Preliminary System Requirements

020.10.15.10.00-0003-REQ
Status: **GENERATED**

Approved By:		
Name	**Role**	**Signature**
R. Selina	ngVLA Project Engineer	
Released By:		
Name	**Role**	**Signature**
M. McKinnon	ngVLA Project Director	

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.

Contents

1. INTRODUCTION

1.1. Purpose

This document aims to present a preliminary set of system requirements for the ngVLA that should guide the conceptual design of the facility.

Many requirements flow-down from the ngVLA Science Requirements documented by Murphy et. al. [AD 01]. These Science Requirements support the Key Science Goals [RD 15] defined by the Science Advisory Council (SAC), and were informed by the Science Use Cases [RD 16] submitted by the Science Working Groups (SWGs).

In addition, an attempt has been made to incorporate performance and functional requirements that support non-traditional users such as NASA/JPL, and the Near Earth Sensing (NES) community. Programmatic, operational, maintenance, and safety requirements are also reflected where they drive technical decisions. These stakeholder requirements are summarized in AD 02.

1.2. Scope

The scope of this document is the entire ngVLA system, from the reception of external signals to the generation and delivery of data products to the archive for storage and access by users.

The content of these requirements is aimed at the system-level, but describes functional or performance requirements of sub-systems where necessary. Some assumptions on the system architecture [AD 04] are included here, but only to the degree necessary to define these system requirements.

This document is primarily aimed at the functional elements of the array rather than supporting infrastructure. These functional elements include:

- Hardware and software systems from the antenna and feed through to the data archive.
- Software and control systems required to monitor and operate the array.

Requirements for supporting operational infrastructure and personnel will flow directly from the stakeholder requirements, and are not enumerated here.

2. RELATED DOCUMENTS & DRAWINGS

2.1. Applicable Documents

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

Reference No.	Document Title	Rev / Doc. No.
AD 01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD 02	ngVLA Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD 03	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD 04	ngVLA System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD 05	ngVLA Environmental Specification	020.10.15.10.00-0001-SPE
AD 06	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD 07	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD 08	ngVLA Reference Observing Program	(TBD)
AD 09	ngVLA System Safety Specification	(TBD)

2.2. Reference Documents

The following documents provide supporting context.

Reference No.	Document Title	Rev / Doc. No.
RD 01	EVLA Project Book	
RD 02	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo No. 1
RD 03	Calibration Strategies for the Next Generation VLA	ngVLA Memo No. 2
RD 04	Interferometry & Synthesis in Radio Astronomy. Thomson, Moran, Swenson	Second Edition
RD 05	Gain Stability: Requirements and Design Considerations	ALMA Memo 466
RD 06	Radio Path Length Correction Using Water Vapour Radiometry	R.J Sault, https://arxiv.org/ftp/astro-ph/papers/0701/0701016.pdf
RD 07	Convenient Formulas for Quantization Efficiency	A.R. Thompson Radio Science, Vol. 42, RS3022
RD 08	Reliability and MTBF Overview	Vicor Reliability Engineering
RD 09	ngVLA Cost Model Memo	V3.0, February 24, 2017
RD 10	ngVLA Cost Model Spreadsheet	V3.0, February 24, 2017
RD 11	ngVLA Sensitivity	ngVLA Memo #21
RD 12	Polarization Calibration with Linearly Polarized Feeds	ngVLA Memo #45
RD 13	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106
RD 14	RFI Emission Goals on Internally-Coupled Signals	EVLA Memo #104
RD 15	Key Science Goals for the ngVLA	ngVLA Memo #19
RD 16	Summary of the Science Use Case Analysis	ngVLA Memo #18

Reference No.	Document Title	Rev / Doc. No.
RD 17	ngVLA Time-domain Correlator Considerations	P. Demorest, 01/05/18.
RD 18	ALMA Scientific Specifications and Requirements	ALMA-90.00.00.00-001-B-SPE
RD 19	Synthesis Imaging In Radio Astronomy II	ASP Vol 180. 1998.

3. OVERVIEW OF THE SYSTEM REQUIREMENTS

This document presents the technical requirements of the ngVLA telescope at the system level. These parameters determine the overall hardware and software performance of the telescope.

The L1 Requirements along with detailed explanatory notes are found in Section 5. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the verification procedures.

In many cases the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers are not well 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 value. The goal in such cases is simply to identify parameters that will require definition once the science requirements coalesce, or associated technical issues are understood.

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

The following system-level specifications are documented separately and incorporated by reference:

AD 05	*ngVLA Environmental Specification*	020.10.15.10.00-0001-SPE
AD 06	*ngVLA System EMC and RFI Mitigation Requirements*	020.10.15.10.00-0002-REQ
AD 09	*ngVLA System Safety Specification*	(TBD)

Additional system-level specifications will be documented during the development phase to specify requirements applicable to the design of the ngVLA system and supporting observatory infrastructure.

4. REQUIREMENTS MANAGEMENT

4.1. Requirement Definitions

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

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

4.2. Requirements Flow Down

The L1 System Requirements generally flow from the L0 Science Requirements [AD 01] for the facility. While these requirements dominate, other Stakeholder Requirements [AD 02] also influence or dictate design choices. Examples include programmatic requirements, regulatory compliance requirements, and the life-cycle concepts (e.g., the operations & maintenance concept [AD 03]) for the facility.

The Science Requirements and Stakeholder Requirements fully encapsulate all known L0 requirements. These System requirements and subordinates included by reference (AD 05, AD06) fully encapsulate all known L1 requirements. Supplemental L1 requirements may be developed in future subordinate documents.

Specifications for individual sub-systems (L2) flow from the L1 System Requirements, and may not always be directly attributable to a single system requirement (e.g., phase drift specifications at the system level may be apportioned to multiple sub-systems, or a sub-system spec may be in support of multiple higher-level requirements). Specifications at the L2 level may also flow directly from L0 requirements in some cases. Completeness of the L2 requirements is assessed at the requirements review of each sub-system.

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 implementation of requirements and specifications leads to trade-offs that feedback to higher-level requirements. The end goal is to build the most generally capable system within the programmatic constraints of cost and schedule.

Maintaining enumerated and traceable science requirements, system requirements, and sub-system specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a sub-system 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 AD 07.

5. L1 SYSTEM REQUIREMENTS

System-level requirements apply to performance with all operational calibrations applied. The system can be assumed to be fully functioning, under the precision environmental conditions (defined in AD 05). The system-level requirements are written in an implementation agnostic way whenever possible in order to not unduly constrain the conceptual design.

Sub-system requirements apply to performance before operational calibration corrections are applied. The accuracy of calibration that is needed to meet the higher-level system requirement is included in the system requirements notes and may be reflected in other functional or performance requirements.

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

Requirement traceability is shown to the relevant L0 requirements document, with SCI denoting Requirement IDs in the Science Requirements [AD 01] and STK denoting requirements in the Stakeholder Requirements [AD 02]. Where gaps in L0 requirements exist today, there may be additional notes in the traceability column that will be addressed in future versions of the document set.

A limited number of requirements listed here are not implementation agnostic but are consistent with the system architecture. These requirements are noted with an L2 in the Parameter column for future reconsideration. System-level L2 requirements can also be found in Section 6.

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

5.1. Functional Operating Modes

Parameter	Req. #	Value	Traceability
Functional Modes	SYS0001	The system shall provide a set of defined Operating Modes that produce corresponding data products.	[SCI0006, STK0200]
Interferometric Mode	SYS0002	The system shall provide an Interferometric Operating Mode with concurrent computation of cross-correlations and self-correlations for arbitrary numbers of antennas with tunable spectral and time resolution.	[SCI0006]
Phased Array Mode	SYS0003	The system shall provide a Phased Sum Operating Mode that coherently sums the voltage streams from an arbitrary number of antennas and provides a time-tagged voltage data stream with an adjustable phase center on sky.	[SCI0007, SCI0012, SCI0013]
Pulsar Timing Mode	SYS0004	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to time dispersed pulse profiles with a variable period.	[SCI0012]
Pulsar and Transient Search Mode	SYS0005	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is processed to search	[SCI0013]

		for dispersed pulse profiles w/o a priori knowledge of their period.	
VLBI Mode	SYS0006	The system shall provide a Phased Sum Operating Mode where the time-tagged voltage data stream is recorded in a VLBI-standard recording format for future processing in a VLBI correlator.	[SCI0017]
Total Power Mode	SYS0007	The system shall provide an Interferometric Operating Mode with computation of self-correlations on-source and off-source to quantify the total power spectral density of a fixed field.	[SCI0104]
On The Fly Mapping Mode	SYS0008	The system shall provide an Interferometric Operating Mode where areas larger than the antenna primary beam are mapped by a continuous scan of the field.	[SCI0004]
Solar Observing Mode	SYS0009	The system shall provide an Interferometric Operating Mode tailored to the observation of sources up to 30dB brighter than the cold sky.	[SCI0016]
Concurrent Interferometric and Phased Array Mode	SYS0202	The system shall provide an Operating Modes that supports the computation of limited cross-correlations simultaneous with the phased array capabilities described in SYS0003 through SYS0006. This mode may have restricted processed bandwidth, spectral and time resolution compared to the mode described in SYS0002.	[SCI0007]

5.2. Sub-Array Functional Requirements

Parameter	Req. #	Value	Traceability
Sub-Array Capabilities	SYS0601	The system shall be divisible into a minimum of 10 sub-arrays for operation, calibration and maintenance purposes.	[SCI0009]
Phase Preservation	SYS0602	It shall be possible to preserve electronic phase when adding and/or subtracting an element from a sub-array.	[STK1400, STK1403]
Sub-Array Composition	SYS0603	It is desirable that the composition of a sub-array be configurable to any arbitrary combination of antennas from a single antenna to the full array.	[SCI0009]
Sub-Array Operating	SYS0604	It is a goal that all Operating Modes be available in a sub-array.	[SCI0009, SCI0010]

Modes			
Sub-Array Operating Mode Commensality	SYS0605	The system shall support the commensal sub-array combinations described in Table 1. It is a goal to permit full flexibility in commensal sub-array Operating Modes.	[SCI0010]
Sub-Array Configuration	SYS0606	It is a goal that the configuration of a sub-array be completely independent of all others, permitting different instances and versions of online software between sub-arrays.	[STK1400]

Given the extent of the ngVLA, it is likely that a significant portion of array observing will 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 concept of operation also has a continuous maintenance element, so individual elements and sub-arrays will frequently be deployed for testing and/or diagnostic purposes.

The phase calibration strategy may also employ sub-arrays. It is therefore critical that adding or subtracting an element of a sub-array be possible without disturbing electronic system phase.

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

Table 1 - Required Sub-Array Commensality

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

Table 1 Notes:

1. Full flexibility within the constraints of the maximum data input to the correlator back-end (Value TBD).
2. Minimum functionality must include full-bandwidth cross-correlation in one sub-array, concurrent with phased array in another. Phased array timing, search, and VLBI capabilities as constrained by SYS0203, SYS0301, SYS0401, and SYS0501.
3. Full flexibility within the constraints imposed by SYS0203.
4. Full flexibility within the constraints imposed by SYS0203 and SYS0301.
5. Full flexibility within the constraints imposed by SYS0203 and SYS0401.
6. Full flexibility within the constraints imposed by SYS0203 and SYS0501.
7. Full flexibility within the constraints imposed by SYS0203, SYS0301, SYS0401, SYS0501.
8. The Concurrent Interferometric and Phased Array Mode described in SYS0202 has the same restrictions as modes SYS0003 through SYS0006.

5.3. Interferometric Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Variable Spectral Resolution	SYS0101	The spectral resolution shall be tunable to permit variable resolution across the observed band, maximizing instantaneous bandwidth while still providing high spectral resolution over defined sub-bands.	[SCI0006, SCI0003]
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 (TBC).	[STK1700, STK1704]
Commensal Processing	SYS0104	It is desirable to provide a connection for future commensal processing of visibilities (e.g., transient search) at the native temporal resolution of the observation (prior to any time or frequency averaging).	[SCI0013, STK2901]
Commensal Low-Frequency System	SYS0105	It is desirable to provide physical interfaces, data transmission and correlator bandwidth for a future commensal low-frequency (<1 GHz) front end.	[STK2900]

5.4. Phased Array Operating Mode Functional Requirements

Parameter	Req. #	Value	Traceability
Phased Aperture	SYS0201	The system shall provide phased array capabilities over the full extent of the array (1000km aperture).	[SCI0007]
Number of	SYS0203	The system shall support a minimum of 10	[SCI0008, SCI0009]

Beams		beams distributed over 1 to 10 sub-arrays. It is desirable to support 50 beams distributed over 1 to 10 sub-arrays at reduced bandwidth per beam.	

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

5.5. Transient (Pulsar) Timing Operating Mode Requirements

Parameter	Req. #	Value	Traceability
Timing Capabilities	SYS0301	The system shall include a back-end timing instrument with a minimum of 5 independent de-dispersion and folding threads. Support for up to 50 de-dispersion and folding threads is desirable.	[SCI0012]
Timing Sys. Bandwidth	SYS0302	The timing system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	[SCI0012]
Timing Sys. Frequency Resolution	SYS0303	The timing system shall support channelization for de-dispersion at a frequency resolution better than 1 MHz. Frequency resolution of 50 kHz is desired.	[SCI0012]
Pulse Profile Bins	SYS0304	The timing system shall support a minimum of 2048 pulse profile bins.	[SCI0012]
Polarization	SYS0305	The timing system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations independently and provide full-stokes parameters	[SCI0012]
Pulse Period	SYS0306	The timing system shall be capable of de-dispersion and folding for pulse periods spanning from 1msec to 30 sec.	[SCI0012]
Dump Rate	SYS0307	The timing system shall record to disk at periods no longer than every 10 seconds. It is desirable to record to disk every second.	[SCI0012]

Timing observations will 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 dedispersed, detected, folded (averaged modulo the known pulse period) into the specified number of pulse phase bins, and recorded at the dump rate.

The target of 50 dedispersion and folding threads accommodates the most congested fields of view (currently 37 pulsars in a single cluster) and is consistent with the beamforming capabilities expressed in Section 5.4.

The 8 GHz of bandwidth requirement is based on the projected band definition of the system. The intent is to ingest the full bandwidth of any receiver operating below 20 GHz.

Additional information supporting these requirement derivations can be found in RD 17.

5.6. 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 50 beams.	[SCI0013]
Search Sys. Bandwidth	SYS0402	The search system shall process a minimum of 8 GHz of bandwidth. Processing the full instantaneous bandwidth available in all bands is desirable.	[SCI0013]
Search Sys. Frequency Resolution	SYS0403	The timing system shall support channelization for de-dispersion at a frequency resolution better than 1 MHz. Frequency resolution of 100 kHz is desired.	[SCI0013]
Search Sys. Time Resolution	SYS0404	The search system shall have time resolution of 100 μsec or better. Resolution of 20 μsec is desired.	[SCI0013]
Polarization	SYS0405	The search system shall, at a minimum, process the summed output of both polarizations. It is desirable to process both polarizations of each beam independently and provide full-stokes parameters	[SCI0013]

Additional information supporting these requirements can be found in RD 17. Note that this system needn't be a real-time processing capability if the resultant beams can be recorded to disk for post-processing.

5.7. 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 VLBI compliant formats. It is desirable to support this capability for 5 beams distributed over 1 to five 5 sub-arrays.	[SCI0017]
eVLBI Capabilities	SYS0502	It is desirable, but not required, to interface with network-connected VLBI stations as real-time correlated elements of the ngVLA.	[STK2501]

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

5.8. 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	It is a goal that Standard Observing Modes 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]
Non-Standard Observing Modes	SYS3003	It shall be possible for advanced users to access Non-Standard Observing Modes, and directly generate observing instructions for each functional Operating Mode that are processed by the system and record basic data products.	[STK0702]
Triggered Observations	SYS3004	The system shall include interfaces to receive external (network) triggers to execute previously approved Standard Observing Mode and Non-Standard Observing Mode instructions.	[SCI0005]
Triggered Observation Response	SYS3005	The system shall process a trigger and begin an observation (be configured and on source) in a period not to exceed 10 minutes, with a goal of 3 minutes or less.	[SCI0005]
Trigger Override	SYS3006	The trigger response mechanism shall provide a human Array Operator Override. The Override shall time-out and execute the triggered observation if the observation is not canceled within 60 seconds.	[SCI0005]

The definition of Standard Observing Modes and their associated requirements will be revisited after the completion of a Reference Observing Program, which will define specific observations in support of the ngVLA Key Science Goals (KSGs).

5.9. Data Products

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

5.9.1. Low-Level Interferometric Data Product Requirements

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

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

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

5.9.2. High-Level Interferometric Data Product Requirements

Parameter	Req. #	Value	Traceability
Calibration Pipeline	SYS0703	For Standard Obsering Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed that produces a calibration table to apply direction-independent corrections that were supported by the observation, typically; delay/phase, gain/amplitude, polarization and bandpass corrections.	[STK1000]
Imaging Pipeline	SYS0721	For Standard Observing Modes within the Interferometric Operating Mode, there shall be a standard data reduction performed resulting in a calibrated image cube.	[STK0100]

In order to reduce the burden on users, when using Standard Observing Modes , higher-level data products will provide outputs that today would typically be generated by the user. 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, facilitating multi-wavelength science.

The high-level data products are difficult to define, and may be different for the individual PI and the data archive. E.g., an 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.

ngVLA data will be delivered, by default, as Science Ready Data Products (SRDP). The NRAO SRDP Project is presently defining proposal submission criteria, data processing, and archiving structures. Proposals on all NRAO instruments will conform to SRDP requirements in order 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. Requirements on the Archive that follow also support the delivery of SRDP.

5.9.3. Pulsar Timing and Search Data Product Requirements

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

5.9.4. Data Archive Requirements

Parameter	Req. #	Value	Traceability
Archive Period	SYS0731	All low-level data products shall be archived for the life of the facility (as defined in SYS2801).	[STK1106, STK1102]
Archive Products	SYS0732	High-level data products that are suitable for reuse 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 and to replace existing low-level and high-level data products.	[STK1102]
Archive Backup	SYS0735	A full backup (two copies total) of all archived data shall be incorporated into the design. The two copies shall not be collocated/co-managed to reduce the risk of	[STK1100, STK1106]

		simultaneous failures.	
Archive User Reprocessing	SYS0736	The system shall include an interface for users to request limited reprocessing of data within supported Standard Observing Modes.	[STK1102, STK1101]
Proprietary Period	SYS0738	The proprietary period shall be tunable on a per-project and per-scan basis.	[STK1103]

The high-level goal of the data archive is 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 maximize the 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 scientific productivity of the array.

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 the broad goals of the archive. This data should be archived for the life of the facility.

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

Storage requirements for high-level data products should be revisited after their requirements are defined by the SRDP project.

5.9.5. Data Processing Requirements

Parameter	Req. #	Value	Traceability
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]
Throughput & Latency	SYS0752	The data processing capacity for high-level data products shall be designed to match the expected average system throughput (defined in the Reference Observing Program), with no constraint on latency.	[STK1001, STK1002]
Heterogeneous Arrays	SYS0753	The data processing system shall support data reduction from heterogeneous arrays.	[STK1002, SYS1304]

5.9.6. Data Analysis Requirements

Parameter	Req. #	Value	Traceability
Data Analysis Resources	SYS0761	The system shall provide data analysis resources (both software tools and	[STK1201]

		compute capacity) for users to inspect and analyze the high-level data products from Standard Observing Modes.	

5.10. Frequency Range and RF Coverage

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

While the system shall access all available frequencies in the 1 to 116 GHz, the 8-50GHz range (Frequency Span B) has the most demanding sensitivity requirements (Section 5.12). System performance should be optimized for these frequencies.

Note that these frequency spans are not "Bands", and are not meant to imply a specific receiver configuration. The frequency span division is due to atmospheric windows and different priority levels.

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

5.11. System Bandwidth and Frequency Tunability

Parameter	Req. #	Value	Traceability
Front End Bandwidth Ratio	SYS0901	A minimum bandwidth ratio of 1.5:1 is required, with a 3:1 goal over Frequency Span A	[SCI0100, SCI012]
Instantaneous Digitized Bandwidth	SYS0902	It is desirable for the system to digitize the full bandwidth of each receiver band.	[SCI0003, SCI0100]
Total Instantaneous Processed Bandwidth	SYS0903	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	[SCI0100]

Sub-Bands	SYS0904	If the digitized bandwidth exceeds the instantaneous transmitted and processed bandwidth, the system shall separate the digitized bandwidth into sub-bands for bandwidth selection, transmission and processing.	[SCI0003]
Frequency Tunability	SYS0905	If the front-end bandwidth exceeds the instantaneous transmitted and processed bandwidth, it shall be possible to select discontinuous sub-bands for transmission and processing. I.e., transmitting both the top and bottom of the 70-116 GHz band.	[SCI0003]
Fixed Analog Tunings	SYS0906	While supporting the Frequency Tunability requirement, the analog system setup options shall be minimized to facilitate calibration from catalog values.	[STK1403]
Sub-Band Step Size	SYS0907	It is a goal to have sub-band selection and tunability at a granularity of 200 MHz.	[SCI0003]
Band Switching Time	SYS0908	Switching between any receiver bands shall be achievable within 20 seconds. Goal of less than 10 seconds.	[SCI0018]
Contiguous Bandwidth	SYS0909	Any bandwidth division for transmission and processing shall not create gaps in frequency coverage.	[SCI0003]

The front end bandwidth ratio is most important at lower frequencies where total instantaneous bandwidth will be limited by the receiver rather than the data transmission system.

The 20GHz/pol instantaneous bandwidth goal is consistent with the expected bandwidth of the highest frequency receiver (band 5) in Frequency Span B (30-50GHz). The requirement of 14 GHz approximates the expected band 4 receiver. If the span of these receivers changes, the instantaneous sampled bandwidth requirement and goal should be adjusted to match.

If the full bandwidth of the front end is sampled, any tuning or filtering is expected to be digital only, and implemented in order 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, there must be a mechanism in place to select any frequency over the observable window (e.g., tuned LOs). Any minimum tuning stepsize should be restricted by SYS0907.

5.12. Sensitivity Requirements

Parameter	Req. #	Value	Traceability
Effective Area / Tsys Ratio	SYS1001	The effective area / Tsys ratio of the system shall meet or exceed the values given in Figure 1 while operating in the precision	[SCI0100, SCI0102, SCI0106]

		environmental conditions defined in 020.10.15.10.00-0001-SPE and assuming 1mm of PWV. This requirement must be met over 80% of the bandwidth of any given receiver (i.e., band edges are exempted).	

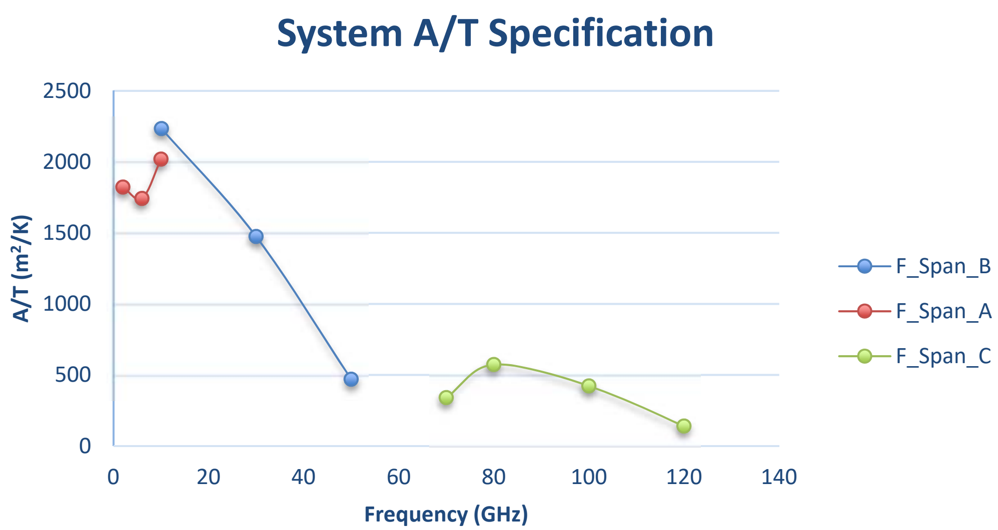

Figure 1 - System A/T specification in m^2/K.

The driving sensitivity requirement is for raw system sensitivity measured in m^2/K [SYS0501]. The values in Figure 1 are based in part on expected degradation in aperture efficiency as a function of frequency and achievable system temperatures. Note that deviations at the edges of each receiver band are expected and allowable.

When considering parameters that affect the effective collecting area of the ngVLA antennas 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 Tsys). In the event that scope contingency is required to fit within cost constraints, this sensitivity requirement may be relaxed.

5.13. System Field of View

Parameter	Req. #	Value	Traceability
Instantaneous Field of View	SYS1101	The system instantaneous FOV (FWHM), when scaled by center frequency, shall be larger than 2 arcmin at 28 GHz.	[SCI0106, SCI104]
Accessible Field of View	SYS1102	The system shall be capable of observing at elevations of 12° to 89°, relative to the local horizon.	[SCI0019]
Slew Rates	SYS1103	The system shall be capable of slewing to	[SCI0005]

		any position within the accessible field of view in less than 2 minutes of time.	
Tracking Rates	SYS1104	The system shall be capable of tracking objects and mapping an area of sky at 10x sidereal speeds when under 70-degrees in elevation.	[SCI0004]

Based on the survey speed requirements of the system, and the projected sensitivity, the FOV must be greater than 2 arcmin at 28 GHz, corresponding to an 18m aperture with a taper coefficient of 1.02.

5.14. Dynamic Range

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

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

Solar requirements depend to some degree on the definition of the sun, given the large differences in output power as a function of solar activity. For the quiet sun at 5780K, and a system temperature of order 30K, the implied analog dynamic range is of order 23dB.

With an antenna SEFD of order 300 Jy, and an active sun definition of 10^8 Jy, an analog dynamic range of 55dB would be required for the active sun. For the strongest signals, a high-noise path (bypassing the LNAs) would therefore be desirable.

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

5.15. 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 420 km with extended baselines (VLB) out to 8600 km.	[SCI0103, SCI0118]
Shortest Baseline	SYS1302	The shortest baselines between antennas shall be shorter than 22 m, with a goal of 10 m.	[SCI0104]
Zero Spacing / Single Dish Total Power	SYS1303	It is a goal that the system measure total power spectral density in the field, with apertures larger than 1.5x the shortest baseline.	[SCI0104]
Integration Time Ratios	SYS1304	If achieving SYS1302 requires multiple array/antenna designs, each array shall sample overlapping spatial scales. The ratio of integration time on one array to the other on these overlapping scales shall note exceed a factor of four, with a goal of matched integration times.	[STK1403]
Fraction of Occupied Cells	SYS1306	The system shall fill at least 50% [TBC] of (u,v)-cells before gridding out to 36 km baselines in a snapshot continuum observation traversing the meridian with a 720kx720k pixel grid. Goal to achieve this fill ratio out to 420 km scales.	[SCI0106, SCI0108, SCI0109]
Distribution and Weighting of Visibilities	SYS1308	The system shall achieve a Gaussian distribution via weighting, with the geometric mean of the weights greater than 0.5 over the full range of scales that correspond to 100 m to 420 km baselines on an 8 hr observation about the meridian. Geometric mean of weights shall also be better than 0.05 at scales corresponding to 8600 km baselines.	[SCI0100, SCI0102, SCI0103, SCI0108, SCI0118.]

The computation for max and min baseline correspond 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 physical configuration of the array and the overall system efficiency. The array must be constructed accounting for practical considerations like geological features, land ownership, proximity to population centers, etc. An idealized power-law distribution for an array of 420km+ in extent is not practical. However, such a distribution is the standard by which the achievable array should be judged and measured against, and should be achievable on 36km scales.

Non-unity weighting of array elements contributes to a loss of observational efficiency. Depending on the angular resolution of interest and the ideal synthesized beam, such non-unity weights will be required.

The shortest baseline requirement will most likely require a separate array of smaller apertures in addition to the main array. The single dish provides total power (power spectral density, PSD) measurements that fill in the "zero-spacing" point of the UV plane. The single dish should ideally sample angular scales greater than the shortest interferometric baseline, in order to minimize gaps in angular scale and resolve large scale structure faithfully.

The Fraction of Occupied Cells metric is an attempt to quantify the snapshot imaging fidelity on scales >100 mas at 20 GHz (SCI0109). A baseline of 36 km accommodates a taper coefficient of 1.2 while achieving the specified resolution. 720,000 x 720,000 cell grid constrains the pixel size to 20m, approximating the antenna diameter. Please consult RD18 for additional information on this metric.

5.16. Spectral Resolution

Parameter	Req. #	Value	Traceability
Highest Spectral Resolution	SYS1401	The available spectral resolution shall be finer than 1 kHz/channel. Goal of 400 Hz/channel.	[SCI0105]
Number of Spectral Channels	SYS1402	A minimum of 240,000 channels shall be supported by the correlator and post processing systems. Goal of 400,000 channels.	[SCI0105]
Flexible Spectral Resolution	SYS1403	The spectral resolution shall be variable between sub-bands, maximizing instantaneous bandwidth while still providing high spectral resolution over selected sub-bands.	[SCI0105, SCI0006]
Doppler Corrections	SYS1404	The system shall include a method to correct/set Doppler corrections to a common reference frame.	[SCI0105]

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

The number of spectral channels proposed is derived from the minimum number of channels necessary to prevent bandwidth smearing during full band, full-beam imaging at the bottom of Frequency Span A [SYS0802] out to 1000km scales.This computation should be revisited as the input parameters are refined.

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 diameter of the antenna, and B_{max} is the longest baseline. The unit-less parameter β is used to characterize the acceptable amount of time and bandwidth smearing:

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

Here $\frac{d\theta}{\theta_{beam}}$ is the fraction of the primary beam to be imaged. Actual calculation of the effects of time and bandwidth smearing depend on the source and field structure. A value of β=0.5 it 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, $\nu_{low} = 1.2\ GHz$, $D =\ 18m$, and $B_{max} = 1000\ km$, the max channel width is of order 10kHz. Spanning 2.4 GHz of bandwidth would require of order 240k channels.

The goal of 400k channels will support blind spectroscopic surveys over a wide digitized bandwidth.

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

5.17. Delay and Phase Stability Requirements

Parameter	Req. #	Value	Traceability
Delay/Phase Variations Magnitude	SYS1501	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.	[STK1402, STK1403, SCI0100]
SNR Loss to Delay/Phase Variations	SYS1502	The instrumental delay/phase noise shall not degrade overall system SNR by more than 1%.	[SCI0100, STK1403]
Phase Noise	SYS1503	Total instrumental integrated phase noise shall not exceed 132 fsec rms.	[SYS1502]
Phase Drift Residual	SYS1504	The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds.	[SYS1501]
Absolute Phase Drift	SYS1505	The absolute phase drift per antenna over 300 second shall not exceed 8 psec. Goal to meet this specification over 1000 seconds.	[SYS1501]

Delay and phase stability are closely related. A delay change produces a signal phase change that is proportional to frequency, arising for example, from a change in cable length. 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 units of time will be used to 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 loss 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.

For the requirements given here, the time scale division between delay/phase **noise** and delay/phase **drift** is defined as one 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 which are a function of time, usually thermally or wind induced.
- Variations which 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 are further separated 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 level of constraint. Different requirements are necessary for small angle changes which impact phase calibration and large angle changes which impact antenna position determination and astrometric observations.

The large angle variations can be estimated from the residual phases after an antenna position determination; however, some systematic instrumental errors may be subsumed into any single antenna position solution.

It is assumed that the temporal and antenna pointing angle phase error contributions are independent and therefore RSS additive. If this proves not to be the case, the derivation and allocation of error contributions throughout the system (i.e., the error budget) should be revised.

For both delay/phase changes with angle and with time, the quantity that is 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). The absolute drift specification aims for less than 2π drift over a calibration cycle. The goal of these requirements is to always allow for the removal of predictably slow instrumental drifts.

5.17.1. Establishing Temporal Delay / Phase Stability Requirements

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

1. That 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. That the instrumental delay/phase noise shall not degrade the overall system SNR by more than 1%.

Statistics of the tropospheric fluctuations 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 [RD 02]).

Five observing and phase calibration techniques have been considered for the ngVLA and are documented in [RD 03]. For the purpose of establishing phase stability requirements, these can be split into three cases:

1. 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.

2. 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.

3. Reference Array or Paired Elements. A phase calibrator is observed at interval T_2, possibly at a different frequency than the target. Separate adjacent antennas observe the science target and a nearby phase calibrator to correct tropospheric phase perturbations on shorter time scales.

These different cases lead to different atmospheric delay/phase residuals and therefore 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 $T_1 \cong 30$ sec. 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 is that for fast fluctuations on time scales ≳ 1 second, corrections based on water vapor radiometry alone produce residuals comparable with fast switching alone, so **Case 1** and **Case 2** may be equivalently stringent. Given the increased water vapor at the VLA site, comparable performance of a 22GHz 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 in order 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 of order 100 meters in this analysis.

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

The residual phase fluctuations for paired elements or a reference array can be compared as follows. The rms residual atmospheric phase after fast switching phase calibration is given by Eq (1),

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

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 m above ground, d is about equal to 35 meters. This means that the residual atmospheric phase is the root of the phase structure function evaluated at 185 meters. For baselines longer than this, 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.

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 100m and 35m respectively in this comparison, resulting in the phase structure function with the same effective baseline of 135 m. Therefore, **Case 3** is the most stringent.

Note that if the physical baselines between paired elements, or the auxiliary array and science array elements, exceeds 100m this analysis should be revisited.

[RD 02] describes a simple model for σ_ϕ that scales with the effective baseline for short baselines.

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

Where β = 5/6. [RD 02] also establishes that with 90th percentile conditions, at 100GHz, σ_ϕ = 7.5 degrees for t_{cycle} = 30 sec, which as described above is equivalent to the residual from an effective baseline of 185m. Scaling by the power law, we can estimate that for b_{eff} = 135m , σ_ϕ would be approximately 5.8 degrees.

Using this approximation, and considering an observation at 120GHz, would yield an allowable phase residual of order 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 <u>drift</u> residual. Phase noise limits are defined below.

Note: The specification for phase drift 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 it is only the residual term, after calibration and subtraction of any linear trend, that affects eventual performance.

Note: This analysis has not accounted for the impact to imaging dynamic range. Rather, it aims to make the troposphere dominate any post-calibration residual. The calibration strategy proposed may be inadequate and needs to be compared to the science requirements.

5.17.2. Establishing a Phase Noise Requirement

As a first order approximation, we will limit phase noise so as to reduce system SNR by no more than 1%. The degradation in SNR due to phase variation is estimated in [RD 04] as:

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

Where $\mathcal{D}$ is the degradation in SNR for a given phase variation φ on baseline mn, and the phase is in radians. A 1% reduction in SNR is equivalent to a rms phase variation of 8.1 degrees.

At our highest observing frequency of 120GHz, this phase variation equates to188 femto-seconds. Assuming phase contributions from each antenna in baseline mn are independent processes, the contributions from each antenna sum in quadrature, and would therefore be 132 femto-seconds $(188/\sqrt{2})$.

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

Note: This analysis should be extended to evaluate the impact on high dynamic range imaging.

5.18. Gain & System Temperature Stability Requirements

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

T_{sys} expected to range from 18K at 10GHz to 175K at 120GHz 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 1mW (0dBm)[1] over an 8GHz bandwidth, a net gain of 77dB to 87dB is required. Gross system gain will be of order 110dB to 120dB, 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.
- The photometric accuracy required.
- The dynamic range of interferometric observations (both brightness and polarization)

5.18.1. Total Power Observations

Parameter	Req. #	Value	Traceability
TP Antennas: Gain Stability	SYS1601	Antenna dG/G shall not exceed 10-3 over a 200 sec period. Goal to not exceed 10-4.	[SCI0104]
TP Antennas: Gain Variations with Antenna Pointing Angle	SYS1603	Antenna dG/G shall not exceed 10-2 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 200 sec period, in the precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	[SCI0104, SCI0110]
TP Antennas: System Temperature Variations with Antenna	SYS1605	TSPILL a TREC shall vary by no more than 0.1% combined, over a 4° change in elevation in the precision operating conditions defined in 020.10.15.10.00-0001-SPE. (TBC)	[SCI0104, SCI0110]

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

Pointing Angle			
TP Antennas: Gain Calibration Reference	SYS1801	The system shall provide a switched flux reference stable to 10-3 over a 20 minute period.	[SCI0104, SCI0110]

Total power observations are based on the difference of auto correlation spectral power (or perhaps analogue total power detector output) between two switched states. For example, these two switched states might be two pointing positions. They also might be the on-source measurements during an OTF scan versus the off-source measurements at the end of the scan. Y-factor measurements to a reference load are another example (See Section 5.18.1.2).

The power spectral density of Gaussian white noise has, by definition, a flat power spectrum, with power level proportional to the bandwidth of the system. 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 accuracy of the calibration of the total power observation and/or add noise when integrating for longer periods.

The value of the total power gain stability requirements are stated in terms of the 2-point Allan standard deviation of the fractional gain variation $\Delta G/G$, as a function of time.

5.18.1.1. Total Power Mode: Gain Stability over Short Time Scales

A goal for system gain stability is that that total power mode sensitivity not be 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 themselves 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 will be assumed to be of order 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 preciptable water vapor (PWV). E.g., for a 1mm change in PWV, T_{atm} at 16GHz may rise ~0.02 K [RD 06]. With a system noise temperature of 20K, this equates to a fluctuation (dT_{atm}/T_{sys}) of 1e-3. So, In order to make atmospheric changes more dominant at all observed frequencies, gain stability (dG/G) of order 1e-3 would be required on antennas operating in a total power mode.

It should be noted that fluctuations in T_{SYS} due to expected changes in T_{REC} or T_{SPILL} have 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 in T_{ATM} as a function of elevation.

5.18.1.2. Total Power Mode: Flux Scale Calibration

Should the gain calibration noise source be well characterized in an absolute sense, it may also provide a reference for flux scale calibration.

The system described above could be characterized by Y-factor measurements in the lab. It's behavior must be characterized over its entire range of operating temperatures. It would be desirable to limit this temperature range in order to simplify 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.

5.18.1.3. 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.

5.18.2. Interferometric Observations

Parameter	Req. #	Value	Traceability
Interferometric Antennas: Gain Stability	SYS4601	Antenna dG/G shall not exceed 10-3 over a 200 sec period. Goal to not exceed 10-4.	[SCI0113, SCI0114]
Interferometric Antennas: Relative Gain Stability	SYS4602	Relative dG/G between polarization pairs shall not exceed 10-3 over a 200 sec period. Goal to not exceed 10-4.	[SCI0114]
Gain Variations with Antenna Pointing Angle	SYS4603	Antenna dG/G shall not exceed 10-2 at 10 GHz over a 4° change in elevation, scaled by frequency (TBC).	[SCI0110]
Gain Calibration Reference	SYS4801	The system shall provide a switched flux reference stable to 10-3 over a 20 minute period.	[SCI0110, SCI0113, SCI0114]

The intent of the gain stability requirements is to constrain the system gain variations that would limit the accuracy of interferometry observations and calibration. 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.

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 the SNR of the image.

5.18.2.1. Interferometric Mode: Gain Stability on Short Time Scales

A goal for system gain stability in interferometric modes is to support the imaging and polarization dynamic range requirements.

SCI0113 calls for a brightness dynamic range of 50 db over the field of view at 10 GHz. As laid out in Section 5.18.2, 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 (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 and that the phase errors, after calibration, are negligible for this analysis in order to put an upper limit of the gain errors that would support the dynamic range requirement. Per RD19 (p279), 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 order 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 order 1e-4 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in section 5.18.3.

5.18.2.2. 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 40 db at 10 GHz in the center of the field of view. Holding the relative gain stability between polarization pairs within a single antenna to 1e-3 should suffice for this requirement, based on similar arguments to those laid out in section 5.18.2.1.

This requirement should be explored in more detail in the future.

5.18.3. 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.

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

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

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

Applied over a bandwidth of 1GHz, the integration time required is of order 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 the accuracy of the gain calibration and add noise. Note that the calibration will allow for the subtraction of any linear drift term, so it is only the residuals (rms) after linear term subtraction that will remain.

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

5.19. Calibration Efficiencies

Parameter	Req. #	Value	Traceability

Calibration Efficiency	SYS1061	Overheads for system calibration shall be minimized, with a goal of 90% of time spent on source for Standard Observing Modes.	[SCI0100, SCI0102, SCI0106, STK1403, STK0704]
Calibration Parallelization	SYS1062	Any real-time calibration pipelines must permit parallelization at the antenna or baseline level.	[STK1403]
Calibration Recall	SYS1063	The system shall remember prior calibration corrections and apply them if their projected accuracy (given time elapsed) still meets the requirements for a given observation. (I.e., a scheduling block need not always include its own calibrators.)	[STK1403]
Relative Flux Scale Calibration Efficiency	SYS1064	The system shall permit relative flux scale calibration to 5% precision without the need for tipping scans in Standard (Interferometric) Observing Modes.	[STK1403, STK0704]
Polarization Calibration Efficiency	SYS1065	Polarization calibration shall be achievable with a single observation of a compact polarized source of unknown polarization angle for Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]
Bandpass Calibration Efficiency	SYS1066	The system shall have adequate gain stability to permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	[STK1403, STK0704]
Gain Calibration Efficiency	SYS1067	Gain calibration shall be achieved with no more than a 2% degradation in system sensitivity as a function of clock time.	[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 phase calibration overheads to 10% of on-source time.	[STK1403]

Total observing efficiency will vary with each observation given its unique calibration needs. Care will be required in the design of the calibration system for phase, gain and other systematics, and the efficacy of each system should be judged by their impact on observational efficiency. Improvements to the phase calibration system that increase operational system efficiency 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 the calibration efficiencies are better thought of as technical parameters that should be optimized for general use cases. This is discussed further in Section 7.4.2.

5.20. Polarization Requirements

Parameter	Req. #	Value	Traceability
Polarization Purity	SYS1901	0.1% post-calibration on-axis residual linear pol leakage (amplitude), where leakage is defined as Stokes Q/ I, U/ I, or V/ I. Goal of 0.01% residual on-axis polarization leakage.	[SCI0114]

As stated in requirement SCI0015, the system will measure all polarization (stokes) products simultaneously. Per SCI0114, the system should achieve 40dB polarization dynamic range.

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

How the error budget should be allocated amongst system elements should be determined once a polarization calibration strategy is developed. 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 that are not common to both polarizations will contribute to this error.

5.21. Temporal Requirements

Parameter	Req. #	Value	Traceability
On-The-Fly Mapping – Data & Control Rates	SYS0106	The system shall support on-the-fly (OTF) mapping rates of 2x sidereal at 28 GHz, with data dump rates and delay update rates <400 msec at the full system bandwidth. Goal to support rates <100 msec at reduced bandwidth or spectral resolution (i.e., fixed data output rate).	[SCI004, SCI0106]
On-The-Fly Mapping – Antenna Tracking Rate	SYS0107	The antenna and any motion control loops shall support on-the-fly tracking rates of 10x sidereal for elevations below 70°. (2.5'/sec)	[SCI004, SCI0106]
Temporal Resolution	SYS2001	Correlator visibility integration time shall be tunable, with a range of 5 sec to 100 msec (possibly at reduced bandwidth), or better.	[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 at most 10 ns (goal of 1 ns). This correction can be retroactive, it is not necessary for it to be known in real time.	[SCI112. SCI0014, SCI0012]

System temporal resolution may be set by either the need to prevent time and bandwidth smearing in imaging, or by the rate of change 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 in order to keep total data rates practical.

There is a relationship between the maximum integration time and maximum baseline length which is limited by circumferential smearing. In order to keep the smearing low, a rule of thumb is to keep the integration time well below [RD 09]:

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

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-m aperture, the maximum image size is approximately 1,000 km / 18 m ≈ 60,000 synthesized beams. Then, a minimum integration time equal to 50% the above expression is of order 100 msec.

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

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

5.22. Spurious Signals

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]
LO Frequency and Sampler Clock Offsets	SYS2105	The system shall include the provisions for frequency offsets and sampler clock offsets at the antenna level to provide additional attenuation of spurious signals.	[SCI0115, SCI0113, SCI0108]
Shielding & Emission Limits	SYS2106	System shielding and emission limits shall comply with 020.10.15.10.00-0002-REQ.	[SCI0116]

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

Spurious signals may be coherent or incoherent signals. While both can affect system performance, coherent signals are more damaging, since they do not average out with more samples/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: (i) that the bandpass be sufficiently stable in time that it does not give false appearance of weak lines, and (ii) that there should not be self-generated spurious features in the output spectra.

In interferometry mode, spurious signals coherent between antennas can lead to a) spurious spectral features, b) closure errors that limit calibration accuracy and thus imaging dynamic range, and c) 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 RD 14, 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 of order 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 of order 20 dB due to phase winding / fringe washing (-53 dB + 20 dB = 33dB / 10kHz). (See AD 06 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 -43dB/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° phase switching (Walsh switching) can be used to further reduce the impact of spurious signal introduced after the 1st 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 the recovery of large scale structure is more applicable on large mosaics with shallower integration.

5.23. Scientific Operations Requirements

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 the analysis of data products.	[STK0801, STK1201, STK1202, STK0805]

Tools need to be supplied for user interaction with the facility. As with current NRAO facilities, these are expected to include proposal preparation, observation preparation and data reduction. Revisions to existing tools, with similar requirements, are expected to be adequate.

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

Note that the design, allocation and location of computing resources are an example of an area where community engagement may be feasible (see Stakeholder Requirements). Computing resources could be hosted at major research universities in a distributed computing model. Community development of software tools, as part of a modular tool-kit, may also be practical.

5.23.1. Proposal Submission & 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	SYS2212	For non-standard observing modes, it shall be possible for the user to define their technical observation parameters as part of their proposal.	[STK0800, STK0801, STK0702]

modes.			
Scientific Proposal Evaluation	SYS2213	A tool shall be available for proposal evaluation and ranking. The tool shall permit the anonymization of proposals during evaluation.	[STK0802, STK0803]
Technical Proposal Evaluation	SYS2214	The proposal evaluation tool shall include technical simulation tools to estimate the observing resources required (sub-arrays, time) to support the science requirements.	[STK0802]

5.23.2. Observation Preparation, Execution & Scheduling

Parameter	Req. #	Value	Traceability
Observation Preparation – Standard Observing Modes	SYS2221	For standard observing modes, the system shall determine the technical configuration of the system and a supporting observation plan that meets the science requirements set by the proposer.	[STK0805, STK0701]
Observation Preparation - Non-Standard Observing modes	SYS2222	The system shall include tools and interfaces to generate observation instructions for non-standard modes without the use of the end-to-end software system.	[STK0402, STK0502]
Observation Scheduling GUI	SYS2223	The observation scheduling system shall include a GUI to display completed and scheduled projects to the Operator, and to initiate manual over-rides and other changes.	[STK0901, STK1502]
Observation Interrupt	SYS2224	It shall be possible to interrupt and cancel an in-progress observation through the observation scheduling system GUI and the Operator Console.	[STK0901, STK1502]
Observation Preparation – Standard Observing Mode Flexibility	SYS2225	For standard observing modes, the proposed observation plan shall be supplied to the user for review, and the user can propose modifications as necessary to support their science requirements.	[STK0705]
Observation Scheduling	SYS2302	System observations shall be automatically scheduled by an observation scheduling system. Manual over-rides to scheduling shall also be possible.	[STK0900, STK0901]

5.24. Array Operation Requirements

Parameter	Req. #	Value	Traceability

Calibration Automation	SYS2303	The calculation and updating of parametric delay and pointing models shall be automated.	[SYS1061, SYS1062 STK1506]
Self-Calibrating Antenna	SYS2304	It is a goal that the antenna self-configure and self-calibrate, with limited intervention from the operator.	[SYS1061, SYS1062, 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]
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., 1s, 3s, etc.)	[STK1700, STK0402, STK0502]
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 alerts.	[STK1703]

The requirements for ngVLA are broad, with a scientific operation concept similar to the VLA, where observers request time for a specific study and define many of the parameters of the observation. 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 observation schedule that maximizes output given system and environmental conditions.

The PI-driven general purpose and flexible model is in tension with operations cost caps. This means that the system operation should be automated where possible, enabling systems to self-monitor, self-configure and self-calibrate in order to reduce the operations burden and staffing required.

There are significant implications for the monitor and control system and supervisory software systems that will need to be elaborated in those sub-system requirements.

5.25. Array Maintenance Requirements

Parameter	Req. #	Value	Traceability
Antenna Maintenance Interval	SYS2401	The system shall be designed with a preventative maintenance interval of no shorter than 1 year.	[STK1800]
Array Element MTBF	SYS2402	The antenna, antenna electronics, array infrastructure, and signal processing system shall be designed with an expected number of failures to be less than four (4) per array element per year.	[STK1802, STK0101]
Modularization	SYS2403	The system shall be modularized into Line Replaceable Units (LRUs) to facilitate site	[STK1802, STK1603]

		maintenance.	
Predictive and Self-Diagnostic Function	SYS2405	The system shall incorporate predictive maintenance and self-diagnosis functions in the case of faults based on recorded monitor data.	[STK1803, STK1702]
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, STK1601]
Engineering Console	SYS2407	The system shall include an engineering console for each major sub-system and/or LRU to communicate system status and assist in real-time diagnosis.	[STK1700, STK1702, STK0402, STK0502]
Engineering Database	SYS2408	The system shall record all monitor data at variable rates for automated use by predictive maintenance programs and for direct inspection by engineers and technicians.	[STK1700, STK1702, STK0402, STK0502]

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

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

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

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

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

For N_{LRU} = 16, in order to have an MTBF of the system of 2,190 hours, the MTBF per LRU required would be of order 35,040 hrs (4 yrs). Apportionment of failures throughout the system in order to have a maintainable array will require further study.

Specifying MTTFs rather than MTBFs may be more appropriate, with a goal of harmonizing the MTTF and the preventative maintenance schedule of the antenna so that maintenance is more closely tied to the preventive maintenance cycle than responsive to failures.

5.26. 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.	[STK1803, STK1702]
LRU Alerts	SYS3102	When an LRU is out of specification it shall generate a prioritized alert for processing by the operator and maintenance scheduler.	[STK1803]
Monitor Archive	SYS3103	Monitor data and alerts shall be archived at variable rates, depending on criticality, for the full life of the instrument. (SYS2801)	[STK1700]
Sub-System Monitoring Screens	SYS3104	Engineering consoles shall be provided for all major sub-systems.	[STK1600, STK1702, STK1506]
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)	[STK1702, STK1506]

5.27. 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]
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 archived at no less than 1 minute periods.	[STK1403]

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

5.28. System Availability

Parameter	Req. #	Value	Traceability
Antenna System Availability	SYS2601	Minimum 90% availability for all antenna systems combined. Availability is defined as time available for science operations, excluding scheduled and unscheduled maintenance downtime. Goal of maintaining 95% availability.	[STK1402]
Centralized Systems Availability	SYS2602	For all centralized systems (LO distribution, correlator, etc) that are required for data collection, system availability shall be no less	[STK1402]

		than 95%. See definition of availability above.	

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

The availability requirement has a flow-down needs to be harmonized with the maintenance requirements established in Section 5.25. The mean time to repair (MTTR) must be calculated for common failures, in order to determine down-time for each failure. A time allocation must also be made for preventive maintenance and testing allocations, and they must add up to no more than 10% of clock time.

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

5.29. Safety & Security

Parameter	Req. #	Value	Traceability
Safety Specification	SYS2700	All sub-system designs shall comply with the System Safety Specification (Doc TBD)	[(TBD)]
Sub-system self-monitoring	SYS2701	All sub-systems to monitor system health and prohibit actions likely to cause damage.	[STK1702]
IT Security	SYS2702	The data processing, networking, and data archive systems will be engineered and operated in accordance with current best practices in IT Security, as defined by the NSF-funded Center for Trustworthy Scientific Infrastructure (https://trustedci.org) and the AUI Cyber Security Policy.	[STK2202]
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 that are likely to cause damage, and respond to conditions that indicate imminent failure. An example would be to auto-stow the antenna if the limits to the operational environment are reached, and not permit the operator to switch back to an operational mode until the condition subsides.

Given modern threats, the system should include provisions to 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 safety of operation and maintenance personnel should be considered at every level of the design. Hazard analysis shall be performed for all common services to motion, high-power, high-voltage or otherwise high-risk systems. The findings from such an analysis shall be incorporated into the sub-system requirements and design.

5.30. 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.	[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, STK0100, STK0101, STK0600]
Sustainability	SYS2803	Sustainability and long-term environmental impact shall be considered in any material or design trade-study.	[STK0302]

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

The system shall be built to with an accounting of the full life-cycle 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 operational cost of the array while still offering competitive life-cycle cost analysis. Examples might include the use of reusable energy generation, or energy-saving technologies for cryogenic or HVAC systems.

5.30.1. Assembly, Integration & Verification Requirements

Parameter	Req. #	Value	Traceability
Test Fixtures	SYS2811	Each sub-system shall provide test fixtures and procedures for sub-system verification.	[STK0400]
Critical Spares	SYS2812	Each sub-system shall identify and provide critical spares and 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	[STK0403]

		produced/ordered in small volumes.	
System Verification Tools	SYS2813	Tools shall be developed to automate test execution and test reporting as part of array element verification. Such tools shall include near real-time data display for interactive diagnosis by engineers.	[STK0402]

6. L2 SYSTEM REQUIREMENTS

The following requirements flow from the L1 requirements listed in Section 5. These requirements are not implementation agnostic but provide sufficient allocation of L1 requirements to allow derivation of supporting sub-system requirements.

These requirements may move to subsidiary documents in the future.

6.1. System Collecting Area

Parameter	Req. #	Value	Traceability
System Geometric Collecting Area	SYS1021	The system gross geometric collecting area shall be 62,000 m2 or greater.	[SCI0100, SCI0102, SCI0106]

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

6.2. System Temperature

Parameter	Req. #	Value	Traceability
Maximum TSYS in Freq. Span A:	SYS1011	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1mm of PWV.	[SCI0100, SCI0102, SCI0106]
Maximum TSYS in Freq. Span B:	SYS1012	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1mm of PWV.	[SCI0100, SCI0102, SCI0106]
Maximum TSYS in Freq. Span C:	SYS1013	Not to exceed values in Table 2 in the precision operating environment, 45-deg elevation, and 1mm of PWV.	[SCI0100, SCI0102, SCI0106]

The system temperature contributes to system sensitivity [SYS0501-SYS0504]. It is possible to compensate for added T_{SYS} with bandwidth and/or collecting area in an effort to optimize sensitivity as a function of cost.

The values given in Table 2 are at the point frequency and assume the environmental conditions of the precision operating environment [AD 05] at an elevation of 45-degrees and assuming 6mm of PWV for SYS1011 and SYS1012. 1mm of PWV can be assumed for SYS1013.

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 receiver complement on the antenna. Note that when comparing various receiver configurations, both the system temperature and the feed illumination efficiency should be equally considered in order to make fair comparisons. This is discussed further in Section 7.4.1.

System temperatures at spans B and C [SYS1012, SYS1013] should be as low as practical, consistent with a desire to maximize sensitivity at these frequencies.

Table 2 - Tsys over Frequency in Precision Environment

Frequency (GHz)	**1.2**	**5**	**7.9**	**8**	**30**	**40**	**50**	**70**	**80**	**100**	**115**
Max T_{SYS} (K)	27	28	30	25	32	42	90	125	75	75	135

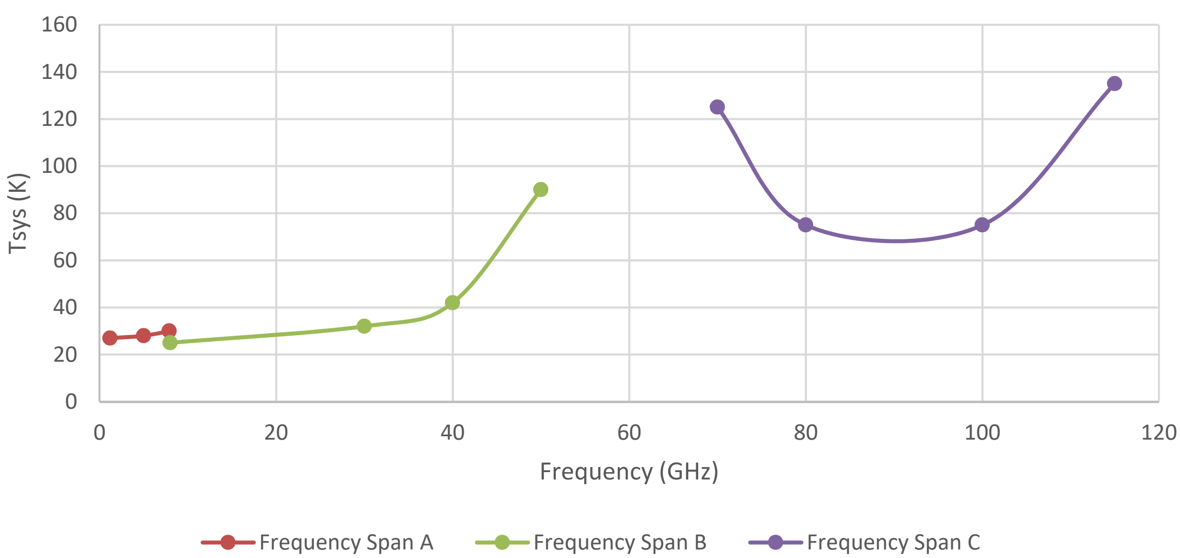

Figure 2- Tsys over Frequency in Precision Environment.

6.3. Analog & Digital Efficiency Requirements

Parameter	**Req. #**	**Value**	**Traceability**
Antenna Efficiency – Precision Environment	SYS1031	The antenna efficiency in the precision operating environment shall exceed the values given in Table 3.	[SCI0100, SCI0102, SCI0106]
Antenna Efficiency – Normal Environment	SYS1032	The antenna efficiency in the normal operating environment shall exceed the values given in Table 4.	[SCI0100, SCI0102, SCI0106]
Minimum	SYS1033	0.96 minimum, including quantization and	[SCI0100, SCI0102,

Interferometer Digital System Efficiency		correlation losses (equiv. to 3.0 effective bits). It is desirable to approach 0.99 efficiency over narrow (<5 GHz) bandwidths for spectral line use cases.	SCI0106]
Minimum Digital Quantization Levels - Narrow Bandwidths (<5GHz)	SYS1034	28 (256 levels), when supported by the front end sampler.	[SYS1033]
Minimum Digital Quantization Levels - Wide Bandwidths (>5GHz)	SYS1035	24 (16 levels)	[SYS1033]
Correlator Precision	SYS1036	8-bit correlation minimum.	[SYS1033]

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

Antenna efficiency includes antenna reflector/structure losses and feed illumination losses. The antenna efficiency is specified at a single frequency within each Frequency Span (see Section 5.10) for simplicity, but elaborated in Section 6.3.1.

The digital system efficiency includes quantization efficiency and any losses from requantization at various parts of the digital signal path. With 3-bit (8-level) effective quantization, efficiency of 0.96 is achievable [RD 07].

6.3.1. Antenna Efficiency Allocations in Precision Environment

The allocation of antenna efficiency errors is shown in Table 3. Additional frequencies are included for clarity. The allocation of efficiencies is based on projected taper and spill contributions of candidate feeds with shaped optics. No allocation is included for blockage or polarization, as unblocked apertures are preferred.

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

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

Table 3 - Antenna Efficiency Budget as a Function of Frequency for Precision Environment

6.3.2. Antenna Efficiency Allocations in Normal Environment

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

Table 4 - Antenna Efficiency Budget as a Function of Frequency for Normal Environment

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

6.4. Allocation of Delay/Phase Noise and Drift Requirements

Parameter	**Req. #**	**Value**	**Traceability**

Allocation of Delay/Phase Noise & Drift	SYS5001	The allocation of instrumental delay/phase errors shall not exceed the values in Table 5.	[SCI0100, SCI0102, SCI0106]

The allocation of temporal delay/phase requirements among the electronics sub-systems and the mechanical structure is given in Table 1. The various quantities are combined in an RSS sense.

Initial allocations are equally distributed between systems. This should be revisited as the technical feasibility of each system is assessed.

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

Table 5 - Allocation of Temporal Instrumental Delay/Phase Errors (per antenna errors, in fsec)

Notes:

1. The delay/phase drift requirements in Table 1 apply on a time scale up to 300 sec, 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 sec.

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

3. The temporal delay/phase error allocation to "Antenna Structure" refers to the mechanical structure of the antenna, and arises from wind or thermal distortions of the antenna. The delay error is a function of the direction of the incident wave front and direction of the antenna distortion.

4. Phase noise is only allocated to the final oscillators in the system that are used for down conversion or data sampling. Note that the digitizer clock stability will scale proportional to the frequency down conversion, so the required stability of the actual digitizer clock for a 7 GHz baseband would be approx.: 76 fsec * 120 GHz / 7 GHz = 1.3 psec.

5. It is assumed that the RTP system will provide slow corrections only, and that the phase noise of the LO distribution system will be largely eliminated by the narrow bandwidth of the PLL for

the antenna LO. The antenna structure retains a contribution due to wind induced stochastic oscillations/jitter.

6. Allocations are an arbitrary equal allocation for contributing system elements. This should be revised based on further analysis and technical feasibility.

7. The phase drift specified exceeds the frequency stability of an active hydrogen maser: frequency stability of order to 10^{-14} equates to phase rms of 3 psec. Providing a coherent frequency reference over the main array scales described in SYS1301 (420 km extent) is required. Sensitivity on the longest baselines is relaxed to account for separate frequency references at each site.

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

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

Table 6 - 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 Nose and Phase Drift Residual.

6.4.1. Calculating Delay/Phase Noise and Drift

When verifying performance to system or sub-system 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-sec average. The requirement applies to the integrated phase noise from the highest significant frequency (~1 MHz) down to 1Hz.

The delay/phase **drift** requirement refers to the 2-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 non-standard.

Strictly speaking, the Allan variance refers to the 2-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 2-sample variance of phase and of gain.

6.5. Allocation of Gain Stability Requirements

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

As described in Section 5.18, gain stability of 1e-3 is required over short (200 second) timescales. (SYS1601, SYS4601)

Typical gain fluctuations as a function of temperature ((1/G) dG/dT) for LNAs are of order 0.03/K for cryogenic devices, and 0.01/K for warm devices. To achieve dG/G of 1e-3 would require thermal regulation to 0.03 K within the dewar and to 0.1 K for warm devices over 200 second scales.

These requirements can be traded against each while still achieving the L1 requirements (SYS1601, SYS4601).

The inclusion of a gain calibration noise source has reduced the period over which this stability is required to 200 seconds as described in Section 5.18.3. This noise source, and any intervening electronics between the noise source and the coupler, must be stable to 1e-3 over 20 minute periods. This 20 minute period corresponds to the expected gain calibration cycle on astronomical sources.

6.6. Bandpass Requirements

Parameter	Req. #	Value	Traceability
Bandpass Stability	SYS1701	The bandpass amplitude shall be stable to 0.3% over 60 minutes. (TBC)	[SCI0115, SYS1061]
Bandpass	SYS1702	The analog bandpass ripple across a	[SYS1033]

Ripple		digitized band shall be constrained to less than 3dB peak to peak.	
Bandpass Flatness	SYS1703	The bandpass of an individual digitized band shall have slope no greater than 3dB, measured across 80% of the bandwidth.	[SYS1033]
Sideband Separation	SYS1704	The sideband separation in any dual-sideband frequency conversion system shall be better than 30dB. Goal of 40dB separation.	[SCI0115, SCI0113, SCI0116, SYS2104]

The stability requirement is closely related to the spectral line performance as well as the imaging dynamic range. Both specifications require stable gains as a function of time.

The bandpass ripple and flatness specifications are constrained to maintain the minimum effective number of bits of the sampler over the full sampled frequency band.

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

6.7. Triggered Observation Requirements

Parameter	Req. #	Value	Traceability
Trigger Response Time Allocations	SYS5101	The trigger response time allocations for major activities shall be consistent with Table 7.	[SYS3005]

The control system will need to have ports to receive and process external triggers to meet SYS3004-SYS3005. The response time desired will limit human intervention/assessment, so it is preferred that the system process them in an automated fashion.

Approximate time budget for response time (typically meeting 3 minute goal of SYS3005):

Action	Time Allocation	Cumulative Time	Notes
Reception of External Trigger	1 sec	1 sec.	
Termination of Current Scheduling Block	20 sec.	21 sec.	
System Setup to new Scheduling Block	20 sec.	41 sec.	
Antenna Slew To Source	2 min max	161 sec.	@ 90-deg/min Az., 45 deg/min El.;

			Ignores Acceleration time.
Antenna Settle Time	10 sec. max.	171 sec.	
Receiver Band Selection	20 sec. max.	181 sec.	during slew

Table 7 – Triggered Response Time Budget

The time budget above imposes the following sub-system requirements:

- Antenna slew rates of 90-deg/min in Azimuth and 45 deg/min in Elevation.
- Antenna settling time of 10 sec max.
- Requirement to permit band selection during an antenna slew. Impact on electrical system size.
- The time of a scheduling block should be limited to 20 seconds, and/or be interruptible by the control system.

7. TECHNICAL PERFORMANCE MEASURES

This section provides the Technical Performance Measures (TPMs) that should be monitored throughout the design and development phase of the project. These are parameters that have a high influence on 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, and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

7.1. Definitions

Key Performance Parameters (KPPs): The most essential parameters to achieving the key science goals. These are capabilities or characteristics so significant that failure to reach the threshold value of performance can cause the system concept to be reevaluated, or even the program to be reassessed or terminated. Must have a threshold and an objective value. In a trade-study, everything can be traded-off except a KPP.

Measures of Effectiveness (MoEs): Measures of how well an astronomical observation is accomplished. Can be expressed on a scale with no fixed threshold. Examples for ngVLA include sensitivity as a function of time, or survey speed.

Measures of Performance (MoPs): Measures that are components of, or contribute to, MoEs. An examples of an MoPs contributing the MoEs above may be collecting area.

7.2. Key Performance Parameters

See the ngVLA Science Requirements document (AD 01) for the KPPs associated with each Key Science Goal (KSG).

7.3. Measures of Effectiveness

The following are the measures of effectiveness identified for monitoring throughout the design phase.

Measures of Effectiveness	Req. #
Surface Brightness Sensitivity - Continuum	SCI0100
Surface Brightness Sensitivity – Spectral Line	SCI0102
Point Source Sensitivity - Continuum	SCI0100
Point Source Sensitivity - Spectral Line	SCI0102
Survey Speed	SCI0106
Largest Angular Scale	SCI0104
Maximum Resolution	SCI0103

Table 8 - ngVLA Measures of Effectiveness

As estimates of each measure are updated, the impact on the KSGs identified in AD 01 should be assessed.

7.3.1. Surface Brightness Sensitivity - 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 – either 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. Frequency and integration time must be fixed. For this analysis, one hour of observing time be used for all cases, at five frequencies of interest as tabularized below.

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

10^5 K					

Table 9 - Example tracking table for SB sensitivity.

7.3.2. *Surface Brightness Sensitivity - Spectral Line*

Similar to 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 brightness temperature of sources that can be investigated for spectral features at a given spectral resolution and frequency. As with continuum surface brightness sensitivity, it also changes as a function of spectral resolution.

The parameter will be fixed at 10 km/s spectral resolution for an observation of 1 hour. It is expressed in K, as a function of time, spectral resolution and frequency. (e.g. 0.3K/hr @ 10km/s @ 1cm).

7.3.3. *Imaging Sensitivity - Continuum*

Imaging continuum sensitivity is a representation of 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 1hr observation will be used.

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 and angular scale, while meeting the beam quality metrics established in the Science requirements.

7.3.4. *Imaging Sensitivity - Spectral Line*

Spectral line sensitivity is closely related to continuum sensitivity, but the bandwidth is limited by a given spectral resolution desired. A 1 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 or system temperature.

7.3.5. *Continuum Survey Speed*

When mapping large areas, the FOV that can be imaged is important in addition to 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 10uJy 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 and angular scale, while meeting the beam quality metrics established in the

Science requirements.

7.3.6. Largest Angular Scale

Interferometers are insensitive to large-scale structures since they are 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 arcsec, this parameter provides an indication of 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.

7.3.7. Maximum Angular Resolution

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

7.4. Measures of Performance

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

Measures of Performance	Req. #
Effective Aperture / Tsys	SYS1001
Distribution and Weighting of Visibilities	SCI1308
Observing / Calibration Efficiency	SYS1061
Instantaneous FOV (FWHM)	SYS1101
B_{MIN}	SYS1302
B_{MAX}	SYS1301

Table 10 - ngVLA Measures of Performance

Interpretation notes for each are enumerated in the subsections below.

7.4.1. Effective Aperture / System Temperature

This measure is indicative of the sensitivity of the array 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.

7.4.2. Distribution and Weighting of Visibilities

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

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

7.4.3. Observing / Calibration Efficiency

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

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

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

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

The following calibration overheads shall be included:

- Phase
- Gain and Bandpass
- Relative Flux scale

Further assumptions that will be used for this estimation include:

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

With a 1hr observation window, there is scope to improve both the time spent on each calibrator as well as the major cycle time between calibrator visits. Changes in either parameter will be apparent in the observing efficiency.

8. VERIFICATION

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

Verification by Design: The performance shall be demonstrated by a proper design, which may be checked by the ngVLA project office during the design phase by review of the design documentation.

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 tests.

Multiple verification methods are allowed.

8.1. L1 System Requirements

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

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

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS0001	Functional Modes	*				
SYS0002	Interferometric Mode	*			*	
SYS0003	Phased Array Mode	*			*	
SYS0004	Pulsar Timing Mode	*			*	
SYS0005	Pulsar and Transient Search Mode	*			*	
SYS0006	VLBI Mode	*			*	
SYS0007	Total Power Mode	*			*	
SYS0008	On The Fly Mapping Mode	*			*	
SYS0009	Solar Observing Mode	*			*	
SYS0202	Concurrent Interferometric and Phased Array Mode	*			*	
SYS0601	Sub-Array Capabilities	*			*	
SYS0603	Sub-Array Composition	*			*	
SYS0604	Sub-Array Operating Modes	*				
SYS0605	Sub-Array Operating Mode Commensality	*	*		*	
SYS0602	Phase Preservation	*				*
SYS0606	Sub-Array Configuration	*			*	

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS0101	Variable Spectral Resolution	*			*	
SYS0102	Polarization Products	*			*	
SYS0103	Autocorrelation Products	*			*	
SYS0104	Commensal Processing	*		*		
SYS0201	Phased Aperture	*				*
SYS0203	Number of Beams	*			*	
SYS0301	Timing Capabilities	*		*		
SYS0302	Timing Sys. Bandwidth	*			*	
SYS0303	Timing Sys. Frequency Resolution	*			*	
SYS0304	Pulse Profile Bins	*			*	
SYS0305	Polarization	*				
SYS0306	Pulse Period	*				*
SYS0307	Dump Rate	*			*	
SYS0401	Search Capabilities	*		*		
SYS0402	Search Sys. Bandwidth	*			*	
SYS0403	Search Sys. Frequency Resolution	*			*	
SYS0404	Search Sys. Time Resolution	*			*	
SYS0405	Polarization	*			*	
SYS0501	VLBI Recording Capabilities	*			*	
SYS0502	eVLBI Capabilities	*	*			
SYS3001	Standard Observing Modes	*				
SYS3002	Number of Standard Observing Modes	*	*			
SYS3003	Non-Standard Observing Modes	*			*	
SYS3004	Triggered Observations	*				
SYS3005	Triggered Observation Response	*	*			
SYS3006	Trigger Time-Out	*			*	
SYS0701	Uncalibrated Data	*		*		
SYS0702	Flagged Data Table	*		*		
SYS0703	Calibrated Data Table	*		*		
SYS0721	Imaging Pipeline	*				*
SYS0741	Pulsar Timing Data Product	*				
SYS0741	Pulsar Search Data Product	*				
SYS0731	Archive Period	*	*			
SYS0732	Archive Products	*				
SYS0733	Proprietary Data Rights	*		*		
SYS0738	Proprietary Period	*		*		
SYS0734	Archive Batch Reprocessing	*		*		
SYS0736	Archive User Reprocessing	*			*	
SYS0735	Archive Backup	*	*	*		
SYS0751	Data Processing Resources	*	*			
SYS0752	Throughput & Latency	*	*			
SYS0753	Heterogeneous Arrays	*			*	
SYS0761	Data Analysis Resources	*			*	
SYS0801	System Frequency Range	*				

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS0802	Optimized Frequency Range	*				
SYS0803	Freq. Span A:	*				
SYS0804	Freq. Span B:	*				
SYS0805	Freq. Span C:	*				
SYS0806	Continuity of Frequency Coverage	*			*	
SYS0901	Front End Bandwidth Ratio	*				
SYS0902	Instantaneous Digitized Bandwidth	*		*		
SYS0903	Total Instantaneous Processed Bandwidth	*				*
SYS0904	Sub-Bands	*				
SYS0905	Frequency Tunability	*			*	
SYS0906	Fixed Analog Tunings	*				
SYS0907	Sub-Band Step Size	*				
SYS0909	Contiguous Bandwidth	*				
SYS0908	Band Switching Time	*				*
SYS1001	Effective Area / Tsys Ratio	*	*			
SYS1101	Instantaneous Field of View	*				
SYS1102	Accessible Field of View	*	*			
SYS1103	Slew Rates	*	*			
SYS1104	Tracking Rates	*	*			
SYS1201	Input Dynamic Range	*				*
SYS1202	Gain Calibration System Dynamic Range	*				
SYS1203	Provision of Variable Attenuators	*				
SYS1204	Input Protection	*	*			
SYS1205	High-Noise Path	*				
SYS1301	Longest Baseline	*				
SYS1302	Shortest Baseline	*				
SYS1303	Zero Spacing / Single Dish Total Power	*				
SYS1304	Integration Time Ratios	*	*			
SYS1306	Fraction of Occupied Cells	*	*			
SYS1308	Distribution and Weighting of Visibilities	*	*			
SYS1401	Highest Spectral Resolution	*				
SYS1402	Number of Spectral Channels	*				
SYS1403	Flexible Spectral Resolution	*				
SYS1404	Doppler Corrections	*			*	
SYS1501	Delay/Phase Variations Magnitude	*	*			
SYS1502	SNR Loss to Delay/Phase Variations	*	*			
SYS1503	Phase Noise	*	*			*
SYS1504	Phase Drift Residual	*	*			*
SYS1505	Absolute Phase Drift	*	*			*
SYS1601	TP Antennas: Gain Stability	*	*			*
SYS1603	TP Antennas: Gain Variations with	*	*			*

Req. #	Parameter / Requirement	D	A	I	DM	T
	Antenna Pointing Angle					
SYS1604	TP Antennas: System Temperature Stability over Time	*	*			*
SYS1605	TP Antennas: System Temperature Variations with Antenna Pointing Angle	*	*			*
SYS1801	TP Antennas: Gain Calibration Reference	*	*			*
SYS4601	Interferometric Antennas: Gain Stability	*	*			*
SYS4602	Interferometric Antennas: Relative Gain Stability	*	*			*
SYS4603	Gain Variations with Antenna Pointing Angle	*	*			*
SYS4801	Gain Calibration Reference	*	*			*
SYS1061	Calibration Efficiency	*	*			
SYS1062	Calibration Parallelization	*				
SYS1063	Calibration Recall	*				
SYS1064	Relative Flux Scale Calibration Efficiency	*				*
SYS1065	Polarization Calibration Efficiency	*				
SYS1066	Bandpass Calibration Efficiency	*				*
SYS1067	Gain Calibration Efficiency	*	*			
SYS1068	Phase Calibration Efficiency	*	*			
SYS1901	Polarization Purity	*	*			*
SYS2001	Temporal Resolution	*				
SYS2002	Temporal Accuracy	*	*			
SYS2104	Self-Generated Spurious Signal Power Level	*	*			*
SYS2105	LO Frequency and Sampler Clock Offsets	*			*	
SYS2106	Shielding & Emission Limits	*	*			*
SYS2201	Provision of Software Tools	*				
SYS2202	Provision of Computing Resources	*	*			
SYS2301	Operations Concept	*				
SYS2302	Observation Scheduling	*			*	
SYS2303	Calibration Automation	*			*	
SYS2304	Self-Calibrating Antenna	*				
SYS2401	Antenna Maintenance Interval	*	*			
SYS2402	Antenna MTBF	*	*			
SYS2403	Modularization	*				
SYS2404	Central Repair Facility	*				
SYS2405	Predictive and Self-Diagnostic function	*			*	

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS2501	Weather Monitoring	*		*		
SYS2502	Safety Weather Monitoring	*		*		
SYS2601	Antenna System Availability	*	*			
SYS2602	Centralized Systems Availability	*	*			
SYS2701	Sub-system self-monitoring	*				
SYS2702	IT Security	*		*		
SYS2703	Hazard Analysis	*		*		
SYS2801	Design Life	*	*			
SYS2802	Cost Optimization	*	*			

8.2. L2 System Requirements

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

The order of requirements in the table corresponds to the order in which they are found in Section 6.

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS1021	System Geometric Collecting Area	*				
SYS1011	Maximum T_{SYS} in Freq. Span A:	*	*			*
SYS1012	Maximum T_{SYS} in Freq. Span B:	*	*			*
SYS1013	Maximum T_{SYS} 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 - Narrow Bandwidths (<5GHz)	*				
SYS1035	Minimum Digital Quantization Levels - Wide Bandwidths (>5GHz)	*				
SYS1036	Correlator Precision	*				
SYS5001	Allocation of Delay/Phase Noise & Drift	*	*			*
SYS4901	LNA Gain Fluctuations w Temperature	*				
SYS4902	Warm Electronics Gain Fluctuations w/ Temperature	*				
SYS4903	Dewar Temperature Regulation	*	*			*
SYS4904	Warm Electronics Temperature Regulation	*	*			*
SYS1701	Bandpass Stability	*				*

Req. #	Parameter / Requirement	D	A	I	DM	T
SYS1702	Bandpass Ripple	*		*		
SYS1703	Bandpass Flatness	*		*		
SYS1704	Sideband Separation	*				*
SYS5101	Trigger Response Time Allocations	*	*			*

9. APPENDIX

9.1. Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/submillimeter Array
AST	Division of Astronomical Sciences (NSF)
BW	Band Width
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
LO	Local Oscillator
MoE	Measure of Effectiveness
MoP	Measure of Performance
MREFC	Major Research Equipment and Facilities Construction (NSF)
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PLL	Phase Locked Loop
PSD	Power Spectral Density
PWV	Precipitable Water Vapor
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SEFD	System Equivalent Flux Density
SKA	Square Kilometer Array
SWG	Science Working Group
SNR	Signal to Noise Ratio
SRDP	Science Ready Data Products

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

9.2. Derivation Notes from the Level-0 Science Requirements

Derivations that support the science requirements are aggregated here. Information is duplicated from the main text, but reorganized to better show the traceability to individual science requirements.

9.2.1. Functional Requirements

Parameter	Req. #	SciCase	Value
Frequency Coverage	SCI0001	All	The ngVLA should be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits are bracketed by spectral line emission from H_I and CO respectively.

This functional requirement translates directly, requiring continuous frequency coverage from 1.2 GHz to 50 GHz, and from 70 GHz to 116 GHz. The 50 GHz and 70 GHz boundaries are soft, based on the atmospheric temperature and opacity of the O2 line. The band edges should be set by practicalities in the receiver design.

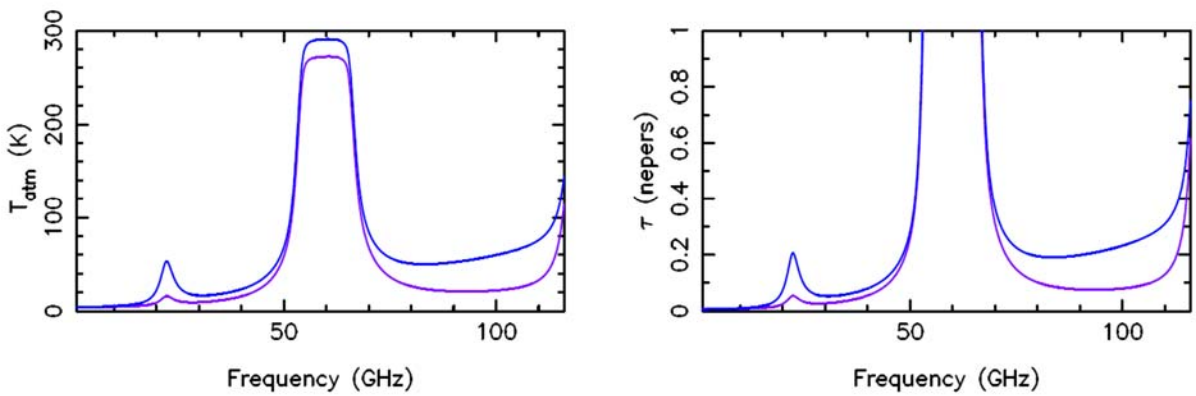

Figure 3 - Atmospheric Temperature and Opacity for wet (blue) and dry (purple) conditions. [RD 11]

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: [….]. Overlap of 1% in band edges is therefore desirable.

The dominant requirements 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 following table lists spectral lines at z=0 below 50 GHz that should be avoided in verification of this requirement:

[Insert Table]

Parameter	Req. #	SciCase	Value
Front End 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.

Interpreted as requiring the capability to digitize and process an arbitrary bandwidth (trade off with spectral resolution) that is 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 subbands for Band 6 (which is wider than 20 GHz) would of necessity 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 larger fields of view 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.)

Of the survey speed cases described in SCI0106, the most demanding is a shallow survey to 10μJy @ 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 $1/10^{th}$ 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 300km aperture, well in excess of natural beam width which is equivalent to ~165km 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 low frequency.

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 no to exceed 10 minutes are required for transient science, while response times of 3 minutes are desired.

The control system will need to have ports to receive and process external triggers. The response time required will likely preclude human intervention/assessment, so it is preferred that the system process them in an automated fashion.

Approximate time budget for response time:

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

Table 11 – Triggered Response Time Budget

The time budget above imposes the following requirements:

- Antenna slew rates of 90-deg/min in Azimuth and 45 deg/min in Elevation.
- Antenna settling time of 10 sec max.
- Requirement to permit band selection during an antenna slew. Impact on electrical system size.
- The time of a scheduling block should be limited to 20 seconds, and/or be interruptible by the control system.

Parameter	Req. #	SciCase	Value
Observing Modes	SCI0006	All	System shall observe in both narrow (spectral line) and wide-band (continuum) modes simultaneously. Goal 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 18m 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 of order 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	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 commensal interferometric capability is understood to ideally be 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, KSG5-003	The array shall have the ability to have multiple (minimum 10) beams (phase centers within the primary beam) within a single subarray, or distributed amongst multiple subarrays.

Parameter	Req. #	SciCase	Value
Sub-Array Capabilities	SCI0009	KSG5-003	System shall be divisible into multiple (i.e., at least 10) sub-arrays for operation and calibration purposes. All functional capabilities listed above should be available in a sub-array.

The combination of SCI008 and SCI009 suggest total beamforming capabilities of at least 10 beams in aggregate. Desirable to have many more.

Combinations of functional capabilities between concurrent sub-arrays must be looked at closely – commensality of modes could be a design complexity/cost driver.

Parameter	Req. #	SciCase	Value
Sub-Array Commensality	SCI0010	N/A	Sub-arrays will need to 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 subarray.

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

A reference 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, in Table 1.

Parameter	Req. #	SciCase	Value
Pulsar Timing Capabilities	SCI0012	KSG4-001 KSG4-005, KSG5-003, KSG5-005	Timing multiple pulsars within a single primary beam is required. Support for 5 or more independent de-dispersion and folding threads is desired.

Imposes a functional requirement for a pulsar timing system that can support de-dispersion and folding for 5 beams over the full bandwidths of the receivers. Will assume that this requirement is only applicable to bands below ~20GHz, limiting the bandwidth processed by this system to of order 8 GHz.

Parameter	Req. #	SciCase	Value
Time Domain Search Capabilities	SCI0013	KSG4-001 KSG5-009	System shall provide time-domain transient search capabilities on 100 μs scales in the phased array mode, with 20 μs scales desired.

This requirement is assumed to apply to phased-array modes only. Requires a blind/incoherent search capability, with a temporal resolution of 20-100 μs.

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 AD 11 for further elaboration of supporting requirements.

Parameter	Req. #	SciCase	Value
Timing Capabilities	SCI0014	KSG4-001, KSG5-005	The system shall provide transient timing capabilities with resolution of order 20 μs.

This requirement is for coherent timing modes. See RD 17 for further elaboration of supporting requirements.

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

Correlator must process parallel-hands and cross-hands simultaneously in order to produce the four stokes polarization products.

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 order 30K, the implied analog dynamic range is of order 23dB. With an antenna SEFD of order 300 Jy, and an active sun definition of 10^8 Jy, an analog dynamic range of 55dB would be required for the active sun.

In order to meet the sensitivity requirements for the array, no additional RF components shall be introduced in front of the first gain stage (LNA). The analog dynamic range of the receiving elements shall have a minimum of 30dB of headroom with a goal of 50dB. The former will support observations of the sun under most conditions but would rely on offset antenna pointing for an additional 20dB of signal attenuation (sun in 1st side lobe).

Variable attenuation prior to the digitizer shall also have a range of 50dB.

Any calibration strategy should also accommodate this change in source flux, so any calibration system injection requires a variable input power of at least 30dB.

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.

Parameter	Req. #	SciCase	Value
VLBI Capabilities	SCI0017	KSG5-002	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). 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 size of the array and resultant beam, it is necessary to record a minimum of three phased beams within a sub-array, permitting recording of both the science target and two calibrators simultaneously. Recording capabilities must match for all three 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 the order of 10 – 20 seconds 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 observation 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 order 12°, in order to provide a minimal track length during an observation.

9.2.2. *Performance Requirements*

Parameter	Req. #	SciCase	Value
Continuum Sensitivity	SCI0100	KSG1-002	A continuum sensitivity of better than 0.02 μJy/bm at 30 GHz and 0.2 μJy/bm 100 GHz is required for studying protoplanetary disks.

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 (0.98), 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: 0.02 uJy/bm @ 30 GHz:

Assuming 214 18m apertures, with 0.85 aperture efficiency, and 13.5GHz of instantaneous bandwidth, T_{sys} of 33K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 110 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to of order 440 hours. This is the most demanding of the identified sensitivity requirements.

Case B: 0.2 uJy/bm @ 100 GHz:

Assuming 214 18m apertures, with 0.60 aperture efficiency, and 14.0GHz of instantaneous bandwidth, T_{sys} of 62K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 8 hours on source.

Assuming η_{weight} of 0.5 increases the integration time on source to of order 30 hours.

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

Instantaneous bandwidth is the simplest case, and should be set at a minimum to the available bandwidth with the 30 GHz receiver. This suggest a minimum of 14 GHz of instantaneous bandwidth. A goal of 20 GHz of bandwidth should be retained for consistency with previous messaging to the community.

A/T as a function of frequency requires definition of time. We will arbitrarily set the maximum time on source to 100 hours for comparision to other cases. Using these parameters and instantaneous BW of 14 GHz yields A/T values of 2947 m^2/K @ 30 GHz and 289 m^2/K at 100 GHz.

Parameter	Req. #	SciCase	Value
Line Sensitivity	SCI0102	KSG2-002, KSG3-001, KSG3-004, KSG3-005	A line sensitivity of 30 μJy/bm/km/s for frequencies between 10 and 50 GHz is required to support both astrochemistry studies and deep/blind spectral line surveys. A line sensitivity of 1 – 100 mK at 5" – 0.1" angular resolution and 1 – 5 km/s spectral resolution between 70 and 116 GHz is required to simultaneously support detailed studies of CO and variations in gas density across the local universe.

The 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 of order 7 hours. Assuming η_{weight} of 0.5 increases the integration time on source to of order 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 33.3KHz channels. Assuming 214 18m apertures, with 0.77 aperture efficiency, T_{sys} of 25K, η_Q of 0.96, η_C of 0.99, and natural weights, this requirement is fulfilled in 14 hours on source.

Assuming η_{weight} of 0.5 increases integration time on source to of order 56 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.

Case D: Line sensitivity of 1mK at 5" angular resolution and 1 km/s spectral resolution at 90 GHz.

1 km/s spectral resolution corresponds to 300 kHz. With 35% of the array contributing on 5" scales (η_{weight} of 0.35) 1mK brightness sensitivity is met with of order 4.2 hours on source.

Case E: Line sensitivity of 100mK 0.1" angular resolution and 5 km/s spectral resolution at 90 GHz.

5 km/s spectral resolution increases our channel width to 1.5 MHz. With η_{weight} of 0.5, 100mK brightness sensitivity is reached in of order 254 hours on source.

Significantly improving upon this performance would require either increases in aperture efficiency (better dish surface), more antennas, or reductions in η_{weight} through improved imaging algorithms.

Since Case E is the most stringent 90-100GHz case, we will use this case to define the target A/T of the system at high frequency. We will arbitrarily set the maximum time on source to 100 hours. Using these parameters yields A/T values of 875 m^2/K at 90 GHz.

Parameter	Req. #	SciCase	Value
Angular Resolution	SCI0103	KSG1-001, KSG1-003, KSG5-001	A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz.

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 of order 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.

Cost modeling suggests the main array aperture should be relatively large 18-25m to meet the sensitivity targets, and minimum spacing requirements are of order 1.5*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 /single dish capability is not strictly required to recover the specified scales.

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 order 400 Hz.

At 3.2 GHz (lowest center frequency where 4 GHz of bandwidth could plausibly be sampled), the corresponding channel width is of order 1 kHz, necessitating of order 400k channels to ingest that broad of a bandwidth. This is the upper limit to the number of spectral channels required in the central signal processor.

Parameter	Req. #	SciCase	Value
Survey Speed	SCI0106	KSG5-006, KSG5-007	The array shall be able to map a ~10 square degree region to a depth of ~1 μJy/bm at 2.5 GHz and a depth of ~10 μJy/bm at 28 GHz within a 10 hr epoch using the naturally weighted beam.

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: 10 deg^2 @ 1 uJy/bm @ 2.5 GHz, 10 hr epoch.

Assuming 214 18m apertures, with 0.78 aperture efficiency, and 2.3GHz of instantaneous bandwidth, T_{sys} of 23K, η_Q of 0.96, η_C of 0.99, η_{calib} of 0.9, η_{weight} of 1.0, a single pointing reaches 1 uJy/bm in 11 minutes on source.

The primary beam FWHM is of order 23.4' wide, for an area of order 0.152 deg^2. Such a system would only map of order 8.2 deg^2 in a 10 hour period. Improvements in Tsys or collecting area would be required to meet this specification.

Case G: 10 deg^2 @ 10 uJy/bm @ 28 GHz, 10 hr epoch.

Assuming 214 18m apertures, with 0.85 aperture efficiency, and 13.5GHz of instantaneous bandwidth, T_{sys} of 33K, η_Q of 0.93, η_C of 0.98, η_{calib} of 0.9, η_{weight} of 1.0, a single pointing reaches 10 uJy/bm in a mere 2 seconds on source. This case drives the on-the-fly mapping mode requirements discussed in section 9.2.1.

The primary beam FWHM is of order 2.1' wide, for an area of order 0.001 deg^{2}per pointing. Such a system would map of order 22.2 deg^2 in a 10 hour period.

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).

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.

This requirement needs to be studied in greater detail, with an emphasis on the beam quality metrics and their relationship to other performance parameters.

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 armin to mass scales to sculpt a beam to meet the imaging fidelity requirement. However, the algorithmic complexity and sensitivity penalty implied are not yet well quantified.

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.

100mas at 20 GHz corresponds to baselines of order 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 31-51 km in diameter or larger, 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 (~50km).

Parameter	**Req. #**	**SciCase**	**Value**
Photometric Accuracy	SCI0110	KSG3-006	The system photometric accuracy shall be better than 1% for programs requiring accurate photometry,

This photometric accuracy requirement must be met through flux-scale calibration. The specification implies absolute (rather than relative) accuracy, so 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.

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

Parameter	**Req. #**	**SciCase**	**Value**
Relative Astrometric Accuracy	SC10111	KSG5-001, KSG-002	The instrument shall achieve an astrometric accuracy 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, the centroid error (proportional to SNR), and …. [TBD]

With 1000 km baselines, system resolution could be of order 2.1 mas at 30 GHz. 1% of synthesized beam would therefore correspond to of order 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.

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

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

The 30-minute requirement suggests frequency stability of order 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.

Parameter	Req. #	SciCase	Value
Brightness Dynamic Range	SCI0113	KSG3-011	The system brightness dynamic range shall be better than 50 db deep field studies at 10 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 the SNR of the image. Both the 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 in order to put an upper limit of the gain errors that would support the dynamic range requirement. Per RD19 (p279), 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 order 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 order 1e-4 would be desirable.

The period over which this stability must be maintained is typically related to the astronomical gain calibration cycle (~20 minutes), but can be reduced by transferring some of the stability requirements to a calibrated noise source as described in section 5.18.3.

Parameter	Req. #	SciCase	Value
Polarization Dynamic Range	SCI0114	KSG3-011	The polarization dynamic range shall be better than 40 db for deep field studies at the center of the field of view at 10 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 order 10^{-3}. (TBC, using analysis for SCI0113)
- Relative gain stability of the two polarizations of 10^{-3}. (TBC, using analysis for SCI0113)

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

Parameter	Req. #	SciCase	Value
Spectral Dynamic Range (Emissive)	SCI0115	KSG2-006	The spectral dynamic range shall be better than 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 order 0.3% (50dB) after calibration. We will assume a calibration cycle of one 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 50dB of separation for spectral line observations is not required since fringe washing will provide ~20 dB of attenuation of adjacent emitting sources. LO offsets or sampler clock offsets could provide a further ~20 dB of attenuation.

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

This requirement may also impose channel isolation requirements in the central signal processor, but this has not yet been evaluated. We expect that 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 uJy/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 RD 14, 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 of order 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 of order 20 dB due to phase winding / fringe washing (-53 dB + 20 dB = 33dB / 10kHz). (See AD 06 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 -43dB/MHz for interferometric antennas. While the derivation above is given at 30 GHz, the requirement is comparable over the given frequency range.