103	Autocorrelation Products			*	
SYS0105	Limited Polarization Products			*	
SYS0108	Phase Center			*	
SYS0201	Phased Aperture				*
SYS0202	Concurrent Interferometric Visibilities			*	
SYS0203	Number of Beams			*	
SYS0204	Open-Loop Calibration			*	
SYS0205	Closed-Loop Calibration			*	
SYS0206	Beamforming		*		
SYS0207	Polarization Correction				*
SYS0208	Beamforming Efficiency	*			
SYS0209	Concurrent Visibility Spectral Resolution			*	
SYS0301	Timing Capabilities		*		
SYS0302	Timing System Bandwidth			*	
SYS0303	Timing System Frequency Resolution			*	
SYS0304	Pulse Profile Bins			*	
SYS0305	Polarization		*		
SYS0306	Pulse Period				*
SYS0308	Dispersion Measure Range				*
SYS0309	Timing System SNR	*			
SYS0401	Search Capabilities		*		
SYS0402	Search System Bandwidth			*	
SYS0403	Search System Frequency Resolution			*	
SYS0404	Search System Time Resolution			*	
SYS0405	Polarization			*	
SYS0406	Search System SNR	*			

Req. #	Parameter/Requirement	A	I	D	T
SYS0407	Periodicity			*	
SYS0501	VLBI Recording Capabilities			*	
SYS0503	VLBI Bandwidth Setting			*	
SYS0504	VLBI Quantization Setting			*	
SYS0505	VLBI Recorded Bandwidth			*	
SYS3001	Standard Observing Modes		*		
SYS3002	Number of Standard Observing Modes	*			
SYS3003	Non-Standard Observing Modes			*	
SYS3004	Triggered Observations		*		
SYS3005	Triggered Observation Response	*			
SYS3006	Trigger Override			*	
SYS0701	Uncalibrated Data		*		
SYS0702	Online Flagged Data Table		*		
SYS0705	Online Flagged Data Table Metadata		*		
SYS0703	Calibration Coefficients Table		*		
SYS0704	Offline Flagged Data Table		*		
SYS0721	Imaging Pipeline Products				*
SYS0722	Quick Look Image Pipeline Products				*
SYS0741	Pulsar Timing Data Product		*		
SYS0742	Pulsar Search Data Product		*		
SYS0745	Phased Sum Voltage Stream		*		
SYS0746	VLBI Data Stream		*		
SYS0801	System Frequency Range		*		
SYS0803	Freq. Span A:		*		
SYS0804	Freq. Span B:		*		
SYS0805	Freq. Span C:		*		
SYS0806	Continuity of Frequency Coverage			*	
SYS0901	Front End Band Edge Ratio		*		
SYS0903	Total Instantaneous Processed Bandwidth				*
SYS0905	Frequency Selection			*	
SYS0906	Fixed Analog Tunings		*		
SYS0907	Sub-Band Step Size		*		
SYS0908	Band Switching Time				*
SYS1001	Effective Area to Noise Temperature Ratio	*			
SYS1101	Instantaneous Field of View		*		
SYS1102	Accessible Field of View	*			
SYS1103	Slew Rates	*			
SYS1105	Azimuth Wrap		*		
SYS1201	Instantaneous Dynamic Range				*
SYS1203	Input Dynamic Range Across Setups		*		
SYS1204	Input Protection	*			
SYS1206	IP3 Headroom	*			
SYS1301	Longest Baseline		*		
SYS1302	Shortest Baseline		*		
SYS1303	Zero Spacing / Single Dish Total Power		*		
SYS1304	Integration Time Ratios	*			

Req. #	Parameter/Requirement	A	I	D	T
SYS1306	Baseline Distribution	*			
SYS1309	Collecting Area on VLB Baselines		*		
SYS1401	Highest Spectral Resolution		*		
SYS1402	Number of Spectral Channels		*		
SYS1403	Variable Spectral Resolution		*		
SYS1404	Doppler Corrections			*	
SYS1501	Amplitude and 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 with 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 Short Term				*
SYS1802	TP Antennas: Gain Calibration Reference Long-Term				*
SYS4601	Interferometric Antennas: Gain Stability – Precision Environment				*
SYS4602	Interferometric Antennas: Relative Gain Stability				*
SYS4603	Gain Variations with Antenna Pointing Angle				*
SYS4604	Interferometric Antennas: Gain Stability – Normal Environment				*
SYS4801	Gain Calibration Reference				*
SYS1900	Full Stokes			*	
SYS1902	Polarization Correction	*			
SYS0104	Variable Time Resolution			*	
SYS0106	On-The-Fly Mapping – Data & Control Rates			*	
SYS0107	Tracking Rates			*	
SYS0109	Near-Field Delay Corrections				*
SYS2001	Temporal Resolution		*		
SYS2002	Temporal Accuracy	*			
SYS2003	Timestamp Corrections		*		
SYS5701	Phase Center Update Rates				*
SYS2104	Self-Generated Spurious Signal Power Level	*			
SYS2106	Shielding & Emission Limits				*
SYS2107	Electromagnetic Compatibility		*		
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	Subarray Support		*		
SYS2218	Proposal Attributes		*		
SYS2221	Observation Preparation – Standard Observing Modes		*		

Req. #	Parameter/Requirement	A	I	D	T
SYS2222	Observation Preparation – Shared Risk Observing Modes		*		
SYS2223	Observation Scheduling GUI			*	
SYS2224	Observation Interrupt			*	
SYS2225	Observation Preparation – Standard Observing Mode Flexibility			*	
SYS2226	Observation Time Model		*		
SYS2227	Observation Scheduling Criteria		*		
SYS2228	Observation Scheduling Priority		*		
SYS2302	Observation Scheduling			*	
SYS2310	Observation Execution Logs			*	
SYS2311	Simulated Observation Execution			*	
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			*	
SYS2205	Manual Data Quality Assurance			*	
SYS2207	Automated QA of Data Products			*	
SYS2208	Quality Assurance Tools for Standard Modes			*	
SYS2209	Data Provenance Tracking		*		
SYS2210	Observation Monitor Data Query Tool			*	
SYS2303	Calibration Automation			*	
SYS2304	Self-Calibrating Antenna			*	
SYS2305	Single Baseline Data Display			*	
SYS2306	Calibration Data Display			*	
SYS2307	Operator Console			*	
SYS2308	Operator Interface Location		*		
SYS2309	Safe Restart		*		
SYS2312	Operator Log Interface			*	
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		*		
SYS3114	Subsystem Automation			*	
SYS2501	Weather Monitoring		*		
SYS2502	Safety Weather Monitoring		*		
SYS2503	Weather Archive		*		
SYS2504	Atmospheric Phase Monitor			*	
SYS2601	System Operational Availability	*			
SYS2602	Subarray Operational Availability	*			
SYS2603	Preventive Critical Maintenance	*			
SYS2604	Data Loss from RFI Saturation	*			
SYS2605	Telescope Inherent Availability	*			

Req. #	Parameter/Requirement	A	I	D	T
SYS2606	Support System Availability Contribution	*			
SYS2607	Power Quality Failure Immunity	*			
SYS2610	Array Element MTBM	*			
SYS2611	Array Element MTTR	*			
SYS2700	Safety Specification		*		
SYS2701	Subsystem self-monitoring	*			
SYS2705	Safety Interlocks		*		
SYS2801	Design Life	*			
SYS2802	Cost Optimization	*			
SYS2803	Sustainability		*		
SYS2805	Part Selection for Maintainability		*		
SYS2812	Critical Spares		*		
SYS2821	Projected Environment & Risk Exposure	*			
SYS2811	Test Fixtures		*		
SYS2813	System Verification Tools			*	
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 High-Level Data Product 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		*		
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		*		
SYS3861	Remote Support Station Sizing		*		

Req. #	Parameter/Requirement	A	I	D	T
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		*		
SYS2403	Modularization		*		
SYS2405	Self-Diagnostic Function			*	
SYS2406	Configuration Monitoring		*		
SYS2407	Engineering Console			*	
SYS2408	Monitor Data Stream		*		
SYS2409	Variable Monitor Data Rates			*	
SYS3200	Preventive Maintenance Schedules	*			
SYS3201	Maintenance Tiers		*		
SYS3203	Criteria for Scheduling Maintenance		*		
SYS3204	Use of Failure Analysis in Spares Planning	*			
SYS3205	Manual Reporting of Failures and Anomalies			*	
SYS3209	Maintenance Metrics Definition		*		
SYS3211	Operations and Maintenance: Transfer of Deliverables		*		
SYS3221	Provision of Predictive Tools			*	
SYS3222	Maintenance Scheduling Tools			*	
SYS3223	Remote Updates			*	
SYS3224	Local Control		*		
SYS3225	Automated Reporting of Failures and Anomalies			*	
SYS3230	Antenna Maintenance Personnel		*		
SYS3231	Field Maintenance LRU		*		
SYS3232	LRU Interchangeability		*		
SYS3233	Electronic Identification		*		
SYS3234	Identify Failures Physically		*		
SYS3235	Report Failure Information			*	
SYS3236	Report Predicted Failures			*	
SYS3237	Failure Information Source			*	
SYS3238	Record Failures		*		
SYS3900	Inventory Tracking System			*	
SYS3901	Shipping and Receiving Logistics		*		
SYS3902	Tracking of LRUs			*	
SYS3903	Observatory-controlled Logistics		*		
SYS3904	Packaging – ESD Protection		*		
SYS3905	Packaging – Mechanical Protection		*		
SYS3910	Logistics Tools and Resources		*		
SYS3911	Issue Tracking-Tool			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS3912	Packaging – AIV		*		
SYS3400	System Calibration Database		*		
SYS3401	Astronomical Calibrator Database		*		
SYS3402	Monitor Database		*		
SYS3403	RFI Database		*		
SYS3404	Quality Control Database		*		
SYS3405	System Configuration Database		*		
SYS2703	Security Specification		*		
SYS2704	Physical Security		*		
SYS2702	IT Security		*		
SYS4100	RFI Flagging			*	
SYS4101	Standard Mode RFI Mitigation	*			
SYS4102	Non-Standard Mode RFI Mitigation			*	
SYS3700	Quality Control Data Access Tool			*	
SYS3701	Quality Control Data Access Tool Location		*		
SYS3702	Quality Control of Deliverables		*		
SYS0502	eVLBI Capabilities	*			
SYS5600	Commensal Processing		*		
SYS5601	Commensal Voltage Streams		*		
SYS5602	Commensal Low-Frequency System		*		
SYS5603	Commensal Metadata		*		
SYS3600	Identification by Serial Numbers		*		
SYS3601	Configuration Management Tools		*		
SYS3602	Version Control for Software and Firmware		*		
SYS3603	Configuration Retrieval			*	
SYS3604	Configuration Monitoring			*	
SYS2401	SRDP Integration		*		
SYS4200	Open Source Software		*		
SYS4201	DMS Integration		*		
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		*		
SYS0730	Data Delivery via Observatory Archive		*		
SYS0731	Archive Products – Low-Level	*			
SYS0732	Archive Products – High-Level		*		
SYS0733	Proprietary Data Rights		*		
SYS0734	Archive Batch Reprocessing		*		
SYS0735	Archive Backup	*			
SYS0736	Archive User Reprocessing			*	
SYS0737	Archive Image Selection			*	
SYS0738	Proprietary Period		*		
SYS0740	External Data Products			*	
SYS0743	Proprietary Period Trigger		*		
SYS0761	Data Analysis Resources			*	

Req. #	Parameter/Requirement	A	I	D	T
SYS0762	Data Quality Assurance		*		
SYS0750	Data Processing for Standard Observing Modes				*
SYS0751	Data Processing Resources	*			
SYS0752	Throughput & Latency	*			
SYS0753	Heterogeneous Arrays			*	
SYS0754	Processing Triggers			*	
SYS0755	Processing Priorities		*		
SYS0756	Processing in Place		*		
SYS0757	Support for Large and Legacy Programs		*		
SYS0760	Interactive Processing		*		
SYS6001	As-Built Drawings		*		
SYS6002	Operations and Maintenance Manuals		*		
SYS6003	Units		*		
SYS6004	Language		*		
SYS6005	Electronic Document Format		*		
SYS4000	Grassland Impact	*			
SYS4001	Sustainable Roads		*		
SYS4002	Existing Roads		*		
SYS4003	Fences		*		
SYS4004	Ranching Impact	*			
SYS4500	Array Core Location		*		
SYS4301	Standard Observing Mode Calibration	*			
SYS4310	Real Time Amplitude and Delay Calibration				*
SYS4311	Antenna Pointing Calibration				*
SYS4320	Standard Calibration Automation			*	
SYS4330	Storage and Retrieval of Calibration Parameters		*		
SYS4331	Automated and Triggered Re-Measurement of Parameters in Subarrays		*		
SYS1061	Calibration Efficiency	*			
SYS1063	Calibration Recall		*		
SYS1064	Relative Flux Scale Calibration Efficiency				*
SYS1065	Polarization Calibration Efficiency		*		
SYS1066	Bandpass Calibration Efficiency				*
SYS1067	Amplitude Calibration Efficiency	*			
SYS1068	Phase Calibration Efficiency	*			
SYS4401	Power Spectral Density Scale			*	
SYS4402	Autocorrelation Integration Intervals			*	
SYS4403	PSD Differencing			*	
SYS5700	Variable Slew Rates	*			
SYS5702	Scanning Patterns			*	
SYS6101	Photometric Accuracy				*
SYS6102	Relative Astrometric Accuracy				*
SYS6103	Brightness Dynamic Range				*
SYS6104	Polarization Dynamic Range				*
SYS6105	Spectral Dynamic Range – Absorptive				*
SYS6106	Spectral Dynamic Range – Emissive				*

Req. #	Parameter/Requirement	A	I	D	T
SYS6107	Image Fidelity				*
SYS6108	Image Fidelity – Snapshot				*
SYS6109	No Self-Calibration				*
SYS9990	Electrical Power Conservation			*	

9.2 L1.1 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 7.

Req. #	Parameter/Requirement	A	I	D	T
SYS1021	System Geometric Collecting Area	*			
SYS1011	Maximum TSYS in Freq. Span A:				*
SYS1012	Maximum TSYS in Freq. Span B:				*
SYS1013	Maximum TSYS in Freq. Span C:				*
SYS1031	Antenna Efficiency – Precision Environment				*
SYS1032	Antenna Efficiency – Normal Environment				*
SYS1033	Minimum Interferometer Digital System Efficiency	*			
SYS1034	Minimum Digital Quantization Levels – Span A, B		*		
SYS1035	Minimum Digital Quantization Levels – Span C		*		
SYS5001	Allocation of Delay/Phase Noise & Drift				*
SYS4901	LNA Gain Fluctuations w/ Temperature		*		
SYS4902	Warm Electronics Gain Fluctuations w/ Temperature		*		
SYS4903	Dewar Temperature Regulation – Precision Environment				*
SYS4904	Warm Electronics Temperature Regulation – Precision Environment				*
SYS4905	Dewar Temperature Regulation – Normal Environment		*		
SYS4906	Warm Electronics Temperature Regulation – Normal Environment		*		
SYS1701	Bandpass Stability				*
SYS1702	Bandpass Ripple		*		
SYS1703	Bandpass Flatness		*		
SYS1704	Sideband Separation				*
SYS2105	LO Frequency and Sampler Clock Offsets			*	
SYS5101	Trigger Response Time Allocations				*

10 Appendix

10.1 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
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

10.2 Definitions

1% Compression Point – The power input or output level where the device output deviates by 1% from a linear response. We will standardize on reporting this value relative to the *input* power level, for a *broadband* signal. Note that most components specify the compression point for a narrow-band tone, not the broadband response, which is typically lower. The 1% compression point is a convenient metric to use for defining the maximum input power (and associated dynamic range) of a device as it relates very clearly to the required performance. However, it is unfortunately very difficult to measure, which reduces its value as a specification. We will therefore determine the desired 1% compression point based on higher level requirements, and use this to specify the 1dB compression point and the 3rd order intercept (IP3), in order to have more verifiable specifications.

1dB Compression Point – The power input or output level where the system output deviates by 1dB (~20%) from a linear response. We will standardize on reporting this value relative to the *input* power level, for a *broadband* signal. Note that the 1dB compression point is typically specified for components assuming a narrowband tone for an input signal, and the equivalent point can be appreciably lower for a broadband input signal. We note that at the 1dB compression point the noise floor may be rising, with significant intermodulation products visible above the quiescent background level.

3rd Order Intercept Point Headroom – We will use this term to refer to the difference of the operating point on cold sky to the 3rd order intercept point (IP3). We will standardize on reporting this value relative to the input power (IIP3). This is most often tested in response to a narrowband tone, and is a figure of merit that indicates the non-linearity of a device.

Array Element – An antenna inclusive of all receiving, digitization, data transmission, and ancillary components necessary for operation as an element of a subarray.

Bandpass – this term is used to describe the passband gain of the system, as a function of frequency.

Bit Depth – The total number of bits per sample produced by an analog to digital converter (ADC). This is a headline specification that ignores the quantization noise and added distortion of the device.

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

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

Dynamic Range Across Setups – This is a system-level specification for dynamic range addressing the expected change in noise power, over a receiver band, which can be expected *across* all observations and system setups. It is the ratio of the maximum input power to be observed to the system noise power on cold sky. We define this as a ratio, rather than simply a maximum input power, to make the specification easily translatable to any element of the signal chain (i.e., we can ignore preceding gain).

Effective Area – the effective collecting area of an antenna or the combined array. The effective area is the geometric collecting area times an efficiency term, eta (η), that addresses losses in feed illumination or the antenna reflector structure. The illumination term is a combination of feed taper (η_T), feed spillover

(η_S), blockage (η_B), or polarization leakage (η_X). The structural term includes defocus (η_F) due to mechanical tolerances or deformation, surface roughness (η_{RUZE}), and ohmic losses (η_{OHM}).

Effective Number of Bits (ENOB) – This is a figure of merit for ADCs that attempts to quantify the dynamic range of the device in bits, accounting for quantization noise. The formula is derived from the SNR formula, solving for N_{bits}. A common definition of ENOB is given by:

$$ENOB = \frac{SINAD - 1.76}{6.02}$$

Where the coefficients are the same as those given for SNR. SINAD substitutes for SNR in this definition, which becomes readily testable since SINAD is determined empirically.

In order to provide a top-down specification for ENOB, we will modify the definition to relate it again to the desired SNR, which is a more derivable quantity. We will use this modified ENOB for specification purposes, but the traditional measure using SINAD can still be used for verification, as the inclusion of the distortion power in the prior definition will always lead to a more conservative measure. The definition of ENOB in this memo will be given by:

$$ENOB = \frac{SNR - 1.76}{6.02}$$

Extended Baselines – The array elements that extend beyond the *Main Array*. These array elements are expected to have separate primary frequency and time references due to their distance from the center of the *Main Array*, and may also be grouped differently for calibration and logistics purposes.

Functional Operating Modes – these are the available states of the system, and each encapsulates a set of functional and performance requirements and produces corresponding data products. Functional Operating Modes are arranged in a class structure, with sub-classes within higher modes. An example Functional Operating Mode is an Interferometric Operating Mode or Phased Array Operating Mode.

Gain (Calibration) – A complex term representing the change in *Amplitude* and *Phase* of a signal as it passes through a component or signal chain.

Image Fidelity – The normalized deviation of the formed image brightness I measured relative to M, which is the true sky brightness convolved with a Gaussian restoring beam, weighted by $\beta_i = \max(|I_i|, |M_i|)$ and integrated over the field extending to 10% of the primary beam FWHM modified by the window function W:

$$F \equiv 1 - \frac{\sum_{pix} \beta_i W_i \, |I_i - M_i|}{\sum_{pix} \beta_i^2 W_i}$$

where $W_i = 1$ over the region of interest and is 0 outside. It is generally acknowledged that this quantity is difficult to estimate in practice since only well-understood effects can be included in a simulation, and it is possible that poorly understood effects may dominate.

Instantaneous Dynamic Range – This is a system-level specification for dynamic range within a single system setup or observation, representing the ratio of the maximum input power to the minimum input power to a receiver or corresponding segment of the signal chain. Typically, this is the ratio of the maximum permitted noise power in the observation, inclusive of RFI, to the noise power on cold sky. I.e., it is the RFI headroom allocation. However, for a bright source, it could also represent a measurable change in source irradiance (e.g., during observations of the active sun).

Line Replaceable Unit (LRU) – A modularized assembly with standard interfaces that is interchangeable between antennas. This is the standard unit of replacement in field service by a technician.

Main Array – The array elements that form a connected-element array out to 700km in extent. Additional array elements beyond the main array form *Extended Baselines*.

Observatory – The observatory should generally be interpreted as being the National Radio Astronomy Observatory (NRAO). The ngVLA is a facility within NRAO.

Observing Modes – Observing modes provide end-to-end data standards, starting with proposal attributes, to generate observation instructions and deliver quality assured data products to scientific requirements. An example of an Observation Mode might be a Continuum Observing Mode, which uses the Interferometric Operating Mode.

Offline System – The portions of the computing and software system engaged in data post processing or analysis that inspect or manipulate the data post observation.

Online System – The portions of the computing and software system engaged in the near real-time execution and monitoring of an observation.

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

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

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

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

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

Positional Uncertainty – The rms positional uncertainty is given by:

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

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

Signal to Noise Ratio (SNR) for an ADC – A measure of dynamic range that is the simple ratio of the digitized signal power to the noise level at the output. In general, both the signal and noise powers depend on the input signal, and so does the SNR. Thus, we will not assume a proportional relationship between signal power and SNR by default. In our application, the 'signal' is the output of a receiver – a combination of thermal noise, RFI, and astronomical signals. The 'noise' is the noise added by the digitizer.

The SNR of an ideal digitizer (for a tone input at full scale) is given by:

$$\mathrm{SNR} = 6.02 * \mathrm{N_{bits}} + 1.76$$

The coefficient 6.02 converts bits to dB (~20*$\log_{10}(2)$), and the coefficient 1.76 (~10*$\log_{10}(3/2)$) accounts for the SNR of a sinusoid with an amplitude of 0.5 bits embedded in a quantization noise uniformly distributed between ±0.5 bits.

Signal-to-Noise and Distortion Ratio (SINAD) – A measure of the quality of the signal from a device, usually expressed in dB. It is given by:

$$SINAD = \frac{P_{signal} + P_{noise} + P_{distortion}}{P_{noise} + P_{distortion}}$$

In our application, the 'signal' is the input to the ADC – a combination of thermal noise, RFI and astronomical signals. The 'noise' and 'distortion' is limited to the quantization noise and distortion of the digitizer. SINAD is measured by injecting a strong narrowband tone into the digitizer and isolating the noise and distortion components in the frequency domain.

Spectral Dynamic Range, Emissive – The ratio of the brightness in the strongest channel compared to the rms of the residual brightness in the instrument bandpass of nearby channels:

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

Spectral Dynamic Range, Absorptive – The ratio of the brightness in the strongest absorption channel to the rms of the brightness in the nearby continuum channels:

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

Support System – The collection of maintenance and logistics functions that maintain the array. These are all ancillary systems that are not directly engaged in the execution of end-to-end observations activities. This system includes the maintenance team that service the array.

System Temperature – A representation of the noise power received by an antenna, combined with the added noise from the receiving electronics. System Temperature (T_{SYS}) is defined as $T_{SYS} = T_{ATM} + T_{REC} + T_{SPILL} + T_{CMB} + T_{SRC}$, the noise contributions from

- the column of atmosphere in the main beam (ATM),
- the receiver and electronics (REC),
- the spillover (SPILL), which is the atmosphere and ground outside the main beam,
- the cosmic microwave background (CMB), and
- the astronomical sources in the field (SRC), respectively.

Timing Accuracy – The Allan standard deviation in time, relative to the adopted time standard over a given time interval.

Quantization Efficiency (η_Q) – We will use a simplified definition for quantization efficiency, relating the signal at the input of the digitizer to the signal at the output of the digitizer. Using this approach, achieving a given quantization efficiency requires keeping the added noise at the output to less than $1/\eta_Q$-1. This allows us to relate the desired quantization efficiency to the required SNR and ENOB. Maximizing the efficiency of the real system requires knowledge of the signal characteristics and the correct level setting of the input to the digitizer. This simple definition will allow us to ensure that the desired quantization efficiency is achievable, based on an allocation to the SNR budget for the digitizer, while deferring the details of input level setting.

10.3 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 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[3] 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 $T_1 \sim 30$ 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 $T_2 \sim 300$ 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

[3] We will assume use of the same receiver band for requirements derivation. Calibrating in a different receiver band adds complexities that will impact system requirements (e.g., B2B stability) and commissioning effort. Gain/Phase calibration in the same band may still permit access to a less opaque or more stable part of the atmosphere than the science frequency, if necessary.

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 11, 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.

This derivation will be extended to evaluate the impact on high dynamic range imaging as part of the system calibration requirements derivation.

10.4 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 an 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 1 MHz.

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

10.5 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).

10.5.1 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.

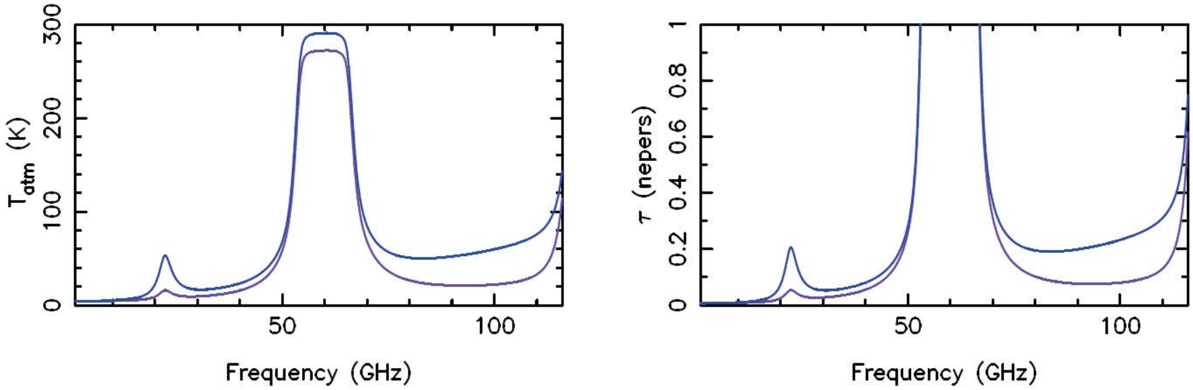

Figure 4 – Atmospheric temperature and opacity for wet (blue) and dry (purple) conditions. [RD11]

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	30 sec	31 sec
System Setup to New Scheduling Block	20 sec	51 sec
Slew To Source	2 min max @90-deg/min Az, 45 deg/min El. Ignores acceleration time.	171 sec
Settle Time	10 sec max	181 sec
Band Selection	20 sec max (during settle)	191 sec

Table 24 – 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 slew or settle time; 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.

10.5.2 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:

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

Case A: 0.07 μJy/bm @30 GHz: Assuming 214 18m apertures[4], 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.

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.

[4] 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.

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 7. 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 10.5.1.

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 mass 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 6.14.3.

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, and could support the spectral dynamic range requirement in total power observations.

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 7), 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.