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Calibration Strategy and Requirements

020.22.00.00.00-0001-REQ-A-ARRAY_CALIBR_STRATEGY_REQS

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
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Change Record

Version	Date	Author	Affected Sections	Reason
01	2018-11-01	Hales	All	Initial framework based on ALMA Calibration Specifications and Requirements [RD01].
02	2019-05-28	Hales	All	First complete draft.
03	2019-07-12	Hales	1,6	Minor clarifications and corrections following review by the Calibration Working Group. Revised pointing requirements.
A	2019-08-02	Hales, Lear	All	Updated cover page and headers in preparation for approvals and release.

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1 INTRODUCTION

1.1 Purpose

This document presents preliminary calibration strategies and associated requirements for the ngVLA.

The calibration requirements flow-down from the initial draft of the ngVLA Science Requirements [AD01], the ngVLA Stakeholder Requirements [AD02], and the ngVLA Preliminary System Requirements [AD03].

The preliminary requirements presented in this document will guide the design of the facility including hardware, software, and operational elements. This document will form part of the submission of the ngVLA Reference Design documentation package.

Some revisions to the System Requirements are anticipated as the facility concept matures. Similarly, the Science and Stakeholder Requirements may change depending on the degree of alignment with the National Academy of Sciences Astro 2020 Decadal Survey goals.

1.2 Scope

The scope of this document is the set of key quantities that will need to be measured or taken into account in order to collect and calibrate ngVLA data.

This document does not explicitly address all calibration parameter space. Instead, it focuses on key aspects of calibration that drive design and are necessary to support the higher-level science, stakeholder, and system requirements. These in turn yield implicit constraints on performance throughout the remaining parameter space.

This document does not explicitly define observing modes, nor calibration strategies for particular observing modes, nor does it lay out work for commissioning, operating, or maintaining the telescope. This document does, however, provide a foundation for addressing/constraining each of these aspects.

This document focuses primarily on interferometric requirements for ngVLA. Requirements for single dish capabilities are currently under consideration and will be addressed in a future version.

This document represents a snaphot in time in the design evolution of the ngVLA. There are known inconsistencies between the requirements derived in this document and capabilities presented elsewhere in the Reference Design package. These differences will form the basis for future decisions as the facility concept matures.

2 RELATED DOCUMENTS

2.1 Applicable Documents

The following documents may not be directly referenced herein, but provide necessary context or supporting material.

Reference No.	Document Title	Rev. / Doc. No.
AD01	ngVLA Science Requirements	020.10.15.05.00-0001-REQ
AD02	ngVLA Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD03	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD04	ngVLA System Reference Design	020.10.20.00.00-001-REP
AD05	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD06	ngVLA Environmental Specifications	020.10.15.10.00-0001-SPE
AD07	ngVLA Reference Observing Program	020.10.15.05.10-0001-SPE
AD08	ngVLA System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD09	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD10	ngVLA Front End Reference Design Description	020.30.03.00.00-0003-DSN

2.2 Reference Documents

The following references provide supporting context.

Reference No.	Document Title	Rev. / Doc. No.
RD01	ALMA Calibration Specifications and Requirements (Version D, 5/18/2006)	ALMA-90.03.00.00-001-A-SPE
RD02	Taperability Study for the ngVLA and Performance Estimates	Rosero, 2019, ngVLA Memo 55
RD03	Image Dynamic Range Limits Arising From Visibility Errors	Hales, 2019, ngVLA Memo 60
RD04	Antenna Tolerance Theory – A Review	Ruze, 1966, Proc. IEEE, 54, 633
RD05	The Primary Antenna Elements	Napier, 1999, Synthesis Imaging in Radio Astronomy II, 180, 37

Reference No.	Document Title	Rev. / Doc. No.
RD06	Fast Switching Phase Calibration at 3mm at the VLA Site	Carilli, 2015, ngVLA Memo 1
RD07	Interferometry and Synthesis in Radio Astronomy	Thompson, Moran & Swenson, 2017, Springer, 3rd Ed.
RD08	Microarcsecond Radio Astronomy	Reid & Honma, 2014, ARAA, 52, 339
RD09	Astrometric Effects of Secular Aberration	Kopeikin & Makarov, 2006, AJ, 131, 1471
RD10	A new concept of the International Celestial Reference Frame: the epoch ICRF	Xu et al., 2013, MNRAS, 430, 2633
RD11	The pointing self calibration algorithm for aperture synthesis radio telescopes	Bhatnagar & Cornwell, 2017, AJ, 154, 197B
RD12	Wide-field wide-band Interferometric Imaging: The WB A-Projection and Hybrid Algorithms	Bhatnagar et al., 2013, ApJ, 770, 91
RD13	Requirements for Subreflector and Feed Positioning for ALMA Antennas	Butler, 2003, ALMA Memo 479
RD14	Temporal and Spatial Tropospheric Phase Fluctuations at the VLA (and Beyond) and Implications for Phase Calibration	Hales, 2019, ngVLA Memo 61
RD15	Calibration Errors in Interferometric Radio Polarimetry	Hales, 2017, AJ, 154, 54
RD16	Phase calibration and water vapor radiometry for millimeter-wave arrays	Lay, 1997, A&AS, 122, 547
RD17	Astrometry and Geodesy with Radio Interferometry: Experiments, Models, Results	Sovers et al., 1998, Rev. Mod. Phys., 70, 1393
RD18	Temporal and Spatial Ionospheric Phase Fluctuations at the VLA (and Beyond) and Implications for Phase Calibration	Hales, 2019, ngVLA Memo 62 (in prep.)
RD19	Spectra of L-band ionospheric scintillation over Nanjing	Fang et al., 2012, Chin. Sci. Bull., 57, 3375
RD20	A Search For Sub-Second Radio Variability Predicted To Arise Toward 3C84 From Intergalactic Dispersion	Hales et al., 2016, ApJ, 823, 93
RD21	Measurement of the Parallax of PSR B0950+08 Using the VLBA	Brisken et al., 2000, ApJ, 541, 959
RD22	An ionospheric index suitable for estimating the degree of ionospheric perturbations	Wilken et al., 2018, J. Space Weather Space Clim., 8, A19

Reference No.	Document Title	Rev. / Doc. No.
RD23	How Close to the Sun Should We Observe With the VLA?	Butler, 2005, VLA Test Memo 236
RD24	An Accurate Flux Density Scale from 1 to 50 GHz	Perley & Butler, 2013, ApJS, 204, 19
RD25	Flux Density Models for Solar System Bodies In CASA	Butler, 2012, ALMA Memo 594
RD26	Atmospheric Opacity at the VLA	Uson, 1986, VLA Sci. Memo 157
RD27	Temporal and Spatial Tropospheric Opacity Fluctuations at the VLA (and Beyond) and Implications for Amplitude Calibration	Hales, 2019, ngVLA Memo 63 (in prep.)
RD28	On Determining Visibilities from Correlation Products	Perley, 2010, EVLA Memo 145
RD29	The ALMA Calibrator Database I: Measurements Taken During the Commissioning Phase of ALMA	van Kempen et al., 2014, ALMA Memo 599
RD30	Understanding radio polarimetry. II. Instrumental calibration of an interferometer array	Sault et al., 1996, A&AS, 117, 149
RD31	CASA Interferometric Pipeline Polarization Calibration & Imaging Requirement & Design Specifications	Hales, 2017, ALMA Memo 603
RD32	Radio circular polarization of active galaxies	Rayner et al., 2000, MNRAS, 319, 484
RD33	The Synthesis Radio Telescope at Westerbork. Methods of Polarization Measurement	Weiler, 1973, A&A, 26, 403
RD34	Determining full EVLA polarization leakage terms at C and X bands	Sault & Perley, 2013, EVLA Memo 170
RD35	Integrated Polarization Properties of 3C48, 3C138, 3C147, and 3C286	Perley & Butler, 2013, ApJS, 206, 16
RD36	Polarimetric calibration and dynamic range issues	Sault & Perley, 2014, EVLA Memo 177
RD37	Dipole Alignment Tolerance for the JVLA's Low-Band System	Perley, 2016, EVLA Memo 200
RD38	ALMA EOC Polarization Commissioning Report	Cortes et al., 2015, ALMA Tech. Note (draft version Nov 23)

Reference No.	Document Title	Rev. / Doc. No.
RD39	Polarization Calibration of the VLBA Using the D-terms	Gomez et al., 2002, VLBA Sci. Memo 30
RD40	JVLA calibration stability at L-band over 5.5 years	Hales & Stephenson, 2019, EVLA Memo 208
RD41	Dual differential polarimetry. A technique to recover polarimetric information from dual-polarization observations	Marti-Vidal et al., 2016, A&A, 593, A61

3 REQUIREMENTS MANAGEMENT

3.1 Requirements Definitions

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")

3.2 Requirements Flow Down

The L1 System Requirements generally flow from the L0 Science Requirements [AD01] for the facility. While these requirements dominate, other Stakeholder Requirements [AD02] also influence or dictate design choices. Examples include programmatic requirements, regulatory compliance requirements, and the life-cycle concepts (e.g. the Operations and Maintenance Concept [AD05]) for the facility.

The Science Requirements and Stakeholder Requirements fully encapsulate all known L0 requirements. The System Requirements [AD03], subordinates [AD06,AD08], and this document fully encapsulates 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 specification 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 lead 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.

Details of the requirements management strategy can be found in AD09.

4 OVERVIEW OF CALIBRATION REQUIREMENTS

Calibration is the process of removing corrupting effects from measured data, with the aim to produce corrected data that resembles within acceptable limits the true input signals that would have been measured in vacuum by a perfect system. Corrupting effects include the atmosphere, electronics, physical hardware such as antennas and how they perform under varying observing conditions, and signal propagation effects such as solar gravitational deflection and even secular aberration.

This document presents the technical requirements for calibration of the ngVLA telescope. These requirements determine the overall form of the calibration strategy and, in-turn, aspects of the hardware, software, and operational elements of the Reference Design.

Section 5 presents system level requirements (L1) and associated explanatory notes. Section 6 presents sub-system level requirements (L2) and associated explanatory notes. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification process. For ease of identification, all L1 requirements in this document are prefixed with CAL01. The L2 requirements begin at CAL02. Note that requirement IDs are static once assigned and therefore not always in sequential order due to subsequent revisions of the associated documents.

The notes contain an explanation or an analysis of how the numeric vales of the requirements were derived. For brevity and clarity, each derivation typically only considers the most demanding scenario(s) under which the requirement of interest influences the system. Where numbers are not well substantiated, this is 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 calibration strategy and overall system design.

Traceability is indicated for each requirement. This is not exhaustive; typically only the major drivers are identified.

The requirements presented in this document have been developed by converting science and stakeholder requirements into performance requirements for the ngVLA system. This process has resulted in some requirements that are more demanding than can be delivered by the current Reference Design. These differences will be addressed as the facility concept matures. This document informs the trade-space for potential future compromises between science performance, technical capabilities, project risk, and cost. If, however, the ngVLA can be delivered with better performance than required below, while remaining within cost limitations, then this should be pursued.

5 L1 CALIBRATION REQUIREMENTS

This section presents system-level requirements that are relevant to calibration (broader context is provided by the material referenced in Section 2). Traceability is shown to the relevant L0 requirements document, with SCI denoting Requirement IDs in the Science Requirements [AD01] and STK denoting requirements in the Stakeholder Requirements [AD02]. 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.

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 AD06). The system-level requirements are written in an implementation agnostic way whenever possible in order to not unduly constrain the conceptual design.

5.1 Observing Modes

Parameter	Req. #	Value	Traceability
Observing Modes	CAL0101	The goal is for $> 80\%$ of the scientific program to use a diverse but well-defined set of standard observing modes. Flexibility shall be provisioned, where justified, for PIs to make changes to support non-standard instrument configurations and/or non-standard data processing.	STK0700, STK0702, STK0704, STK0705
Triggered Observations	CAL0102	Capability to perform rapid automated calibration with minimal set of necessary parameters (e.g. limited bandwidth or lack of robust amplitude calibration), or where possible full solutions, to support triggered observations that interrupt the execution of another observing program.	STK0901

The standard observing modes are defined in the Preliminary System Requirements [AD03]. These are: Interferometric, Phased Array, Pulsar Timing, Pulsar and Transient Search, VLBI, Total Power, On The Fly Mapping, Solar, and Concurrent Interferometric and Phased Array. The commensality matrix for these modes is presented in AD03.

5.2 Computing

Parameter	Req. #	Value	Traceability
Provision of Software Tools	CAL0103	The system shall include tools for the preparation and calibration of observations, and the reduction and analysis of data products.	STK1201, STK1202, STK0801, STK0805

Parameter	Req. #	Value	Traceability
Pipeline Use for Standard Observing Modes	CAL0104	Calibration and data processing for standard observing modes will be undertaken through an automated pipeline developed and run by the Observatory.	STK1000, STK1302, SYS2201

5.3 Operations

Parameter	Req. #	Value	Traceability
Storage and Retrieval of Calibration Coefficients	CAL0105	Parameters for standard mode observations determined by calibration (such as delays or bandpasses) shall be stored and automatically retrieved as needed, i.e. there shall be a calibration database. This database may also be useful for non-standard observations, though this is not guaranteed.	STK1300
Automated Re-Measurement of Calibration Parameters	CAL0106	Re-measurement of calibration and related scientific performance characteristics of the array shall be automated and performed as an Observatory function, possibly using small subarrays of antennas contemporaneously with science observing on larger subarrays.	STK1301
Calibration Recall	CAL0107	The system shall apply prior calibration corrections 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, SYS1063

Parameter	Req. #	Value	Traceability
Automated Observation Preparation	CAL0108	The system shall have an automated procedure for defining the appropriate calibration strategy for any given standard observing mode. This system will account for current and predicted future atmospheric and interplanetary conditions.	STK0701, STK0805, STK1506, SYS2221, SYS2304
Environmental Monitoring	CAL0109	Parameters that affect system scheduling or are used for calibration (e.g. wind speed, temperature, pressure, solar activity, ionospheric stability) shall be measured over the full extent of the array and utilized accordingly.	STK0900, SYS2501
Antenna Automation	CAL0110	Individual antennas and sub-systems within the array shall perform basic system configuration and monitoring functions without the need for human intervention.	STK1704

5.4 Observational Efficiency

Parameter	Req. #	Value	Traceability
Observational Efficiency	CAL0111	The system shall be designed to maximize the array's resources and time spent on science observations (vs maintenance, testing, development efforts, and calibration).	STK1402
Calibration Efficiency	CAL0112	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, SYS1061

Parameter	Req. #	Value	Traceability
Bandpass Calibration Efficiency	CAL0113	The system shall have adequate gain stability to permit application of cataloged bandpass solutions for Standard (Interferometric Continuum) Observing Modes.	STK1403, STK0704, SYS1066
Complex Gain Calibration Efficiency	CAL0114	Complex gain calibration overheads (involving source adjacent to science target) shall not exceed 100% of on-target time for observations at 116 GHz when operating in the precision operating conditions.	STK1403, SYS1068
Polarization Calibration Efficiency	CAL0115	Polarization calibration overheads shall be minimized.	STK1403, STK0704, SYS1065
Subarrays for Scheduling	CAL0116	A limited number of predefined science subarrays will be used by the Observatory to simplify scheduling of the scientific program.	STK1401

Regarding CAL0112, note that 90% observing efficiency implies an allowance of 10% of real-time (2.4 hours/day or 3 days/month) to be allocated to calibrations and array maintenance.

5.5 Bandwidth

Parameter	Req. #	Value	Traceability
Total Instantaneous Processed Bandwidth	CAL0117	The system shall transmit and process a minimum of 14 GHz/pol from each antenna. Transmitting and processing 20 GHz/pol is desired.	SCI0100, SYS0903
Spectral Resolution	CAL0118	A spectral resolution of 0.1 km/s must be supported (and in conjuction with CAL0125).	SCI0105

5.6 Calibration Accuracy

Parameter	Req. #	Value	Traceability
Photometric Accuracy	CAL0119	The system shall be capable of delivering 1% absolute flux density accuracy for programs requiring accurate photometry. The system shall be capable of delivering 6% absolute flux density accuracy in Standard (Interferometric) Observing Modes, without the need for specialized observations.	SCI0110, STK1403, STK0704, SYS1064
Polarization Purity	CAL0120	0.01% post-calibration on-axis residual linear polarization leakage (amplitude), where leakage is defined as Stokes Q/I, U/I, or V/I. Goal of minimizing off-axis residual polarization leakage (including on-axis contribution) to within 0.1% at any point within the -5 dB primary beam power contour.	SCI0114, SYS1901
Relative Astrometric Accuracy	CAL0121	The instrument shall achieve an astrometric accuracy that is $< 1\%$ of the synthesized beam FWHM for a bright (SNR $>$ 100) point source.	SCI0111
Amplitude/Phase Variation Magnitudes	CAL0122	Amplitude and phase variations caused by the instrument should be smaller than those caused by the natural environment for at least 90% of the time. The natural limits are those imposed by the residual amplitude and phase fluctuations after all available corrections have been applied (e.g. troposphere, ionosphere).	STK1402, STK1403, SCI0100, SYS1501

CAL0119 is traced to SCI0110 which calls for 1% photometric error. According to the definition in AD01, this is not the fractional error in absolute flux densities, but rather the fractional error in the observed flux densities prior to scaling by a flux density standard. SCI0110 therefore effectively implies that if we measure the flux density for a target source with infinite signal to noise in several independent observations, the absolute amplitude calibration scale maintained internally by the telescope over the time period encompassing all the observations should be sufficiently stable to deliver flux densities within 1% of each other. However, while theoretically possible, it is unrealistic to demand of the ngVLA a stable internal amplitude scale over indefinite time periods. Therefore, periodic referencing of a celestial flux density standard will be inevitably required. As a result, the accuracy in the measured flux densities will be affected by not only the amplitude stability of the instrument, but also the accuracy at which the celestial calibrator's absolute flux density is known (unlikely to be better than 1%, e.g. RD24) as well as any variability that the calibrator might exhibit. To avoid complicating the requirements while satisfying the objective of SCI0110, CAL0119 is defined more conservatively in terms of absolute flux density.

CAL0120 refers to continuum polarimetry. Largely unavoidable degradation in spectral residual polarization leakage is expected due to the band edge response of polarizers.

5.7 Dynamic Range

Parameter	Req. #	Value	Traceability
Brightness Dynamic Range	CAL0123	The brightness dynamic range in total intensity shall be better than 50 dB to support deep field studies at 10 GHz.	SCI0113
Polarization Dynamic Range	CAL0124	The brightness dynamic range in linear and circular polarizations shall be better than 40 dB to support deep field studies at the center of the field of view at 10 GHz.	SCI0114
Spectral Dynamic Range	CAL0125	The spectral dynamic range in total intensity 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, with particular focus in the frequency range 16–50 GHz.	SCI0115

Brightness dynamic range in total intensity refers to the ratio between peak brightness in the field relative to the rms noise in a source-free region. Polarization dynamic range refers to the ratio for a given source between Stokes I and artifacts in linear polarization (Stokes $L = \sqrt{Q^2 + U^2}$) or circular polarization (Stokes V). Spectral dynamic range refers to the ratio between the brightest source in one channel relative to the rms in a line-free channel.

6 L2 CALIBRATION REQUIREMENTS

This section presents sub-system level requirements. These are implementation-specific in that they are calculated using numeric values for fundamental parameters such as antenna diameter, number of antennas, and maximum baseline length. General assumptions are presented in Section 6.1. Other assumed values are stated in each case. The L2 requirements, and possibly the associated calibration strategies, will therefore need to be reassessed if the parameter values change significantly in the future.

6.1 Assumptions

Parameter	Value	References
Antenna	All antennas shall be alt-az mounted without third axis rotation (i.e. without dish rotators).	AD04
Feed Basis	All antennas shall be equipped with dual orthogonal linear feeds in all frequency bands.	AD04
Receiver Bands	Front end 6 band design spanning the following frequency ranges: 1.2 – 3.5 GHz (band 1), 3.5 – 12.3 GHz (band 2), 12.3 – 20.5 GHz (band 3), 20.5 – 34.0 GHz (band 4), 30.5 – 50.5 GHz (band 5), 70.0 – 116.0 GHz (band 6).	AD10
Sensitivity	A canonical array of 123×18 m antennas shall be used for deriving L2 requirements below.	SCI0100, SCI0102, SCI0103, SCI0108, SCI0118, CAL0116
Self-Calibration	Requirements shall be derived without allowing for potential benefits from self-calibration, as easy application may not be possible in every standard observing scenario.	—

The Reference Design [AD04] calls for alt-az antennas and linearly polarized feeds. The latter is to facilitate larger bandwidth ratios than circular feeds, though this is only strictly relevant for the lower frequency bands. Linear feeds are not necessarily required at the higher bands, though the choice removes the additional complication of requiring conversion between linear to circular polarization, which in turn reduces cost and improves performance (circular polarizers will slightly degrade sensitivity). This document will assume the use of alt-az antennas and linearly polarized feeds. However, given the significance of polarization feed basis to the overall facility design, Section 6.6 provides an independent and unbiased justification of the choice to use linear feeds from a calibration perspective, and also investigates the optimal orientation of the linear feeds.

Several L2 requirements in the following sections are driven by the number of antennas in the array. The most demanding ngVLA science cases are expected to use most if not all antennas to achieve objectives of resolution and/or sensitivity. Imaging performance simulations [RD02] indicate that the bulk sensitivity resulting from tapering to achieve a nominated angular resolution scale will be provided by approximately half of the collecting area. The full (reference) array contains 244×18 m antennas and 19×6 m antennas [AD04], equivalent to 246×18 m antennas (0.06 km^2 collecting area). Therefore, the L2 requirements below will assume a canonical array with 123×18 m antennas.

The L2 requirements presented below have been developed without including potential benefits from self-calibration (direction independent or dependent). This is because it cannot be assumed that self-calibration can be used in all cases for ngVLA observations. For example, direction-independent gain self-calibration may be difficult for extended targets especially if they are not fully spatially sampled. Similarly, direction-dependent pointing self-calibration may be difficult for fields in which there is negligible off-axis emission.

6.2 Antenna Characteristics

Antenna requirements are presented below for Pointing, Surface Setting and Primary Beam, Feed Positioning, and Motion. See AD06 for definitions of Precision and Normal operating conditions.

6.2.1 Pointing

Parameter	Req. #	Value	Traceability
Antenna Pointing	CAL0201	Precision: $18''$ blind, $3''$ offset; Normal: $42''$ blind; $7''$ offset. These are 2D errors. The offset values must be satisfied over a 3° angle.	CAL0123

Parameter	Req. #	Value	Traceability
Spectral Line Noise Leakage (Arising From Pointing)	CAL0202	Implement software and heuristics for estimating worst-case noise level leaked from strong spectral lines at different spatial locations due to limited pointing accuracy.	CAL0201, CAL0125

Antenna pointing will be affected by several slowly varying systematic terms such as imperfections of the antenna and the pad, gravitational forces, wind loading arising from the mean wind velocity, and thermal loading from the sun. Depending on the needs of the astronomical observation, these slowly varying effects can be removed by frequent offset pointing observations. In addition, there will also be random pointing errors arising from more rapidly varying effects such as wind gusts (about the mean wind velocity) and anomalous refraction. Random errors will also be present at some level due to the limited mechanical repeatability of antenna pointing, arising for example from solar orientation and thermal gradients.

Errors in antenna pointing will lead to amplitude and spectral index errors. Accurate pointing is important for high dynamic range observations and for mosaiced observations, particularly at the higher frequencies where the beam size is smaller. It is anticipated that a significant fraction of ngVLA observations will be mosaiced, perhaps 60% overall and involving all frequency bands [AD07].

When required, pointing calibration must be performed prior to astronomical observations or else the data will be corrupted. In general, pointing solutions cannot be interpolated backwards in time (this can be mitigated in some cases by performing pointing self-calibration [RD11], which requires emission to be present at locations throughout the primary beam). This makes pointing calibration critical for observations that require offset pointing. When needed, pointing solutions must be updated on a timescale that is short enough to over-sample all slowly-varying dynamic effects.

Requirement CAL0123 calls for 50 dB imaging dynamic range[1] at 10 GHz. This can be translated to a pointing requirement by first considering the (idealized) relationship between the dynamic range limit for a Stokes image (e.g. Stokes I) from a snapshot observation, D, and antenna-based amplitude errors (correlated for both polarizations on a given antenna), ϵ, for an array comprising N antennas, given by RD03 as

$$D \approx \frac{\sqrt{N}}{\epsilon} \, . \tag{1}$$

Next, by approximating the true profile of an antenna's primary beam (e.g. Airy disk or cosine-squared) with a Gaussian, the relationship between pointing error β and the resulting amplitude error can be

[1] Note that the anticipated continuum sensivity of the ngVLA using $N = 123$ antennas will be sufficient to deliver 50 dB dynamic range in 1 hour on unresolved sources as faint as 130 mJy in band 6 and 35 mJy in band 3 [AD04].

estimated using

$$\epsilon \approx 1 - \exp\left(-4\beta^2 \ln 2\right) , \quad (2)$$

where $\beta = \Delta\theta/\mathrm{HPBW}$ is the fractional error in units of primary beam HPBW arising from pointing offset $\Delta\theta$. These relationships indicate that to achieve 50 dB dynamic range with $N = 123$, the induced amplitude errors must be less than 0.011% and pointing errors must satisfy $\beta < 1/160$. This translates to $\Delta\theta = 3''$ with 18 m dishes at 8 GHz (center of 8 GHz bandwidth between 4 GHz to 12 GHz, encompassing the target 10 GHz from CAL0123) and sets the ngVLA requirement for pointing accuracy under the most favourable observing conditions.

Prior to examining the requirements for pointing under less optimal conditions, the effects of observing with pointing accuracy $\Delta\theta = 3''$ are explored below with focus on mosaics and frequency dependence.

For pointing error $\beta = 1/160$, the amplitude errors per polarization per antenna resulting from a point source located at the nominal primary beam -0.1 dB, -2 dB, and -12 dB contours (radial offsets HPBW/10, $\mathrm{HPBW}/\sqrt{6}$, and HPBW) will range between approximately 0.3%, to 0.6%, and 0.01%, respectively. These errors will be important when imaging extended sources, reconstructing spectral indices, and attempting high dynamic range imaging of single-pointing fields if there are strong sources located off-axis. They will also be important for mosaiced observations.

For a hexagonal mosaic with pointing separation $\mathrm{HPBW}/\sqrt{2}$ (typical widest separation sufficient to obtain approximately uniform mosaic sensitivity), and assuming that each contributing primary beam is only imaged out to the HPBW (imaging further provides negligible sensitivity gain), the worst-case amplitude error in the mosaic will be located equidistant from 3 contributing pointings at their overlapping -2 dB primary beam contours. For $\beta = 1/160$ with $N = 123$, the dynamic range limit in a single pointing that contains a point source located at the -2 dB contour is 33 dB. Thus, the dynamic range range limit in a mosaic with $\mathrm{HPBW}/\sqrt{2}$ beam throw could be as low as 35 dB, despite the 50 dB dynamic range limit expected at the center of each individual pointing. (Note that this calculation assumes that pointing errors from contributing pointings are statistically independent. This is likely to be approximately true because a common source would sample different locations in each antenna's primary beam in each pointing.)

For reference, Table 1 presents dynamic range limitations for imaging scenarios in which a single point source is located at the center of a single pointing, D_1, at the -2 dB primary beam contour in a single pointing, D_2, and at the overlapping -2 dB contours in a hexagonal mosaic (described above), D_3, for frequencies f specified at band edges in the 6 band reference design. The estimates assume an array with 123 antennas, precision offset pointing accuracy $\Delta\theta = 3''$, no other errors, and no self-calibration. Note that the D_2 and D_3 values represent approximately worst-case dynamic range limits for single pointing and mosaiced images, in which the brightest source in the visibility data is located near a pointing's -2 dB primary beam contour.

f (GHz)	D_1 (dB)	D_2 (dB)	D_3 (dB)
1.2	66	41	43
3.5	56	36	39
12.3	45	31	33
20.5	41	28	31
34	37	26	29
50.5	33	25	27
70	30	23	25
116	26	21	23

Table 1: Dynamic range limitations arising from 3″ precision offset pointing errors.

These limits may be improved in certain cases, for example by performing on-the-fly observations to scan over the vicinity of a strong source while sampling as many different primary beam locations as possible (i.e. attempting to 'average out' the pointing error for each antenna), or by employing pointing self-calibration if there is sufficient signal-to-noise within the primary beam to obtain pointing solutions on sufficiently short timescales to sample the true pointing variability. Heuristics will need to be developed to identify appropriate observing and pointing conditions for every proposed observation, including the option to employ pointing self-calibration in post-processing when it is likely to be beneficial.

Importantly, it should also be noted that for continuous observations that effectively comprise M statistically-independent snapshots (where M depends on the dynamical timescale of antenna pointing variations as well as the timescale for rotation of each baseline), Equation 1 will be improved by factor $\sqrt{M}$ [RD03]. This will lead to improvement beyond the values derived above, perhaps by an order of magnitude or more in dynamic range over the course of a few hour observation. This improvement should therefore enable 50 dB image dynamic range across a full mosaic at 10 GHz. For example, if dynamic wind loading produces statistically independent pointing errors on timescales no slower than 20 sec over the course of a 15 hour observation (see Section 6.3.2.1 for motivation behind 15 hours), then $M = 2700$ and the off-axis dynamic range limits for D_2 and D_3 will rise to 50 dB. The benefit from $\sqrt{M}$ is neglected in the calculations presented earlier in order to derive robust worst-case pointing requirements that will support high dynamic range from short observations.

Antenna pointing errors can be separated into systematic errors (i.e. statistical accuracy, requiring offset pointing corrections to account for slowly-varying systematic effects) and statistical errors (i.e. statistical precision). There are 4 states for which pointing requirements are needed, spanning the matrix of normal and precision operating conditions, and blind and offset pointing modes. The precision offset pointing requirement is defined by requiring that CAL0123 will be satisfied under precision operating conditions; as described earlier, this requires $\Delta\theta = 3''$ to satisfy $\beta = 1/160$ with 18 m dishes at 10 GHz. The normal offset pointing requirement is driven by the desire to support a reduced dynamic range of 40 dB at 10 GHz without requiring precision conditions; this requires $\beta = 1/50$ which translates to $\Delta\theta = 7''$. To obtain good offset pointing solutions, historical analogues (including the VLA) suggest that systematic pointing errors cannot be larger than approximately 6 times the statistical pointing errors. Note that this is only applicable at frequencies where the statistical and systematic pointing errors are not substantial fractions of the primary beam width. For example, consider performing offset pointing in band 4, where the HPBW is $100''$ for an 18 m dish at the upper frequency bound at 34 GHz. The normal offset pointing requirement of $7''$ is then approaching HPBW/10. This should be sufficient to obtain good pointing solutions. This also suggests that it will not be appropriate to calculate offset pointing corrections using band 5 in normal observing conditions. However, assuming factor 6, if the systematic pointing error is $42''$, this is a substantial fraction of the $50''$ half-power half-width, suggesting that band 3 is likely preferred for calculating offset pointing corrections. Assuming factor 6, to support offset pointing at 10 GHz, the blind pointing requirements are $\Delta\theta = 18''$ in precision conditions and $\Delta\theta = 42''$ in normal conditions. These requirements have implications for array scheduling. For comparison with Table 1, Table 2 presents 'worst-case' dynamic range limits arising from normal blind pointing with accuracy $\Delta\theta = 42''$.

f (GHz)	D_1 (dB)	D_2 (dB)	D_3 (dB)
1.2	43	29	32
3.5	33	25	27
12.3	23	19	22
20.5	18	17	20
34	15	15	17
50.5	12	12	15
70	11	11	13
116	10	10	13

Table 2: Dynamic range limitations arising from $42''$ normal blind pointing errors.

The offset requirements must be satisfied over a 3° slew. This is necessary to support gain calibration for which the antennas must repeatedly slew between a science target and adjacent calibrator. A maximum angle of 3° will facilitate gain calibration up to and including band 6 (see Section 6.2.4). No requirement for minimum timescale is placed on the offset pointing requirements because this is an operational matter that depends on the quality of the observing conditions; degraded observing conditions will require more frequent pointing calibration observations to track systematic antenna pointing changes.

Finally, requirement CAL0125 calls for 50 dB spectral dynamic range (emissive) at up to 50 GHz. For observations in which only a single spatial position exhibits a strong spectral line, 50 dB spectral dynamic range can be facilitated without requiring the imaging dynamic range limit to be anywhere near 50 dB. However, it is possible that multiple spatial locations in a cube could exhibit a 50 dB spectral line with respect to the nominal channel noise level, where the spectral lines may peak in different channels. At 50 GHz, under the most favourable precision offset observing conditions with $\Delta\theta = 3''$, the per-channel image dynamic range limits will be 33 dB if sources are confined to the center of a single pointing, 25 dB if sources are located at the -2 dB primary beam contour in a single pointing, and 27 dB if sources are located at the overlapping -2 dB contour in a hexagonal mosaic (following details presented above). Taking an example in which two spectral lines are detected at the 0 dB (on-axis) and -2 dB contours in a single pointing, with each detected at a different frequency, then the spectral dynamic range in the on-axis spectrum will be limited to 25 dB (rather than 33 dB) when taking the ratio between the line peak and the noise level in the channel corresponding to the line peak of the off-axis source. The dynamic range will still remain 50 dB when taking the ratio between the line peak and other channels. Thus a form of noise leakage will occur in which bright spectral features in one spatial source will affect the spectra of other spatial sources. Heuristics will need to be developed to identify these situations and to estimate the impact on spectra throughout a single pointing or mosaiced cube. Note that the benefit from $\sqrt{M}$ described earlier will certainly minimize this effect. However, some contamination may still occur, and it is highly likely that an investigator interested in detecting faint spectral lines at 50 dB would also be interested in knowing where in the cube potential spurious detections might be located, even if the amplitude of these effects may be uncertain within some factor.

6.2.2 Primary Beam and Surface Setting

Parameter	Req. #	Value	Traceability
Primary Beam Model Accuracy	CAL0203	Determine the power pattern for each polarization on each antenna to a measureable and repeatable accuracy of better than 0.1% of the boresight response and within phase error $0.03°$, at all points within the -10 dB power contour (-5 dB voltage contour), under precision conditions. This means that at the -10 dB power point the accuracy of a power measurement is 1%. These power patterns must be measured at different parallactic angles, elevation angles, and sampled with sufficient frequency resolution to enable a global model to be developed per antenna. This is a requirement for band 2 and a goal for all other bands. Best achievable accuracy beyond -10 dB is desired.	CAL0120, CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Antenna Surface Setting	CAL0204	Precision: $170\,\mu$m, Normal: $400\,\mu$m (primary and secondary surfaces combined); Error scatter pattern: Equation 4 on-axis (satisfying this requirement may require smaller surface errors than $170\,\mu$m and $400\,\mu$m)	CAL0123

Errors in the assumed model of the primary beam will lead to spectral index errors and dynamic range limitations in single pointing and mosaiced observations. Surface errors will scatter power from the main beam into the sidelobes, reducing the surface efficiency and limiting dynamic range. Surface errors can be thought of as leading to statistical errors about the systematic assumed primary beam model.

Visibility errors will arise from errors in the assumed primary beam model (see terms in the numerator sum in Equation 7 from RD12). To satisfy 50 dB image dynamic range at 10 GHz (CAL0123; this will also satisfy CAL0124), the antenna power (proportional to voltage squared) pattern for each polarization needs to be known to better than 0.1%. This requirement needs to apply out to the point in the beam where the power response is 10% of the peak, so as to support high dynamic range imaging for single pointing observations and mosaiced observations. This requirement is calculated by considering Equation 1 with $N = 123$ and with the additional improvement factor $\sqrt{M}$ [RD03]. Conservatively, it is unlikely that sources will be viewed through less than $M \sim 100$ statistically-independent primary beam alignments throughout an observation lasting a few hours (as relevant to deep field studies that drive the 50 dB requirement), regardless of whether the ngVLA dish surfaces will be constructed from multiple panels or a single mold. Antenna elevation and wind loading will contribute to M here, as will baseline rotation. The resulting requirement for power pattern accuracy is then 0.1% of the boresight power response. The corresponding requirement on phase errors is half this [RD03], namely $0.03°$. These calculations assume that primary beam model errors are statistically independent per polarization and antenna, which should be approximately true. The power patterns must be measured at different parallactic angles, elevation angles, and sampled with sufficient frequency resolution to enable a global model to be developed per antenna. Future work is required to assess requirements for primary beam accuracy in far-out sidelobes. Future work is also required to assess implications for primary beam accuracy arising from scenarios that require offset pointing (i.e. differential heating over an antenna).

Accuracy in the primary beam model is also called for by CAL0120, which requires 0.01% on-axis post-calibration residual linear polarization leakage and a goal of 0.1% off-axis. The on-axis residual is given by $\sigma_d/\sqrt{N}$ in the linear feed basis [RD15], where σ_d is the accuracy (systematic residual after averaging all channels in a band for one polarization) with which antenna leakage moduli are known (see Section 6.6.3), while the off-axis residual will arise from the approximately quadrature sum of the antenna leakage accuracy and the primary beam model accuracy. Assuming $N = 123$, $\sigma_d = 0.1\%$ (yielding on-axis residual leakage 0.01%), and taking the primary beam model accuracy 0.1% from above, the spurious off-axis linear polarization residual is expected to be $\sim 0.1\%$. This result is dominated by the off-axis residual. Note that the interplay between primary beams and feeds (the latter dominating the on-axis leakage component) will need to be carefully considered to account for possible feed changes. For example, a maintenance visit may result in a swapped integrated receiver and digitizer (IRD) package (see also Section 6.6.3).

Surface errors must be minimized in order to maximize the forward gain of an antenna and limit amplitude errors arising from the antenna scatter response. The surface efficiency is given by Ruze [RD04] as

$$\eta_{\rm sf} = \exp\left[-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right] , \quad (3)$$

where σ is the rms surface error for the primary and secondary reflectors combined, and where σ will produce a path length error of 2σ in the aperture plane. A surface error of 170 μm is required to deliver no worse than -3 dB loss at 116 GHz (i.e. $\sigma = \lambda/15.1$). The equivalent surface error at 50 GHz is 400 μm. Losses within -3 dB are preferred to avoid primary beam aberrations that may force the need for correction schemes like A-projection [RD12] at modest or even low dynamic range limits.

More restrictive values of σ may be required to offset the presence of correlated surface errors. For reflector diameter D with errors correlated over distances D/R (e.g. due to panel setting errors, or setting errors in the backing structure fixture points that support a single-piece mold surface), a scatter pattern will be produced that is R times broader than the diffraction-limited main lobe [RD04, RD05]. Antenna surfaces with larger number of R segments will exhibit larger and less symmetric near-in sidelobes which must be compensated using a more restrictive surface error requirement.

To satisfy CAL0123 following a similar argument as for primary beam model accuracy above, the error scatter response $E(\theta)$ on-axis[2] (where $\theta = 0$) must satisfy

$$E(\theta = 0) < 10 \log_{10}\left(\sqrt{100\, N_{\rm ant,indep}}\right) - 50 \ \ {\rm dB} \ , \quad (4)$$

where the contribution of -50 dB is given by the dynamic range requirement, $N_{\rm ant,indep}$ is the number of antennas with statistically independent surface errors, and where $M = 100$ has been assumed and incorporated into the equation. In the most extreme case $N_{\rm ant,indep} = 1$ and $E(\theta = 0) < -40$ dB, for example if all antennas are cast from the same full-surface mold, attached to infinitely rigid backup structures, transported to each station without deformation, and mounted identically. In the opposite extreme, if $N_{\rm ant,indep} = 123$, then the requirement is $E(\theta = 0) < -30$ dB. A requirement for error scatter response therefore depends on the choice of antenna design. If Equation 4 is satisfied, then the error scatter response will not dominate pointing or primary beam model errors.

[2] For simplicity, Equation 4 assumes that the off-axis scatter response is approximately the same as the on-axis response. In reality the off-axis response will be lower, but this difference is unlikely to be significant until beyond the HPBW.

6.2.3 Feed Positioning

Parameter	Req. #	Value	Traceability
Feed Setting	CAL0205	Positioner errors shall distort the primary beam power pattern by no more than 0.05% of the boresight response and $< 0.01°$ phase within the -10 dB power response.	CAL0203, CAL0121
Band Switching	CAL0206	It shall be possible to regularly (every few minutes) switch between frequency bands (particularly bands 1 and 2) within a few seconds including settling time.	CAL0303

The ngVLA antenna reference design for both the 6 m and 18 m dishes incorporates a fixed subreflector and a motorized adjustable feed positioner (X-Y plane). Accurate setting of the feed positioner is required to prevent loss in efficiency and primary beam abnormalities.

Errors in feed positioning will lead to systematic distortions in primary beam power and phase patterns. To ensure that these distortions remain within the error budget calculated for CAL0203, variations in the power and phase patterns arising from positioner errors must be kept to within 0.05% of the boresight power response and $0.01°$ for each polarization on each antenna. If total errors are approximated by adding the systematic and statistical errors in quadrature, this requirement will ensure that feed positioner errors contribute no more than $\sim 15\%$ to the error budget.

Note that feed positioning errors are also relevant for in-beam calibration. CAL0121 requires relative astrometric accuracy $< 1\%$ of the synthesized beam FWHM for a bright $(\mathrm{SNR} > 100)$ point source (this requirement is discussed further in Section 6.3.1). Phase differences between two points within the -10 dB primary beam must therefore be kept within $0.01 \times 360° = 3.6°$. Assuming worst-case feed positioning errors that lead to correlated primary beam errors between polarizations, there are N statistically independent primary beams over the array. Thus for $N = 123$, the requirement is that any phase gradient per antenna polarization arising from a feed positioning error must be less than $40°$. This is satisfied by the much stricter requirement above.

RD13 presents equations to convert between positioner error and efficiency loss. To satisfy CAL0205, a similar model will need to be developed to convert between feed setting errors in physical units and the primary beam distortions examined above.

The motivation behind CAL0206 is presented in Section 6.3.2.2.

6.2.4 Motion

Parameter	Req. #	Value	Traceability
Antenna Motion	CAL0207	Slew 3° in 7 sec in precision conditions, including time to settle within offset pointing error.	CAL0112

In order to calibrate fluctuations in atmospheric delay (described in more detail in Section 6.3.2), the antennas must be capable of repeatedly switching between a science target and nearby calibrator, transferring the atmospheric delay on the calibrator to the science target within a cycle time that is short compared to the atmospheric stability timescale. This demands fast slew and settle rates to maximize observing efficiency (time on science target). Antennas with fast slew rates are also needed to minimize time spent slewing between widely separated sources, minimize time spent performing offset pointing calibration (slew to calibrator, raster scan, return), and to enable rapid cancellation of atmospheric fluctuations when observing in total power mode (slew across extended source).

While there are technical solutions for maximizing time between calibrator scans (such as water vapor radiometry), which will in turn minimize required slew rates without sacrificing observing efficiency, the fast switching approach must remain feasible and part of ngVLA design in order to minimize overall project risk. Assessment of the fast switching approach therefore drives this anntena motion requirement, regardless of the technique that will be ultimately implemented for calibrating fluctuations in atmospheric delay.

The most demanding requirement for antenna motion arises from considering slew rates for gain calibration at the highest frequencies, where radio source counts are lower and angles to suitable nearby calibrators are larger. In an early design study, RD06 concluded that a 1 minute cycle time between science target and calibrator should be sufficient to correct for atmospheric delay in band 6 at night throughout most of the year. RD06 also found that a suitable calibrator with minimum required 3 sec integration time should be available within 2° of any position in the sky. This observing strategy is incompatible with CAL0112, which states a goal for observing efficiency greater than 90% in standard observing modes. However, for the sake of deriving a risk-mitigating antenna motion requirement, it is justified to consider fast switching that delivers lower observing efficiency. Assuming a 1 minute switching timescale and 6 sec integration time on the calibrator (double 3 sec because RD06 assumes $N = 200$ antennas rather than $N = 123$), 70% efficiency can be obtained by requiring that antennas are capable of slewing 3° and settling at the new desired pointing location within 7 sec. This requirement must be satisfied under precision conditions, suitable for observing in the highest frequency band. While 70% efficiency does not satisfy the goal from CAL0112, it does satisfy the firm requirement from CAL0114.

6.3 Delay

The ngVLA is envisaged to operate as a quasi-connected-element[3] interferometer, including over continental scale baselines, with correlation taking place in near real-time. Delays must therefore be calculated and applied at the time of observing. Their calculation must account for several contributions, including source position, earth orientation, atmosphere (neutral and ionized), station locations, antenna structure, and electronics. Each of these contributions must be correctly calculated or measured.

There is an additional fluctuating portion of delay due to the atmosphere, antenna, and electronics. Delay fluctuations limit resolution, limit the dynamic range of images, introduce artifacts, and reduce sensitivity by decorrelation. Without effective calibration of these fluctuations, the maximum usable baseline (exhibiting say $> 90\%$ coherence) at 116 GHz would be only 380 m [RD07 Equation 13.118].

In this document, the term "delay" τ will be used to implicitly indicate requirements for both delay and phase. A delay (or change in delay) will produce a (change in) signal phase ϕ that is proportional to frequency ν, namely $\phi = 2\pi\nu\tau$, arising for example from the presence (or change in length) of a cable. Alternatively, all frequencies in a bandpass range can be shifted by the same phase if the local oscillator experiences a phase shift.

Delay can be specified in units of path length and time. These are connected by the speed of light $c \approx 300\,\mathrm{nm/fs}$ and can be used interchangeably. The corresponding fractional phase change is given by $\phi/(2\pi) = \tau_{\mathrm{path}}/\lambda = \tau_{\mathrm{time}}\nu$. At 116 GHz, a phase change of 1 deg corresponds to a delay of 24 fs.

The requirements presented below refer to antenna-based delays. This document will assume uncorrelated variations in antenna-based delays, in which case the resulting baseline-based delays will be $\sqrt{2}$ larger. If this condition will not be met in practice, then the calculations below will need to be re-evaluated.

Furthermore, the requirements presented below are separated into delay drift (accuracy) and delay noise (precision), reflecting the systematic and stochastic components of delay, respectively. The drift component includes fluctuations that do not integrate down with time in the way that white noise would. The timescale for differentiating between these components is defined where appropriate in the sections below. The delay requirements below imply measurement and application with residuals within the specified values. The drift component may refer to residuals after a trend has been removed (e.g. subtract linear trend between scans on an astronomical calibrator), or in some cases (e.g. electronics) refer to deviations from common-mode drift. None of the drift requirements below refer to absolute drift.

[3]It is anticipated that multiple masers will be required over the array, with a single maser supplying antennas within the central ~ 300 km and others supplying more distant antennas [AD04].

6.3.1 Source Location

Parameter	Req. #	Value	Traceability
Geometric Delay	CAL0301	0.8 ps drift, 40 fs noise	CAL0121
Coordinate Equinox	CAL0302	J2000.0 but with flexibility to change in future	–

CAL0121 requires relative astrometric accuracy $< 1\%$ of the synthesized beam FWHM for a bright ($\mathrm{SNR} > 100$) point source. The astrometric accuracy of an observation results from a combination of statistical errors (uncertainty in calibrator positions, centroid measurement) and systematic errors (reference frame positioning). Uncertainty in calibrator position will not be considered here; note that both first and second order effects can be important [RD07 Sec. A12.2, RD08 Sec. 5.4]. The centroid error within a reference frame is given by $\mathrm{FWHM}/(2\,\mathrm{SNR})$, which is $< 0.5\%$ of the beam for $\mathrm{SNR} > 100$. To ensure that the combination of all position errors remains below the 1% requirement, the reference frame must be accurately positioned, in turn requiring accurate calculation of the geometric delay τ_g (among other delays).

For absolute astrometry, the precision of the applied geometric delays (i.e. delay model accountability, or knowledge of the precise delays that were applied as a function of time) is of greater importance than their accuracy because the latter can be corrected (within reason, as examined below) in post-processing as part of the delay model fitting procedure. For maximum baselines $B = 9000$ km at 116 GHz, the synthesized beam FWHM is 60 μas. To point the delay tracking center to within 0.5% of a beam ($\Delta\theta = 0.3\ \mu$as), it is required that the applied geometric delay is known to within $\Delta\tau_g < B\Delta\theta/c = 40$ fs. This requirement will ensure that geometric delays do not limit the absolute astrometry down to 1% of the FWHM.

The relative astrometric accuracy can be estimated by considering gain calibration, where the delay toward a target source will be corrected using the delay toward an adjacent calibrator located at separation angle θ_{sep}. The relative astrometric uncertainty will be dictated by any delays that differ at the two locations, in this case focusing on inaccurate geometric delay tracking. The relative positional uncertainty is calculated using the equation for absolute positional uncertainty, but improved by the factor θ_{sep} [RD07 Sec. 12.2.3, RD08 Sec. 4.1]. Thus, assuming a worst-case 3° separation, the required accuracy for geometric delay is given by $\Delta\tau_g < B\Delta\theta/(c\,\theta_{\mathrm{sep}}) = 0.8$ ps. This is the accuracy needed for correlation.

Both the 0.8 ps accuracy and 40 fs precision requirements are needed in order to satisfy the most flexible reading of CAL0121; absolute astrometry is effectively relative to a global reference frame.

The ngVLA should plan to use J2000.0 coordinates, including full corrections for time and motion of the Earth and solar gravitational deflection [RD07 Sec. 12]. However, it is possible that an IAU adopted frame replacing J2000.0 may become available during the lifetime of the ngVLA (perhaps even as a result of ngVLA measurements). For example, the clear detection of galactic acceleration (secular aberration[4]) in the existing J2000.0 frame (> 150 μas over 30 years) has motivated the proposal for an epoch ICRF [RD10]. Thus, flexibility should be provisioned; nowhere in the project should J2000.0 be assumed.

For radio sources located within approximately 30 light years, the near-field effect of the curvature of the wave front will need to be accommodated in the delay model (e.g. see Section III.A.2 from RD17).

6.3.2 Atmosphere

Parameter	Req. #	Value	Traceability
Atmospheric Delay	CAL0303	*Neutral:* 7 fs drift over 5 min, 190 fs noise in 1 s; *Ionized:* $0.2/\nu^2$ ps drift over 5 min, $6/\nu^2$ ps noise in 1 s, where ν is in units of GHz	CAL0112, CAL0123
Tropospheric Delay Measurement	CAL0304	Radiometers are required (e.g. 22 GHz WVR). These must be capable of full radiometric correction (i.e. including path between calibrator and target) and must be situated on every antenna.	CAL0303
Amplitude and Phase Coherence Over Multiple Observations	CAL0305	The observatory scheduling process and data reduction pipeline shall be capable of executing an observing strategy and processing the resulting data in which the flux density scales and positional (phase) reference frames are aligned over multi-epoch observations.	CAL0123

[4]Peculiar acceleration arising from the motion of the Sun with respect to the local standard of rest is expected to be an order of magnitude smaller than galactocentric acceleration [RD09].

Parameter	Req. #	Value	Traceability
Ionospheric Delay Measurement	CAL0306	The pipeline shall be capable of measuring and correcting for ionospheric delay fluctuations using frequency-switched (where required) band 1 observations of a phase calibrator located on-axis. Goal is to achieve this over an arbitrary field in which the brightest source may not be located on-axis. The scheduler shall ensure sufficient time on calibrator to achieve the necessary solution accuracy from CAL0303.	CAL0303
Ionospheric Disturbance Monitoring	CAL0307	The scheduler shall ingest and utilize a real-time spatio-temporal map of ionospheric disturbances on ~ 5 min timescales over the array.	CAL0303, CAL0109
Proposal Content: Estimated Dynamic Range	CAL0308	Proposals for ngVLA observing time must specify the required image dynamic range, which shall then be used by the scheduler to make informed decisions about optimal project selection including early termination if weather conditions deteriorate.	CAL0303, CAL0111
Scheduler Start/Stop/Restart	CAL0309	The scheduler shall be designed to make informed decisions about early termination of scheduling blocks if weather conditions deteriorate, and to account for previously stopped observations in the ranking process.	CAL0308, CAL0111
Interplanetary Medium Monitoring	CAL0310	The scheduler shall ingest and utilize real-time estimates of conditions in the interplanetary medium to avoid observing certain projects too close to the Sun.	CAL0303, CAL0109

Radio waves from an astronomical source must pass through intergalactic, interstellar, interplanetary, and terrestrial atmospheric media. The neutral and ionized components of these media will each produce a delay relative to propagation in vacuum. However, it is only in the immediate vicinity of the Earth that ray paths propagating toward Earth-based antennas will exhibit an appreciable difference in their delays. These differential delays will perturb the wavefront, causing decorrelation and leading to a degradation in dynamic range. Differential delays must be compensated to minimize these effects.

The image dynamic range limit for uncorrelated antenna-based phase errors ϕ is given by [RD03]

$$D \approx \frac{\sqrt{MN}}{2\phi}\,, \tag{5}$$

where the factor M represents the number of statistically independent successive snapshots in an observation. In the present context, M is related to the atmospheric coherence time over which phase fluctuations remain below a nominated threshold. Requirement CAL0123 calls for 50 dB imaging dynamic range at 10 GHz.

Phase fluctuations in the neutral atmosphere are predominantly caused by temporal variations in tropospheric water vapor (dry atmospheric gases also contribute, as do ice particles when present). Phase fluctuations in the ionized atmosphere are mostly caused by variations in total electron content in the ionosphere. These neutral and ionized contributions to atmospheric delay are examined in turn below.

6.3.2.1 Troposphere

Radio waves propagating through the Earth's neutral atmosphere are most affected by the troposphere, located below altitudes of approximately 10 km, and in particular by water vapor that is poorly mixed in the troposphere. Tropospheric phase fluctuations can be treated as turbulent eddies that remain fixed as the atmospheric layer advects over the ground at a characteristic velocity aloft.

RD14 examines statistics of tropospheric phase fluctuations at the VLA during best-case observing conditions in winter and worst-case conditions in summer. RD14 infer from these data, together with worldwide water vapor statistics, a general equation that conservatively predicts the growth of rms phase fluctuations on a baseline over time that is independent of baseline length, time of day, time of year, and geographic location (including altitude). This equation is relevant to ngVLA where the size and geographic distribution of the array implies that subsets of antennas will concurrently experience different atmospheric conditions. Using the rms phase growth relationship, RD14 assesses several phase calibration strategies for their capacity to support a 50 dB image dynamic range requirement. The phase calibration strategies examined were fast switching (rapid transfer of phase solutions from nearby calibrator to target), paired array calibration (where a subset of antennas view a nearby calibrator while the others view the target), self-calibration (using a bright unresolved source in the field of view), simultaneous multi-frequency observations (effectively self-calibration but utilizing an in-beam source that is brighter in a lower frequency band), and radiometric phase correction (e.g. using the 22 GHz water line, see RD07 Sec 13.3.2). RD14 find that at 10 GHz, tropospheric phase fluctuations must be tracked with approximately 1 sec cadence in order to attain 50 dB image dynamic range from a 15 hour observation (i.e. $M = 54000$). The corresponding antenna-based phase error in Equation 5 is $\phi < 0.7°$. An observation length of 15 hours is selected for two reasons. First, this is the approximate timescale over which the anticipated continuum sensitivity of the ngVLA at 10 GHz [AD04] with $N = 123$ is expected to yield 50 dB image dynamic range for an unresolved source with flux density 10 mJy. And second, as derived in RD14, 10 mJy is the approximate flux density threshold at which the noise within a 1 second self-calibration solution will induce phase errors in Equation 5 that exceed the threshold necessary to achieve 50 dB dynamic range (i.e. self-calibration will not be suitable with unresolved sources fainter than 10 mJy). RD14 conclude that the only calibration strategy capable of sampling phase fluctuations on a 1 sec timescale and in turn supporting a 50 dB image dynamic range requirement is water vapor radiometry (WVR). To achieve similar performance using fast switching on the most optimistic 10 sec calibration timescale, an order magnitude longer observation would be required. This would in turn lead to thermal noise limits that are wastefully below the dynamic range floor. Additionally, RD14 conclude that a radiometer must be placed on every antenna[5], because tropospheric phase fluctuations on 1 sec timescales will be independent over ~ 10 m distances. This length scale is less than the shortest anticipated baseline length between ngVLA antennas, which have proposed diameters 6 m and 18 m.

Using Equation 6 from RD14 with $N = 123$ and $M = 54000$ (1 sec calibration over 15 hours), the image dynamic range limit as a function of frequency ν in GHz arising from tropospheric phase fluctuations, independent of weather conditions (short of observing through thunderstorms), is predicted to be

$$D_{tropo} \approx \frac{10^6}{\nu} \quad . \tag{6}$$

Antenna-based phase errors $\phi < 0.7°$ at 1 sec cadence at 10 GHz are required to achieve this performance. This requires[6] antenna-based delay noise within 190 fs. In addition to the stochastic contribution, systematic delay drifts will arise from slowly-varying contributions such as the bulk neutral atmosphere (e.g. from differential elevation, particularly when viewing a low elevation target using long baselines) and systematics within the WVRs. The timescale over which delay drifts can be corrected is given by the timescale over which standard calibrator referencing will be performed. To satisfy 90% on-target observing efficiency (CAL0112) while seeking to attain 50 dB dynamic range at 10 GHz, and assuming a worst-case 30 sec calibrator referencing scan including slew times, this requires a minimum 5 min cycle time. The stochastic contribution on a 1 sec timescale will integrate down to 11 fs on a 5 min timescale. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone, the systematic delay must be less than 7 fs. To relax this requirement, more frequent calibrator referencing will be required, but this will

[5] Of secondary concern here, but worth noting: placement of a WVR on every antenna will increase cost, but it will also reduce costs through reduced project complexity. All antennas will be the same, and overheads for optimizing dynamic scheduling to ensure there is at least one WVR-equipped antenna per grouping of adjacent antennas will not be required.

[6] Note that this requirement has been derived assuming that contributions from atmospheric constituents other than water vapor are negligible. While this is likely to be appropriate, further study is needed to determine the relative contribution toward the 50 dB dynamic range requirement from density and temperature fluctuations in the dry atmosphere. For example, if the dry contribution is within 50 fs, the total tropospheric delay will remain within 3% of 190 fs, otherwise wet delay tracking on timescales faster than 1 sec will be required to satisfy the 190 fs requirement.

come at the expense of reduced on-target observing efficiency. The delay measurement error σ_τ resulting from observation of an unresolved source with flux density S and single-baseline single-polarization flux density error σ_{bp} over bandwidth $\Delta\nu$ is given by $\sqrt{3}\sigma/(\pi S\sqrt{N}\Delta\nu)$ [RD07 Equation 9.178]. Assuming a 4 GHz RFI-free bandwidth, and taking expected $\sigma_{bp} = 1.1$ mJy/b in 15 sec in band 2, a strong calibrator with minimum flux density 2 Jy is required to measure delays to within 7 fs. This will be challenging to satisfy because the sky density of strong calibrators is sparse. However, it should be noted that this 7 fs requirement is based on a worst-case calculation and is likely an overspecification. This will be revisited in future iterations of this requirements flowdown.

Note that full radiometric correction (the ability to connect phases between targets) will be required to account for the change in path between target field and calibrator [e.g. RD16]. This will likely drive the most demanding aspects of radiometer design. Without full correction, large phase errors resulting from traditional phase transfer between calibrator and target field will be imparted to the target visibility data, leading to excessive variability in the positional (phase) reference frames for observations of the target field between calibrator scans, and dramatically reducing the overall image dynamic range limit. Note that absolute radiometry requires careful control over factors like elevation gain dependence and temperature stabilization.

Differences in the positional reference frames between observations in a multi-epoch dataset could, when the data are combined in the visibility domain, limit high dynamic range imaging. To attain 50 dB image dynamic range at 10 GHz (CAL0123), phase errors must be minimized [RD03].The maximum acceptable systematic phase offsets between multiple observations can be estimated as follows. To satisfy CAL0123, Equation 5 indicates that systematic antenna-based phase errors must be smaller than $0.006°$, assuming $N = 123$ antennas, 4 observations of 4 hours each (total observing time ~ 15 hours, as motivated earlier), and where 4 hours is selected as a modest scheduling block length accounting for weather and declination. The phase measurement error σ_ϕ resulting from observation of an unresolved source with flux density S and flux density measurement error σ is given by $\sigma_\phi = \sigma/S$ [RD07 Equation 9.67]. The anticipated full-bandwith continuum sensitivity in just 1 min at 10 GHz using $N = 123$ antennas will be sufficient to deliver 0.0005% flux density uncertainty on a 0.5 Jy unresolved calibrator, yielding $0.003°$ per antenna. Therefore, there should always be sufficient signal to noise on the complex gain calibrator to obtain suitable phase self-calibration solutions per observation and in turn align the positional reference frames between observations. While this strategy invokes self-calibration (cf. Section 6.1), this is only required to accurately align multiple observations, rather than being necessary within any given observation. Section 6.4.2 presents a similar calculation but with a focus on amplitude calibration. CAL0305 requires the observatory to deliver scheduling and pipeline capabilities to ensure, where necessary for high dynamic range projects, alignment of flux density scales (and positional reference frames) across multi-epoch observations.

For a 22 GHz WVR to sense the same 18 m atmospheric patch as viewed by an 18 m dish at an assumed height of 1500 m, it will need to be supported by a ~ 1 m dish. Similarly, a 6 m dish will sense a 6 m atmospheric patch. However, if tropospheric delay corrections are only required every 1 sec, and if the tropospheric advection speed is ~ 10 m/s, then a tropospheric patch of 10 m can be tolerated for a 6 m dish without degrading capabilities, in turn reducing the required size of the WVR dish to approximately 2 m. Furthermore, as earlier, the tropospheric delay requirements are based on worst-case calculations that will be revisited in a future iteration of this requirements flowdown. It is likely that a 2 sec timescale will also be sufficient, in which case a 1 m WVR will also be suitable for the 6 m dishes. This is desireable for reasons of uniformity over the array, maintenance, and cost.

If tropospheric delay corrections are only required every 1 sec, and if the tropospheric advection speed is ~ 10 m/s, then there may be a small number of statistically independent tropospheric delay patches over each 18 m dish; this will not be the case for the 6 m dishes. However, as above, it is likely that 2 sec timescales will also be sufficient. Therefore, direction-dependent (wide-field) corrections for the troposphere do not appear to be required.

Additionally, anomalous refraction is unlikely to be of concern. Anomalous refraction describes the wandering of source positions on timescales of seconds, due to refractive wedges of the troposphere with size equal to the antenna diameter moving across the antenna aperture. Anomalous refraction effectively contributes to the pointing error budget (as well as atmospheric delay errors, which are accounted for above). The rms value of the differential phase shift from a wedge is given by the root phase structure function $\sqrt{D_\phi(d)}$ (units of radians) evaluated at a distance given by the antenna diameter d_a. In the case of 3D turbulence (suitable here for ngVLA antenna diameter length scales, e.g. see RD14), the rms value of the anomalous refraction ξ at zenith angle z is given by [RD07 Equation 13.111, corrected without factor $\sqrt{2}$ because $\sqrt{D_\phi(d)}$ is already direction-independent]

$$\xi \approx \frac{\frac{\lambda}{2\pi}\sqrt{D_\phi(d_a)\,\sec z}}{d_a}\ \text{rad}\ , \tag{7}$$

where λ is the observing wavelength needed to convert $\sqrt{D_\phi(d)}$ to path length delay in units of distance. The ngVLA reference design incorporates antennas with diameters 6 m and 18 m. When combined with $\sqrt{D_\phi(d)}$ given by Equation 3 from RD14 and assuming a typical tropospheric advection speed of 10 m/s [e.g. RD14], this becomes

$$\xi \approx 2.6\,\frac{\sqrt{\sec z}}{d_a^{0.2}}\ \text{arcsec}\ . \tag{8}$$

This relationship is independent of observing frequency. Assuming $z = 60^\circ$ the anomalous refraction is approximately 2.6″ for a 6 m dish and 2.1″ for an 18 m dish. Given that these values are approximately the same as the precision offset pointing requirement (see CAL0201), and that the timescale < 2 sec for anomalous refraction over dish diameters < 20 m will deliver factor M in Equation 5 that is much larger than the sample calculation for pointing errors presented in Section 6.2.1, anomalous refraction is unlikely to affect the ability to satisfy the 50 dB image dynamic range requirement. Therefore, anomalous refraction will not be considered further here.

6.3.2.2 Ionosphere

The ionized portion of the Earth's atmosphere consists of the ionosphere from about 60–1000 km and the plasmasphere which extends to the plasmapause at approximately geosynchronous altitude. The electron column density is dominated by the ionosphere, which can be approximated by a thin shell at a weighted altitude of ~ 400 km. The ionosphere exhibits structure on all scales ranging from centimeters to the fractional-Earth-circumference bulge caused by the Sun's radiation, with corresponding fluctuation timescales from sub-seconds to hours, and three dimensional drift velocities from m/s to km/s. The ionosphere exhibits strong seasonal and regional dynamics due to the solar cycle, solar inclination, day-night cycle, ionospheric anomalies arising from perturbations such as lightning and tropospheric waves, and the dynamics of ionospheric structures like plasma bubbles, gradients, and traveling ionospheric disturbances. Like the troposphere, ionospheric disturbances can be viewed as a spatial pattern translating across the ground and evolving more slowly in its own reference frame, although unlike the troposphere the diversity of patterns described above makes it difficult to construct generalized predictions for spatiotemporal properties.

The ionized atmosphere will induce an excess delay in units of distance given by [e.g. RD17]

$$\tau_{ion} = -\frac{c^2 r_0}{2\pi\nu^2} \int n_e(l)dl \ , \tag{9}$$

where c is the speed of light, r_0 is the classical electron radius, ν is the observing frequency, and the integral over the electron number density n_e yields the total number of electrons per unit area along the line of sight, known as the slant total electron content (STEC). The delay is negative indicating that a monochromatic signal will experience a phase advance relative to vacuum. The corresponding difference in phase between two antennas on a baseline is then given by

$$\Delta\phi_{ion} \approx 480 \, \frac{\Delta N_e}{\nu} \ \mathrm{deg} \ , \tag{10}$$

where ν is in units of GHz, and N_e is the STEC in units of 'unit' TEC where $1 \ \mathrm{TECU} = 10^{16} \, e^- / m^2$. Assuming uncorrelated lines of sight to each antenna, antenna-based phases will be a factor $\sqrt{2}$ smaller. This assumption is suitable here when focusing on small phase fluctuations on short timescales because GPS observations exhibit a power law of temporal fluctuations extending to sub-second timescales (e.g. RD19; see also the high time resolution VLA observations of ionospheric scintillation presented by RD20). From Section 6.3.2.1, to satisfy CAL0123, antenna-based phase errors must be kept below 0.7° on 1 sec timescales over a 15 hour observation ($M = 54000$) with $N = 123$ antennas to enable 50 dB image dynamic range at 10 GHz. To ensure that ionospheric phase fluctuations do not contribute more than 5% toward the quadrature sum of ionospheric and tropospheric contributions, ionospheric phase fluctuations on 1 sec timescales must remain below $\phi < 0.2^\circ$ at 10 GHz. Using the antenna-based phase-STEC relationship, this requires that STEC can be tracked within 0.006 TECU, or that the observed STEC values will remain below this value on 1 sec timescales throughout an observation. This also translates to antenna-based delay noise $6/\nu^2$ ps where ν is in units of GHz. For CAL0123 specified at 10 GHz, the requirement for antenna-based delay noise arising from the ionosphere is therefore 60 fs on 1 sec timescales. Slower variations in the ionospheric electron content must also be removed. As with the troposphere, the timescale over which delay drifts can be corrected is given by the timescale over which standard calibrator referencing will be performed, taken again to be minimum 5 min to satisfy CAL0112. The stochastic contribution on a 1 sec timescale will integrate down to 3.5 fs on a 5 min timescale. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone, the systematic delay must be less than 2 fs at 10 GHz, or $0.2/\nu^2$ ps where ν is in units of GHz. To relax this requirement, more frequent calibrator referencing will be required, but this will come at the expense of reduced on-target observing efficiency.

The dynamic range limit as a function of frequency ν in GHz arising from ionospheric phase fluctuations can be predicted by combining the above limit for ionospheric phase fluctuations ($\phi < 0.2°$) with Equation 5, assuming that this limit on 1 sec cadence is satisfied independent of baseline length, antenna location, and ionospheric conditions (assessed below), and assuming $M = 54000$ and $N = 123$, giving

$$D_{ion} \approx 3.7 \times 10^4 \, \nu \ . \tag{11}$$

Note that this does not include additional benefits from self-calibration using bright sources (which are typically more plentiful at 1 GHz than 10 GHz; for comparison, note from RD14 that self-calibration is not a viable approach for attaining 50 dB dynamic range in deep fields at 10 GHz). Combining Equations 6 and 11 assuming that phase errors from the troposphere ($0.07° \, \nu$) and ionosphere ($2°/\nu$) add in quadrature, where ν is in GHz, the dynamic range limit between 1–116 GHz arising from atmospheric phase fluctuations is predicted to be

$$D_{atmos} \approx \frac{10^6 \, \nu}{\sqrt{816 + \nu^4}} \ . \tag{12}$$

The dynamic range peaks at 51 dB at 5.3 GHz, passing through 50 dB at 10 GHz, and dropping to 45 dB at 1.2 GHz and 39 dB at 116 GHz.

To assess whether the 60 fs delay noise requirement is realistic or not, the following preliminary material is presented from RD18 (in prep.) which focuses on statistics of the ionosphere and implications for phase calibration (i.e. the ionospheric equivalent of RD14). The following data provide a useful and robust reference point, but require further evaluation and comparison with other data before the conclusions should be fully accepted. VLA observations of the calibrator 3C84 presented by RD20 were obtained. The data selected for analysis were observed on 2 Jan 2015 at 00:10 UTC (5:10 pm local time) in C configuration (maximum 3 km baselines) at 1.4 GHz over 100 MHz bandwidth in a single polarization for duration 2 min with 1 sec time sampling. These data exhibit ionospheric scintillation (see RD20). This epoch is near the peak of solar cycle 24, and at a time when the solar elongation was $133°$. The X-ray Sensor on board the *GOES*-15 satellite indicates that all solar flares in the 5 days preceding the observation were of mid-range C class or lower. Reconstructed vertical total electron content (VTEC) data from the International Global Navigation Satellite System Service (IGS), interpolated spatially at the VLA site from GPS data sampled every 2 hr on a grid $2.5^\circ \times 5^\circ$ (lat. $\times$ long.), indicate a rapid drop in electron content with rate 8 TECU/hr over a period of 2 hr centered on 00:00 UTC (typical of conditions at sunset). STEC values, interpolated from the VTEC maps, are around 23 TECU with line-of-sight differences between antennas of no more than 0.03 TECU. The phase time series for each baseline was recovered following RD14, yielding temporal structure functions (growth of rms phase fluctuations on a baseline over time) binned by baseline lengths in the ranges < 0.2 km, 0.2–2 km, and 2–3 km. The brief 2 min duration of the input data implies that statistics are degraded at time lags greater than a few seconds. However, this is sufficient here where the focus is on 1 sec timescales. The data indicate baseline-based phase fluctuations $< 0.7^\circ$ on 1 sec timescales at 1.4 GHz, independent of baseline length. Using Equation 10 this equates to STEC fluctuations < 0.002 TECU.

This value is a third of the requirement presented earlier. However, it is not yet clear whether the magnitude of fluctuations revealed above are typical or atypical. Similarly, the present data do not answer whether 0.006 TECU fluctuations at 1 second cadence are rare or not. This requires an investigation into the scaling (or lack thereof) with overall STEC values, and with baseline length (e.g. over continental scales), for a range of representative observing conditions. The observations above took place during a time of rapid recombination of the ionosphere, under reasonably active solar conditions (though without significant flaring or coronal mass ejection contributions), so it is reasonable to assume that the ionosphere was in a more excited state than usual. However, there are examples of ionospheric disturbances that become enhanced under quiet solar conditions (solar minimum) such as equatorial spread F (a Rayleigh-Taylor like instability prevalent near the magnetic equator in which the underside of the F region becomes highly turbulent during the post-sunset period, and which is suppressed by solar activity; similar phenomena may exist at the $\sim 40^\circ$ magnetic latitude of the VLA site).

Thus, the tentative conclusion is that ionospheric phase fluctuations will not be a significant impediment to satisfying CAL0123. Furthermore, these fluctuations on fast 1 sec timescales will not need to be explicitly tracked. However, changes in the ionosphere on the delay drift timescale (5 min) will need to be tracked. GPS-derived VTEC maps from the IGS or other similar services have best-case accuracies $\sim 1\%$. These will not be sufficient to achieve 2 fs drift accuracy at 10 GHz (these are, however, sufficient to correct for ionospheric Faraday rotation which is sensitive to the STEC above each antenna rather than the much smaller difference in STECs between antennas on a baseline; see Section 6.6.3). Instead, the ionospheric delay $\propto \nu^{-2}$ will need to be measured from the observational data (i.e. by fitting the phase change $\propto \nu^{-1}$ in the parallel hand visibility data over an observing band; see e.g. RD21). This leads to several demands on design.

First, the optimal band for performing such measurements is band 1 where ionospheric delay fluctuations will be largest. $0.2/\nu^2$ ps implies a phase difference of 0.04° over the frequency range 1.2–3.5 GHz. Taking into account the anticipated sensitivity of the ngVLA in band 1 with $N = 123$ antennas, and using the relationship between phase measurement error σ_ϕ resulting from observation of an unresolved source with flux density S and flux density measurement error σ given by $\sigma_\phi = \sigma/S$ [RD07 Equation 9.67], the flux density necessary to measure antenna-based $\sigma_\phi < 0.01^\circ$ within a 200 MHz bandwidth in 10 sec is $S > 2$ Jy. This is realistic for a nearby phase calibrator in band 1. Note that this flux density is an upper limit because the true delay fit uncertainty may be better estimated using the full band 1 bandwidth (an order magnitude larger than 200 MHz). This leads to two options when considering how to implement this in band 2 (or higher frequency bands if ionospheric conditions are particularly poor): the feed could be designed to switch rapidly between bands, or the feed could be designed to support simultaneous observations. The former option would prevent tracking of fluctuations on timescales faster than 5 min (unless CAL0112 can be relaxed), though this could be offset by suitable monitoring of ionospheric conditions as described below. The latter option is not supported in the current reference design, though it is not strictly ruled out in the future (in the current design, when not on-axis, the band 1 feed points to open sky; modifications to facilitate some forward gain are likely to incur significant complexity and cost penalties). If it were available, the band 1 feed would be out of focus during band 2 on-axis observations, but the wide field of view from 18 m dishes could in principle enable ionospheric phase fluctuations to be tracked on timescales shorter than 5 mins and perhaps tens of seconds (depending on signal to noise over that interval). This would enable the ionosphere to be tracked in a similar way to that of the troposphere using radiometry. CAL0206 focuses on the former option and requires the ability to perform regular and rapid band switching (which will have implications for maintenance). CAL0306 requires an automated pipeline data analysis capability to measure and correct for ionospheric delay fluctuations using observations of a calibrator at the phase center, with the goal to expand this capability to arbitrary fields (where requirements on those fields are yet to be defined; the wide field of view of an 18 m dish combined with the high sky density of bright sources in band 1 should ensure that a sufficiently strong celestial signal should always be available regardless of pointing vector).

Second, the ratio of only 3 between the maximum allowable STEC fluctuations (0.006 TECU) and the observed STEC fluctuations (0.002 TECU) indicates that, for contingency, regular monitoring of regional ionospheric conditions must be facilitated for scheduling. CAL0307 requires real-time spatio-temporal GPS-derived monitoring data to be utilized when scheduling observations on the ngVLA, for example using an index like the ROTI (rate of TEC index; e.g. available from the Ionosphere Monitoring and Prediction Center[7]) or the DIXSG (disturbance ionosphere index spatial gradient; RD22). Another useful tracer is the planetary K index.

And third, to ensure optimal scheduling, CAL0308 requires the proposal process to capture the estimated image dynamic range limit, so that degraded ionospheric conditions may be utilized where appropriate. Similarly, CAL0309 requires the scheduler to be capable of starting and stopping scheduling blocks depending on weather conditions across the array, and to account for previously stopped observations in the queue ranking process. Note that it is not clear that adding GPS receivers to ngVLA antennas will be of sufficient benefit, unless they can be programmed to accurately track phase fluctuations by selecting GPS satellites close to the real-time antenna pointing vector. In this case, GPS units could be utilized in an equivalent manner to WVRs. This approach is not yet strictly ruled out, but it is not promoted here because of the larger complexity, risk, and cost compared to measurement of ionospheric

[7] https://impc.dlr.de/

phases from the observational data.

The ~ 400 km height of the ionosphere implies that the electron column density will differ for different lines of sight toward the same antenna (the half-power half-beam-width for an 18 m dish at 10 GHz is $3'$, which corresponds to a lateral distance ~ 350 m at the height of the thin-shell ionosphere). If it is accepted from the results presented earlier that the ionosphere is not dominant at 10 GHz, then CAL0123 does not strictly demand the availability of direction-dependent corrections to account for wide-field distortions from the ionosphere. However, as argued above, it remains plausible (pending further investigation) that the ionosphere could exhibit larger fluctuations that would reduce the dynamic range limit below 50 dB at 10 GHz. These time periods could (perhaps) be sufficiently frequent that they would be difficult to avoid through scheduling choices. A requirement to implement direction-dependent calibration capabilities in the workflow is not currently recommended, though this requires further study before a final decision should be made. Direction-dependent calibration capabilities would certainly be useful in band 1.

6.3.2.3 Interplanetary Medium

While not part of the Earth's atmosphere, the ionized interplanetary medium is turbulent and will induce phase fluctuations over the array. This may be of scientific interest to some observers and problematic for others. CAL0310 requires that estimates of the minimum acceptable angular offset from the Sun shall be calculated (e.g. RD23) from real-time data sources and fed into the scheduler for optimal array management. This will also need to account for real-time transient alerts for events like solar flares and coronal mass ejections (e.g. using the CACTus quicklook catalog[8] from the LASCO instrument on board the *Solar and Heliospheric Observatory* satellite).

6.3.3 Antenna Location

Parameter	Req. #	Value	Traceability
Antenna Location	CAL0311	90 μm	CAL0123, CAL0117, CAL0122
Timing Accuracy Across Array	CAL0312	0.2 μs	CAL0311

The relative positions of the antennas must be accurately determined so that geometric delays can be correctly calculated and supplied to the correlator. Residual delays due to incorrect antenna locations will result in phase errors which change across the observing band, as well as differential phase errors

[8] http://sidc.oma.be/cactus/

between two different sources on the sky (e.g. calibrator and target).

A phase difference $\Delta\phi$ across a bandwidth will reduce the coherence to $\mathrm{sinc}[\Delta\phi/2]$. To facilitate 50 dB dynamic range (CAL0123) and effectively ensure that instrumental delay variations are smaller than residual atmospheric contributions (CAL0122), the antenna-based amplitude errors in Equation 1 must be $< 0.011\%$, assuming $N = 123$ antennas. This requires $\Delta\phi < 3^\circ$. For ngVLA, with a maximum instantaneous bandwidth of up to $\Delta\nu = 20$ GHz (CAL0117), and assuming a limit of 3° for the phase difference across the band, the required baseline accuracy is $c\Delta\phi/(2\pi\Delta\nu) \sim 125\ \mu$m. The error on an individual antenna location determination must then be less than 90 μm, assuming that the errors add in quadrature (not true for any given baseline, but this is a reasonable assumption when averaged over the array).

The differential phase error $\Delta\phi$ between two sources on the sky with angular separation $\theta_{\rm sep}$ in the presence of baseline error ΔB at frequency ν is approximately $2\pi\nu\theta_{\rm sep}\Delta B/c$ [RD07 Sec 12.2.3]. At the highest frequency $\nu = 116$ GHz, with maximum source separation $\theta_{\rm sep} = 5^\circ$, and taking $\Delta\phi = 2.8^\circ$ (one third of the anticipated $0.07^\circ\,\nu$ tropospheric delay from RD14) as the maximum allowable phase error (equivalent to 20μm of path or 67 fs delay), the error in the baseline must be less than approximately 230 μm. The error on an individual antenna location determination must then be less than 160 μm.

The more stringent limit above is selected. Efforts will be required to properly understand how the antenna locations change with time.

The antenna location accuracy also provides a requirement for the timing accuracy across the array Δt constrained by $\Delta B \sim \omega_e \Delta t B_{\rm max}$, where ω_e is the rotation rate of the Earth and $B_{\rm max}$ is the maximum baseline. For 125 μm accuracy over 9000 km baselines this implies a timekeeping accuracy of $\sim 0.2\,\mu$s. Note that $0.2\,\mu$s is orders of magnitude faster than anticipated integration times of order fractions of a second. For example, 0.1 s integration time is required to keep time smearing loss below -20 dB at the primary beam half-power contour for 18 m dishes over 1000 km baselines, independent of frequency [RD07 Equation 6.81]. For 6 m antennas over 100 m baselines the maximum integration time is 300 s, again independent of frequency.

6.3.4 Antenna Structure

Parameter	Req. #	Value	Traceability
Antenna Structure Delay	CAL0313	7 fs drift over 5 min, 90 fs noise, for motions over 3° on the sky	CAL0207, CAL0303

The antenna structures and their motion will contribute delay (e.g. RD17). These can be thought of as modifications to the antenna location. For example, as noted by RD17, the Earth's orbital velocity $10^{-4}c$ must be taken into account to achieve mm accuracy. This motion causes Lorentz effects of order

$10^{-4}L$, which for a 10 m axis offset is 1 mm or 3 ps.

Repeatable parts of the antenna structure delay include the change of main reflector shape with elevation or azimuth, axis non-intersection, illumination offset, bearing runout, and bearing alignment. Most of this repeatable component can be accurately predicted through careful measurements. Non-repeatable (and typically not predictable) parts of the antenna structure delay include thermal[9] and wind deformation of the main reflector shape and feed position, and bearing non-repeatability. The magnitude of each of these contributions, particular from the non-repeatable factors, will likely only be determined by experimentation over time with the final ngVLA antennas.

In order for the delay budget to be dominated by the atmosphere (190 fs; CAL0303) rather than the instrument (CAL0122), the stochastic part of the antenna structure delay must be less than 90 fs so that its quadrature sum with the atmosphere inflates the total by less than 10%. It is reasonable to expect that the stochastic component will be randomized on 1 sec timescales, in which case the requirement can be derived from the 1 sec 190 fs tropospheric requirement so that both integrate down in proportion with time. The repeatable components are likely to be of the same order, but because these should be predictable, it is reasonable to allocate only a small fraction of this to any true residual systematic delay offsets. The timescale over which such systematic delays can be corrected is given by the 5 min calibrator referencing timescale justified in Section 6.3.2.1. To ensure that the quadrature sum of the systematic and time-integrated stochastic parts does not exceed by more than 20% the time-integrated stochastic part alone over a 5 min period, the systematic delay residual must be less than 7 fs. To relax this requirement, more frequent calibrator referencing will be required, but this will come at the expense of reduced on-target observing efficiency. Both the systematic and stochastic requirements relate to motions within a 3° solid angle on the sky, following the justification presented for CAL0207.

6.3.5 Electronics

Parameter	Req. #	Value	Traceability
Electronics Delay	CAL0314	7 fs drift over 5 min, 90 fs noise	CAL0303

There is a component of delay introduced because of the electronics between the feeds on the antennas and the samplers. This will need to be measured for each antenna, receiver, and polarization. The electronics and particularly the local oscillator must be designed so that they are more phase stable than the atmosphere (CAL0122). As in the previous section, this requires the stochastic part to contribute less than 90 fs and the systematic part to contribute less than 7 fs, the latter over stability timescales 5 min.

[9] A rough estimate for the expected thermal expansion rate can be obtained by multiplying the dish diameter by the thermal expansion coefficient, which for a steel 18 m dish is approximately 0.6 ps/$^{\circ}$C.

6.4 Amplitude

Parameter	Req. #	Value	Traceability
Noise Diode Amplitude Stability	CAL0401	1% drift over 1 month, 0.05% stability over 5 min.	CAL0123, CAL0122
Elevation Gain Dependency	CAL0402	Model elevation gain dependency per antenna to within 0.1% in all frequency bands, and to within 0.01% at 10 GHz.	CAL0123, CAL0201
Default Amplitude Calibration	CAL0403	Deliver best-case 1% absolute flux density accuracy added in quadrature with the accuracy at which celestial flux density standards are known at the frequency of interest, for Standard (Interferometric) Observing Modes using database calibration without overheads, i.e. without needing optimized scheduling (e.g. observing near constant elevation) or specialized calibrations (e.g. offset pointing, antenna dips, observations of celestial flux density standards). Using this approach, deliver no worse than 6% (total) absolute flux density accuracy.	CAL0107, CAL0119
Calibrator Database: Flux Density Standards	CAL0404	Monitor celestial flux density standards and their flux density ratios every 1 month, with sufficient sources in each frequency band to identify variability in any source.	CAL0107, CAL0405

Parameter	Req. #	Value	Traceability
Internal Absolute Amplitude Scale	CAL0405	Maintain stable internal scaling between cross-product spectral power and spectral flux density on 1 month timescales using a switched power system, utilizing noise diode stability (CAL0401) and elevation-dependent aperture efficiencies (CAL0402) tied to regular monthly observations of celestial absolute flux density standards. This shall include the capability to return an antenna to the array following an inactive period (e.g. due to maintenance).	CAL0107, CAL0403
Switched power RFI mitigation	CAL0406	Implement signal processing/filtering to prevent RFI from contaminating the switched power system at levels equivalent to greater than 0.05% in noise diode amplitude stability over 5 min.	CAL0405

Two forms of amplitude calibration must be considered. First is the need to deliver accurate relative amplitude calibration, namely stability in the amplitudes measured during an observation. Second is the need to place corrected visibilities onto an accurate absolute flux density scale.

6.4.1 Relative Amplitude Calibration

Relative amplitude calibration is required to ensure amplitude stability within an individual observation in a given instrumental tuning, including in a general sense where that observation could range in elevation from zenith to horizon. To maintain a stable amplitude scale, fluctuations in electronic gain, antenna aperture efficiency, and atmospheric opacity must be considered (e.g. see Equation 1 in RD24). These are addressed in turn below.

Noise diodes placed upfront in the signal path can be used to track changes in electronic gains. The ngVLA Reference Design incorporates one temperature-stabilized noise diode per antenna, with associated bias circuitry to optimize stability in switched power. The noise diodes need to be sufficiently stable to prevent amplitude errors that can limit image dynamic range. The image dynamic range limit resulting from antenna-based amplitude errors (correlated for both polarizations on a given antenna) is given by Equation 1. When modified to include the M factor (number of statistically independent samples) from RD03, this is given by

$$D \approx \frac{\sqrt{NM}}{\epsilon} \,. \tag{13}$$

To satisfy CAL0123 (50 dB image dynamic range at 10 GHz) to levels better than the atmosphere (CAL0122), adopting a dynamic range target of 55 dB, antenna-based amplitude errors ϵ must be no larger than 0.05%, assuming $N = 123$ antennas, and assuming that the errors are randomized on timescales of ~ 5 min (calibrator referencing timescale) throughout a 15 hour observation (see Section 6.3.2.1 for motivation behind 15 hours).

Gravitationally induced deformation of an antenna's surfaces and support structures will lead to loss in forward gain. This loss is largely predictable as a function of elevation angle. When this elevation gain dependency for an antenna is combined with factors like the illumination taper[10] introduced by the feed, the frequency- and elevation-dependent antenna aperture efficiency can be calculated. As the typically dominant contributor to fluctuations in aperture efficiency, the elevation gain dependency of each antenna must be known accurately in order to minimize amplitude errors and in turn raise image dynamic range limits. Importantly, the combination of accurate elevation-dependent aperture efficiencies and noise diode stability can be used to provide a stable internal absolute flux density scale. The accuracy with which the elevation gain dependency can be predicted from an empirical model is given by the pointing error (e.g. see Fig. 2 from RD24). With 3″ pointing at 10 GHz on an 18 m dish (CAL0201), Equation 2 indicates that antenna-based amplitude errors (on-axis) will be 0.01% (the equivalent error is 0.2% at 50 GHz, and 1.3% at 116 GHz). It will therefore be possible to model the elevation gain dependency to better than 0.01% accuracy (or better than 1.3% at 116 GHz) because this model will be generated by averaging over pointing errors. Accuracy in the prediction step will then be given by the pointing error at that moment. With antenna-based gain amplitude errors of 0.01%, the dynamic range limit from Equation 13 with $N = 123$ and $M = 1$ is 50 dB. The dynamic range limit will in fact be higher because the 0.01% error arises from pointing, which will randomize on short timescales ($M > 1$).

The transparency of the troposphere is affected by water vapor and molecular oxygen. The opacity varies as a function of observing frequency (e.g. see Figure 13.7 from RD07). It also varies as a function of time, primarily as a result of changes in water vapor content, ranging from fluctuations on fast-changing second timescales to slow-changing diurnal timescales. To faciliate 55 dB image dynamic range (as above), Equation 13 with $N = 123$ indicates that antenna-based amplitude errors arising from opacity fluctuations on 1 min timescales over a 15 hour observation must be corrected to within 0.1%. For comparison, to assess whether this is a realistic target, the limited investigation by RD26 found that opacity at the VLA site at 23 GHz can vary by 0.5% over 30 mins. More detailed statistics of opacity fluctuations are currently being investigated using EVLA switched power data [RD27, in prep.]. The results presented by RD26 indicate the need for a capability to track and correct for changes in opacity

[10] If the aperture illumination exhibits significant systematic changes with the antenna pointing vector, then like the elevation gain dependency these will need to be modeled so that aperture efficiency can be accurately predicted.

on 1 min timescales. Atmospheric brightness temperatures scale exponentially with atmospheric opacity (e.g. Section 13.1.3 in RD07). This relationship is approximately linear for small changes in atmospheric opacity. If the atmosphere dominates the system temperature, then the requirement above can be facilitated by a switched power system underpinned by noise diodes with stability better than 0.1% on 5 min timescales. This is effectively supported by the electronic gain requirement (CAL0401). Note that this argument assumes that visibility errors are dominated by system noise rather than correlated celestial signals; the present discussion is driven by the need to support deep field imaging at 10 GHz, for which sufficiently strong sources are not expected (for strong targets, regular tracking of a nearby blank sky region may be required). Note also that a switched power system is capable of differentiating between changes in electronic gains and atmospheric opacity [RD28].

Ideally, long timescale fluctuations in atmospheric opacity will also need to be tracked by the switched power system (on timescales of an individual observation, or even weeks as described in the next section), such that the use of model opacities or empirical opacities from antenna dips (tipping scans) will not be required. However, this requires future investigation. It may become evident that accuracy under this scheme can only be maintained by calibrating the internal opacity tracking with data from tipping scans. There may also be a need to combine the tipping data with an atmospheric temperature (or better, a vertical temperature profile), because the atmosphere is mostly transparent down to the horizon at frequencies up to 116 GHz and therefore cannot be used to directly infer the atmospheric opacity. If this is required, further investigation will be needed to determine whether atmopsheric models will be sufficient for this purpose, or whether sensing data (e.g. publicly available radiosonde data, or oxygen sounders operating in the wings of the 60 GHz absorption lines) will be required to ensure sufficient accuracy. If it becomes evident that additional calibrations like tipping scans will need to be added to scheduling blocks to facilitate certain scientific objectives (like high dynamic range), then it may be useful to define a new 'enhanced' amplitude calibration procedure to differentiate from the default procedure in CAL0403. Note that to satisfy CAL0123, the residual systematic antenna-based amplitude error per observation must be within 0.01%. While this level of uncertainty in the amplitude scale between antennas may not be achieved using the internal diode stabilized system (e.g. consider observations performed near the end of the month between celestial re-calibration, when consistency in the amplitude scale maintained by the noise diodes may have degraded), the inclusion within the scheduling block of a celestial flux density calibrator (and other scans like tipping) might not be required because there will likely be sufficient signal to noise on the regularly-observed gain calibrator to align the time-dependent antenna-based amplitude scales. Further work is required to verify these arguments and, if necessary, refine the proposed amplitude calibration procedures and requirements.

Absorption in the ionosphere arises from collisions between electrons with ions and neutral particles and is $\sim 2\%$ at 100 MHz during periods of high ionospheric activity [RD07 Sec. 14.1.4]. This varies with the inverse square of the frequency (i.e. 0.0002% at 10 GHz) and can therefore be neglected here.

6.4.2 Absolute Amplitude Calibration

Uncertainty in the absolute flux density scale assigned to an observation will translate to variability in flux densities measured from the same field at different times, or at different frequencies (unless multiple bands can be observed simultaneously). It is not practical to consider maintaining absolute flux density calibration over an indefinite time period using an instrumental reference source. However, this approach is realistic using noise diodes over approximately monthly timescales, when tied to regular observatory (service mode) observations of celestial flux density standards. CAL0119 calls for the ability to deliver 1% absolute flux density accuracy (consult CAL0119 and the text below it for more details). If a celestial flux density standard is observed on approximately monthly timescales (at high signal to noise, and employing all necessary optimizations to ensure high accuracy such as observing under precision conditions, minimizing the elevation range over which observations are obtained and avoiding low elevations, and including additional calibrations like regular tipping scans and offset pointing), then the absolute flux density scale can be transferred to the instrumental standard and in turn applied to observations during the month-long time window. Note that at any one time, a number of antennas may be removed from the array for maintenance. To reintegrate these antennas into the array, there will need to be a capability to transfer the internal scale maintained by all active antennas to the returned antennas. This could be achieved using regular (as short as daily) brief service-mode observations of bright calibrators with the full array, e.g. in between science blocks. Alternatively, it may be possible to accomplish this using complex gain calibrator data from the science blocks themselves. Heuristics will need to be developed.

To satisfy CAL0119 using the approach above, assuming N statistically independent noise diodes over $N = 123$ antennas (i.e. common between polarizations on any receiver), the noise diode amplitudes per antenna must remain stable and not drift beyond 10% of their $t = 0$ values over a 1 month period (i.e. stable to 1% when averaged over all antennas). To compensate for any possible systematics between diodes at the few percent level on long timescales (not expected, but not impossible), the requirement is 1% per-antenna. This approach has an additional benefit: uncertainty in the flux density scale between observations performed within the 1 month period between celestial recalibration will be 1% or better (whether the noise diodes are statistically independent or if they exhibit some smaller deviation about a systematic 1% error), independent of the intrinsic accuracy to which the flux density of the celestial standard is known. This feature will likely be of particular interest to those in the community that seek to observe transient phenomena over timespans up to a few weeks (e.g. rising or decaying target brightness). Note that intrinsic accuracy in the flux density scale is currently at best 1%–3% depending on frequency between 1–50 GHz [e.g. RD24], rising to near 5% at 116 GHz [e.g. RD25]. The intrinsic accuracy is approximately 1% at 10 GHz.

To improve observing efficiency (CAL0107), CAL0403 defines a default amplitude calibration procedure that minimizes overheads. To illustrate the wording of CAL0403, the absolute photometric accuracy for any individual observation will be given by the quadrature sum of (say) worst-case 1% instrumental stability and (say) 3% uncertainty for a celestial flux density standard at the frequency of interest, yielding 3.2%. This uncertainty (or the worst-case 6% value indicated by CAL0403) also reflects the typical variation expected between flux densities measured from observations taken more than 1 month apart (assuming celestial recalibration takes place on this timescale), though note that uncertainty in the flux density of a celestial standard may be somewhat time-stable (i.e. systematic, yielding improved coherence between observations, with relevance to the transient comment earlier).

To satisfy CAL0403 using the combination of an instrumentally-maintained absolute flux density scale tied down by regular observations of celestial standards, absolute flux densities for celestial standards at all frequencies of interest (1–116 GHz) must be known to better than 5% (currently satisfied, as above), celestial standards must be monitored every month, there must be a capability to identify and handle (unexpected) variability in celestial standards, and (as would be expected to maintain high accuracy) observations of celestial standards must employ all necessary optimizations and additional calibrations as highlighted above.

To achieve this, a grid containing a reasonably small number of stable (including slowly varying) flux density calibrators situated across the sky will need to be monitored regularly, with flux densities stored in a calibration database (e.g. RD29). There will need to be at minimum a few standard sources available in each frequency band. Observations of all flux density standards should be performed as close together in time as possible (e.g. within 24 hours). Should any of the 'standards' exhibit unexpected variability, this will need to be detected by comparing light curves for flux density ratios between sources. The light curve data should be used to inform decisions about whether to base the internal flux density scale on a (possibly temporarily) reduced subset of 'standard' sources. A timescale of 1 month is required between reobserving the celestial standards so as to minimize impacts on science observing efficiency (note CAL0112 and text below it) while ensuring that variability in flux density standards can be detected (and interpolated where necessary) with sufficient time resolution.

Accounting for all uncertainties, including noise diode stability (CAL0401) used to track fluctuations in electronic gain and opacity, and the predictive accuracy of elevation gain dependencies (CAL0402) used to calculate accurate antenna aperture efficiencies, the absolute flux density uncertainty without the final contribution from intrinsic uncertainty in the celestial scale (between 1%–5%, see earlier) is anticipated to be less than 1% in all frequency bands, irrespective of observing conditions (even for $42''$ blind pointing in normal conditions at 116 GHz, for example considering a 20 second pointing randomization timescales across a 15 hour observation). When combined with up to 5% uncertainty from the celestial flux density scale at 116 GHz, the total absolute flux density uncertainty could be as large as 6%.

Future detailed analyses are required to validate the anticipated 1% best-case and 6% worst-case absolute flux density uncertainties targeted above, and to decide if the default amplitude calibration scheme will be sufficient in all cases. If not, an 'enhanced' scheme may be required.

Finally, it is important to note that differences in the absolute amplitude scale between observations in a multi-epoch dataset could, when the data are combined in the visibility domain, limit high dynamic range imaging. To attain 50 dB image dynamic range at 10 GHz (CAL0123), amplitude errors must be minimized [RD03]. The maximum acceptable systematic offset between amplitude scales in multiple observations can be estimated as follows. To satisfy CAL0123, Equation 13 indicates that systematic antenna-based amplitude errors must be smaller than 0.02%, assuming $N = 123$ antennas and 4 observations of 4 hours each (following the similar calculation for systematic phase errors in Section 6.3.2.1). The anticipated full-bandwith continuum sensitivity in just 1 min at 10 GHz using $N = 123$ antennas will be sufficient to deliver 0.0005% flux density uncertainty on a 0.5 Jy unresolved calibrator, yielding 0.006% per antenna. Therefore, there should always be sufficient signal to noise on the complex gain calibrator to obtain suitable amplitude self-calibration solutions per observation and in turn align the flux density scales between observations. While this strategy invokes self-calibration (cf. Section 6.1), this is only required to accurately align multiple observations, rather than being necessary within any given observation. CAL0305, presented earlier in Section 6.3.2.1 with equivalent focus on phase reference frame matching, requires observatory scheduling and data reduction capabilities (pipeline) to ensure, where necessary for high dynamic range projects, coherence in flux density scales across multi-epoch observations.

6.5 Bandpass

Parameter	Req. #	Value	Traceability
Default Bandpass Calibration	CAL0501	Apply bandpass from calibration database. Do not include bandpass scans in science observation scheduling blocks, nor use calibrators from the data to measure the bandpass.	CAL0107, CAL0113
Bandpass Accuracy	CAL0502	The observatory shall measure bandpasses with accuracies 1% in amplitude and 0.3° in phase within 0.1 km/s channels across all frequency space, taking care to ensure that tropospheric and ionospheric systematics are removed to within these accuracies. To enable more accurate solutions to be obtained over broader channels by averaging the 0.1 km/s solutions, the latter will need to be measured and stored in a way that enables accountability of various filter responses (baseband, subband).	CAL0125

Parameter	Req. #	Value	Traceability
Bandpass Stability	CAL0503	The instrumental contribution to the bandpass shall be stable to 0.3% amplitude and $0.08°$ phase per polarization over hourly and monthly timescales.	CAL0122, CAL0123
Calibration Database: Bandpass	CAL0504	The observatory shall supply bandpasses satisfying CAL0502 and CAL0503 in a calibration database, updating solutions where appropriate (e.g. if the advertised accuracy is no longer satisfied due to slow degradation over time or a step change arising from antenna maintenance).	CAL0105, CAL0501
Proposal Content: Estimated Dynamic Range Per Channel	CAL0505	Spectral line proposals must specify the required dynamic range in a single spectral channel. This shall be used by the observatory to decide if the default bandpass calibration procedure is suitable or if custom bandpass calibration is required (note that an 'enhanced' bandpass calibration procedure may yet need to be defined, depending on the outcome of future investigations).	CAL0111, CAL0501

The analog and digital electronics will impose an instrumental spectral imprint on an astronomical signal. The troposphere and ionosphere will also contribute to this imprint. These effects must be measured and removed. The exact shape of the bandpass is not of key importance, as long as it is stable and can accommodate high spectral dynamic range. CAL0125 calls for 50 dB spectral dynamic range to enable imaging in the presence of bright emission lines, with particular focus in the frequency range 16–50 GHz. CAL0118 calls for this dynamic range to be supported for channels as narrow as 0.1 km/s (5 kHz at 16 GHz, or 17 kHz at 50 GHz).

To improve observing efficiency (CAL0113), CAL0501 defines a default bandpass calibration procedure that minimizes overheads by utilizing observatory-supplied bandpasses accessed from a calibration database (CAL0107). These cataloged bandpasses need to be supplied with sufficient accuracy to support the majority of anticipated Standard Observing Mode spectral line projects. Support for CAL0125 (50 dB spectral dynamic range) can be provided without requiring per-polarization per-channel amplitude accuracy anywhere near 0.01% (38 dB, for dual polarizations on $N = 123$ antennas). A more reasonable target for per-polarization per-channel bandpass amplitude accuracy is $\Delta s = 1\%$. This target is not strongly constrained, though the calculation below indicates significant challenges in delivering greater accuracy due to higher signal to noise requirements (at which point atmospheric and pointing limitations will arise). The accuracy in the bandpass is given by

$$\Delta s = \frac{\sigma_{cal}}{S_{cal}} \sqrt{2N} \ , \tag{14}$$

where S_{cal} is the flux density of the bandpass calibrator, σ_{cal} is the array sensitivity (all baselines) for the bandpass calibrator observation, and the factor of 2 represents statistically-independent bandpasses for each polarization on N antennas. To achieve $\Delta s = 1\%$ with $N = 123$, the signal to noise on the bandpass calibrator must be 1500 (32 dB). The anticipated thermal noise of the ngVLA using $N = 123$ antennas over a 30 min integration in a 0.1 km/s channel is approximately 0.85 mJy/beam in the frequency range between 16–50 GHz [AD04]. A 30 min integration is selected here because it may be necessary to quickly recalibrate an antenna following maintenance, e.g. following replacement of an IRD package. This could be achieved using regular brief service-mode observations of bright calibrators with the full array, e.g. in between science blocks (note similar need in Section 6.4.2). Alternatively, if a longer timescale between maintenance and reintegration into the array is acceptable, such as 1 week or 1 month (this will depend on the anticipated fraction of out-of-service antennas in any week or month), then bandpasses can be recalibrated during these windows using longer integration times and in turn fainter sources. Accepting here the worst-case 30 min timescale (per band per maximum number of concurrently observed 0.1 km/s channels), a calibrator with flux density $S_{cal} > 1.3$ Jy will therefore be required for bandpass calibration. This should not be problematic. The corresponding requirement on bandpass phase accuracy is half this [RD03], namely $0.3°$. CAL0502 calls for these accuracies to be maintained within 0.1 km/s channels across all ngVLA frequency space. The various filter responses (baseband, subband) will need to be taken into account in order to average these 0.1 km/s solutions to improve accuracies when using broader channel widths. The calibrations for delay and amplitude described in the previous sections will need to be applied to the data prior to bandpass measurement, so as to remove systematics associated with the troposphere (differential opacity across band) and ionosphere (phase change $\propto 1/\nu$ across band); i.e. bandpasses stored in the calibration database should only contain the instrumental contribution described at the start of this section. It is expected that there will be sufficient accuracy in the delay and amplitude calibrations to remove the atmospheric contributions to the bandpass to well within the target accuracies above. However, this expectation should be subjected to further scrutiny in future investigations. When applying the cataloged bandpasses under the default calibration procedure (CAL0501), the effects of the atmosphere should again be handled by other portions of the calibration workflow.

For reference, the dynamic range limit within a single spectral channel which is limited by errors in continuum subtraction caused by bandpass errors is given by

$$D_s \approx S_{line} \left(\frac{\Delta s}{\sqrt{2N}} S_{cont} \right)^{-1} \quad , \tag{15}$$

where S_{line} is the flux density of the peak of the line and S_{cont} is the continuum flux density of the source. Assuming for argument's sake $S_{line} = 0.1$ mJy/beam, $S_{cont} = 10$ mJy/beam, $N = 123$, and $\Delta s = 1\%$, the channel dynamic range will be $D_s \approx 12$ dB. To improve this dynamic range, greater accuracy in the bandpass will be required. This calculation suggests that either the cataloged bandpasses will require greater accuracy than $\Delta s = 1\%$ to support a wider range of plausible observational scenarios, or instead it may argue for the creation of an 'enhanced' bandpass calibration procedure in which justified proposals can request suitable observations of a bandpass calibrator. Further work is required to compare these alternatives and, if necessary, refine the proposed calibration procedures and requirements (noting as earlier that atmospheric and pointing limitations combined with practical observing time limitations will ultimately prevent significantly improved accuracy beyond $\Delta s = 1\%$ for even wide channel widths). To ensure optimal scheduling, and in anticipation of a decision regarding the options above, CAL0505 requires the proposal process to capture the estimated dynamic range per spectral channel so that a decision can be made as to whether the observatory should supply a more accurate bandpass at the frequency of interest (eventually building up more accurate bandpasses across the full frequency space), or whether custom bandpass calibration procedures should be included in the scheduling blocks for that particular project.

Bandpasses must be stable on short timescales to prevent errors caused by effective amplitude variations (resulting in reduced spectral line and image dynamic ranges) and stable on long timescales to enable reuse of solutions from the calibration database (to optimize observing efficiency). To ensure that systematic errors in bandpass amplitudes (i.e. a systematic offset for all channels across a bandpass) do not limit image dynamic range to less than 53 dB (CAL0123, also CAL0122), bandpass amplitudes must be stable to within 0.3% over 1 hour timescales (calculated using Equation 13 assuming a 15 hour observation of a fractional bandwidth that is spanned in the worst-case by only a single statistically-independent bandpass; recall Section 6.3.2.1 for the motivation behind 15 hours). The corresponding requirement on phase is half this [RD03], namely 0.08°. These requirements also extend to 1 month timescales (or ideally much longer) so as to minimize the frequency of bandpass recalibration and maximize observing efficiency.

6.6 Polarization

Parameter	Req. #	Value	Traceability
Feed Basis	CAL0601	All antennas shall be equipped with dual orthogonal linear feeds in all frequency bands. In each frequency band, all feeds over the array shall be nominally aligned to a common specified orientation with respect to the sky frame (e.g. X feed aligned at specified angle $0°$ from the meridian at zero parallactic angle).	CAL0111, CAL0112, CAL0115
Default Polarization Calibration	CAL0602	Apply leakages from calibration database and measure crosshand bandpass phase from internal pulsed comb generators. Do not include polarization calibration scans in science observation scheduling blocks, nor use calibrators from the data to measure polarization parameters.	CAL0105, CAL0107, CAL0112, CAL0115, CAL0601
Leakage Accuracy	CAL0603	The observatory shall measure absolute leakages within complex error modulus 1% within 10 km/s channels across all frequency space. To enable more accurate solutions to be obtained over broader channels by averaging the 10 km/s solutions, the latter will need to be measured and stored in a way that enables accountability of spectral features.	CAL0120, CAL0123, CAL0124
Leakage Stability	CAL0604	Stable within band-averaged leakage modulus error 0.07% for at least 3 months. Goal: indefinite.	CAL0107, CAL0120, CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Calibration Database: Leakages	CAL0605	The observatory shall supply absolute leakages satisfying CAL0603 and CAL0604 in a calibration database, updating solutions where appropriate (e.g. if the advertised accuracy is no longer satisfied due to slow degradation over time or a step change arising from antenna maintenance).	CAL0105, CAL0602
Calibrator Database: Polarization Calibrators	CAL0606	Maintain register of sources used for leakage, circular polarization, and feed alignment calibrations and capture their polarimetric properties. This information shall be used only for guidance, not for calibration purposes; for example to determine if they exhibit variability (in which case they should be avoided).	CAL0604
Relative Gain Amplitude Stability	CAL0607	Stability between polarization pairs within 0.05% over 5 min.	CAL0123, CAL0124, CAL0401
Crosshand Bandpass Phase Stability	CAL0608	Pulsed comb generator calibration system installed in all receivers on all antennas, delivering channelized crosshand phase error 0.5° per second with sufficient channel width (spectral resolution) to sample all crosshand bandpass features.	CAL0111, CAL0112, CAL0115, CAL0116, CAL0123, CAL0124
Feed Mechanical Alignment	CAL0609	Setting within 2° rms from target alignment (CAL0601) per antenna.	CAL0123, CAL0124
Rotation of Feed Platform	CAL0610	Rotation within 0.01° rms from target alignment (CAL0601) under all environmental conditions.	CAL0112, CAL0123, CAL0124
Pipeline Ingestion of GPS VTEC	CAL0611	The pipeline shall ingest and make use of GPS-derived VTEC data with ~ 5 min time resolution to account for ionospheric Faraday rotation.	CAL0123, CAL0124

Parameter	Req. #	Value	Traceability
Antenna Re-Calibration Following Maintenance	CAL0612	When finalizing ngVLA procedures and designs, consider implications for re-calibrating parameters for antennas that have been recently serviced, for example following an IRD swap. A globally optimized schedule likely argues for a regular (e.g. weekly) 'calibration day', despite some antennas remaining idle between calibration days.	CAL0106, CAL0111, CAL0112

The polarization properties of an astronomical signal will be modified by the polarimetric response of the telescope. Ionospheric Faraday rotation will also contribute toward this imprint. These effects must be measured and removed through polarimetric calibration. There are several antenna-time-frequency dependent parameters of interest: leakage, crosshand bandpass phase, and absolute alignment of linear polarization position angles. These are described below.

Polarization calibration typically requires good coverage in parallactic angle so that the astronomical source contributions which vary sinusoidally in the antenna frame can be separated from the antenna-fixed instrumental contributions. There are a range of possible polarimetric calibration strategies, each somewhat different depending on the receptor feed basis (linear, circular), and each yielding solutions with slightly different degeneracies that result in slightly different errors in calibrated data. For reference, RD31 presents detailed step-by-step procedures for automating a suite of polarimetric calibration strategies in the linear and circular feed bases (designed for the CASA[11] ALMA and EVLA pipelines). RD15 presents a summary of interferometric radio polarization fundamentals, as well as a detailed examination of the roles of parallactic angle coverage and calibrator signal to noise in minimizing on-axis image leakage residuals and linear polarization position angle errors.

The leakage terms ('dipole' terms or d-terms) describe imperfections in the on-axis polarimetric response of each feed, quantifying the degree to which each feed is sensitive to an orthogonally polarized signal (cross-talk). The imperfections can arise from telescope geometry (e.g. asymmetries in antenna illumination, feed horn, optical alignment) and electronic hardware (e.g. polarization splitter, linear to circular polarization converter if present). Leakage solutions can be 'absolute' or 'relative', depending on whether there are sufficient observational constraints to uniquely determine all real and imaginary leakage components, or whether there are two remaining unconstrained degrees of freedom [RD30]. To overcome the degeneracy in the latter case, the real and imaginary components for one feed on one antenna (typically on the bandpass/gain reference antenna) can be (arbitrarily) set to zero, yielding relative leakages for all other feeds. When sufficient constraints are available to uniquely determine all leakage components,

[11] https://casa.nrao.edu/

absolute leakages will be obtained. Crosshand bandpass phase describes the relative phase between two orthogonally polarized feeds on an antenna (this can be separated into delay and phase and solved for independently in the measurement equation; for simplicity here, the term phase will strictly refer to the residual nonlinear frequency dependent part). A crosshand phase arises because the measurement equation is typically refactored to the relative phase frame of the bandpass/gain reference antenna, on which the phases for both polarizations are set to zero (the crosshand bandpass phase for the reference antenna is then propagated over the array). Finally, external calibration is required to determine the absolute alignment of linear polarization in the same way that an interferometer cannot self-calibrate the absolute flux density scale. In the circular feed basis, this requires observation of a celestial source with known position angle. However, in the linear feed basis, this is not always required. Instead, position angle calibration can be satisfied by obtaining absolute leakages (or accepting larger position angle uncertainty using relative solutions) and ensuring that feeds are nominally aligned with respect to the sky frame. See RD15 (and below) for more details regarding these parameters.

Before examining ngVLA requirements related to leakage, crosshand bandpass phase, and absolute position angle, the motivating factors behind the overall proposed polarimetric calibration strategy and related choice of hardware feed basis are described. The following will temporarily ignore the assumption of linear feeds from Section 6.1 and instead identify which of the circular, homogeneously-aligned linear, or heterogeneously-aligned linear feed bases is best suited for ngVLA design.

6.6.1 Motivating Factors for Calibration Strategy

A key requirement for ngVLA design is that polarimetric calibration overheads must be minimized (CAL0112, CAL0115). This must be satisfied regardless of whether a short or a long polarization science observation is requested, i.e. both must be supported. This effectively requires polarimetric calibration overheads (most importantly, leakages) to be decoupled from science observing blocks, for the following reasons. First, options to obtain sufficient parallactic angle coverage are problematic. For short science observing blocks, either the observing block timeframes would need to be artificially inflated, or other science blocks would need to be interrupted to enable the polarization calibrator to be viewed over a range of parallactic angle slices. This would lower observational efficiency and increase scheduling complexity, in turn arguing against such a scheme. And second, calibration using a short observation of a calibrator with known Stokes vector is also problematic. It will be onerous to maintain a database of polarization calibrators with known Stokes vectors (including 'unpolarized' calibrators). While possible, the observational overheads and complexity required to account for source variability in all frequency bands suggests that calibration schemes that require availability of such a database should be disfavored.

For completeness, potential solutions to support short polarimetric science observations are as follows, though these are not advocated here because they require calibration overheads to be included in each science observation. First, it is conceivable to perform leakage calibration using a single observation of a resolved polarized source with spatially varying and unknown (though non-zero) fractional polarization

[RD30]. A second possibility is to utilize the differential parallactic angle over the array to enable calibration using a short observation of a polarized source. However, these two schemes are not generally applicable because it cannot be assumed that all standard mode science observations will require long baselines. While the long baselines could be employed for only the calibration observations, this would require interrupting likely concurrent long baseline science observations and would lead to a reduction in overall observing efficiency. A third possibility in the case of linear feeds is to provide instantaneous parallactic angle coverage over arbitrarily short baselines by (permanently) rotating the mechanical alignments for a subset of the feeds in the array [e.g. RD33]. This heterogeneously-aligned linear feed basis would enable calibration using a short observation of a polarized source. However, this is a complex and potentially costly approach because it would affect designs for the front end including cryostat sizing (or possibly rotation of the entire dewar assembly including positioner), manufacturing scalability, and maintenance. Furthermore, if the need to perform leakage calibration in a snapshot observation is removed, then the need for this additional complexity is also removed because standard calibration techniques can be performed instead (utilizing sufficient parallactic angle during observatory service time).

Instead, to improve observing efficiency (CAL0115), CAL0602 defines a default leakage calibration procedure that minimizes overheads by utilizing observatory-supplied leakages accessed from a calibration database (CAL0105). If the leakages, crosshand bandpass phase, and absolute position angle alignment can be known a priori, and if they remain stable or can be updated as needed with time, then polarimetric calibration overheads will not need to be included in any science scheduling blocks. To achieve this, observatory-managed calibration observations must ensure that sufficient time is dedicated to sampling sufficient parallactic angle coverage to yield accurate leakages. This parallactic angle coverage is needed not only to optimally separate the instrumental and source contributions, but also to provide optimal uv coverage so that resolved source structure can be accounted for in the solutions. This process must yield absolute leakages, regardless of whether circular or linear feeds are selected, to prevent dynamic range limitations at the ~ 30 dB level in polarization[12] [RD36]. A feature of the approach above is that the observatory will only need to identify a small number of ideally highly linearly fractionally polarized sources (as few as one) per frequency band to be utilized as leakage calibrators. Infrequent monitoring of these sources will be required, but only to ensure that their fractional linear polarization has not diminished below a few percent prior to any necessary future leakage re-calibrations.

6.6.2 Choice of Feed Basis

The details of how to implement the strategy above, including effects on overall observing efficiency, depend on the choice of polarization feed basis. Having dispensed of the heterogeneously-aligned linear feed option above, the choice remains between circular and homogeneously-aligned linear feeds. In the following, the term 'linear' will assume the parallel alignment configuration. Historically there have

[12] To first order in the product between d-terms and Stokes Q or U, when observing in the circular or linear feed basis, total intensity image dynamic range will be unaffected when comparing between relative and absolute leakages (cf. RD36). However, this assumes careful calibration so that gain corrections do not prevent cancellation of orthogonal d-terms.

been a number of arguments for choosing circular feeds over linear feeds (e.g. see discussion in RD30). However, (as made clear by RD30) these are based on a number of assumptions that require more careful evaluation for ngVLA, especially when considering the ideal strategy described above. First is the argument that to measure high accuracy linear or circular polarization, a circular or linear configuration, respectively, is desirable. However, for telescopes with good gain stability (as is required for the ngVLA; see in particular Section 6.4), the distinction becomes negligible. A concern in the linear basis might be that the switched power system at low frequencies could become corrupted by RFI (albeit unlikely given that it would need to mimic slow parallactic angle rotation of a polarized source), but this can be addressed by suitable RFI mitigation (i.e. CAL0406). Second, a similar concern is sometimes raised regarding the ability to self-calibrate calibrated total intensity data in the linear basis, due to the need to incorporate knowledge of the target's linear polarization properties (though note that this issue is not strictly relevant here because, following Section 6.1, this document purposely seeks solutions that do not require self-calibration to meet ngVLA performance requirements). There are of course two solutions: iterate using polarization-independent gains (CASA 'T' gains) so that the (slightly incorrect) polarization and leakage contributions in the parallel hands will be mostly canceled (consider $V_{XX}+V_{YY}$ in equations below), or perform full-polarization self-calibration. Third, polarimetric calibration procedures are often simpler in the circular feed basis, but this is only true if relative leakages are acceptable. It is not true if absolute leakages are desired (e.g. see overheads in RD34), as required for ngVLA (see above). Finally, consider absolute position angle calibration. In the circular feed basis, a calibrator with known position angle must be observed. However, this will likely present a challenge for ngVLA because a source model (or set of models for a small number of sources) will need to be measured (and presumably maintained) to ensure that resolved source structure is properly accounted for over the large range of array baseline lengths. While not impossible (especially if motivated as a dedicated observatory deliverable; consider RD35 as a starting point, combined with common VLBI procedures), an easier alternative is provided in the linear feed basis. There, the need for celestial position angle calibration can be simplified if all feeds are aligned to the sky within some mechanical alignment tolerance (e.g. X nominally aligned at a specified angle[13] from the meridian at zero parallactic angle). As with the circular basis, a linearly polarized source will be required to measure the crosshand bandpass phase, but unlike the circular basis, the position angle of this source will not need to be known as the objective is simply to detect the phase difference between the signal paths from the two orthogonal feeds [RD30]. Indeed, because the position angle of the source does not need to be known, an instrument-generated polarization calibration signal can be used in the linear basis to determine the crosshand bandpass phase.

Therefore, from a calibration perspective for ngVLA, there are no strong arguments for ruling out circular or linear feeds, and there is a slight preference for the latter. The unbiased considerations above lend support to the current ngVLA Reference Design, in which all antennas are equipped with dual orthogonal linear feeds in all frequency bands. Given the considerations above, CAL0601 stipulates that all feeds in any given frequency band shall be oriented with the same nominal alignment against the sky frame (i.e. the homogeneously-aligned case).

[13] When the specified angle is 0°, the X and Y feeds may also be termed the vertical V and horizontal H feeds, respectively.

The assumption of linear feeds in the current ngVLA Reference Design is therefore strongly supported by the combination of calibration arguments above, the desire to access wider usable bandwidths than available from circularly polarized feeds (enabling coverage between 1.2 GHz to 116 GHz with fewer receivers), and by the desire to optimize sensitivity and reduce complexity due to lack of polarization conversion from the native linear sampling.

6.6.3 Implications

Implications for ngVLA design will be examined below, motivated by consideration of absolute leakage, crosshand bandpass phase, and absolute position angle calibrations assuming parallel linear feeds.

Following notation from RD15, the model visibilities for a single baseline (antennas indices i and j) corrupted by parallactic angle ψ, complex leakage d_{Ak} (indicating the fraction of orthogonal polarization B sensed by feed A on antenna k), and crosshand phase ρ are given by

$$V_{XX} = (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi \, (d_{Xi} + d^*_{Xj}) \tag{16}$$
$$V_{XY} = [(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\,(d_{Xi} + d^*_{Yj}) - \mathcal{Q}_\psi\,(d_{Xi} - d^*_{Yj})]\,e^{i\rho} \tag{17}$$
$$V_{YX} = [(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\,(d_{Yi} + d^*_{Xj}) + \mathcal{Q}_\psi\,(d_{Yi} - d^*_{Xj})]\,e^{-i\rho} \tag{18}$$
$$V_{YY} = (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi \, (d_{Yi} + d^*_{Yj}) \tag{19}$$

where Stokes $\mathcal{Q}_\psi \equiv \mathcal{Q}\cos 2\psi + \mathcal{U}\sin 2\psi$, Stokes $\mathcal{U}_\psi \equiv \mathcal{U}\cos 2\psi - \mathcal{Q}\sin 2\psi$, and terms multiplied by second order leakages (e.g. $d_{Xi}\,d^*_{Xj}$) are neglected. The terms above are frequency dependent. Antenna feeds are typically engineered with great care to be orthogonal such that $d_{Xi}+d^*_{Yi} = 0$. The approximate level of spurious post-calibration linear ($\mathcal{L}_\epsilon$) or circular ($\mathcal{V}_\epsilon$) polarization for an on-axis target with total flux density $\mathcal{I}$ is given by

$$\frac{\mathcal{L}_\epsilon}{\mathcal{I}} \approx \frac{\mathcal{V}_\epsilon}{\mathcal{I}} \approx \frac{\sigma_d}{\sqrt{N}} \approx \frac{\sigma_{dc}}{\sqrt{N N_c}} \ , \tag{20}$$

where N is the number of antennas in the array, and $\sigma_d = \sigma_{dc}/\sqrt{N_c}$ is the real-valued magnitude of the residual complex error for one polarization on one antenna after band-averaging channelized complex leakage errors with typical magnitude σ_{dc} over N_c channels [RD15]. This equation implicitly assumes $M = 1$ (see notation from RD03), namely that leakages are constant throughout the observation (examined further below).

CAL0120 and CAL0124 call for 40 dB brightness dynamic range in a continuum image of linear or circular polarization. CAL0123 calls for 50 dB brightness dynamic range in total intensity. These requirements place constraints on d-term accuracy. Assuming conservatively $N_c = 200$ channels across a frequency band (note that the edge $\sim 10\%$ of channels in any band will likely exhibit degraded performance) with $N = 123$ antennas, channelized $\sigma_{dc} = 1\%$ ($\sigma_d = 0.07\%$) is required to attain 42 dB image dynamic range in linear or circular polarization. This will also be sufficient to satisfy CAL0123; -42 dB residual leakage from Stokes I to linear polarization implies that, for targets with $\sim 10\%$ linear polarization (approximate upper limit relevant for extragalactic sources in CAL0123 deep field studies), residual leakage from linear polarization to Stokes I will be below -52 dB (e.g. consider forming Stokes I from Equations 16 and 19).

Absolute leakages are necessary for two key reasons. First, as motivated earlier, they are required to facilitate high dynamic range imaging. If relative leakages are obtained, the unknown real and imaginary d-term offsets will limit image dynamic range[14] to ~ 30 dB in polarization [RD36]. For example, the polarization limit can be crudely estimated by considering amplitude errors arising from corruption of Equation 17. Assuming 2% band-averaged leakages[15] per polarization per antenna, in which case the relative real offset over the array will be $\sim 2\%$, and assuming a 5% linearly polarized target, the polarimetric dynamic range will be limited to $1/(0.02 \times 0.05) \approx 30$ dB. And second, absolute leakages are required to set the zero-point for circular polarization. If relative leakages are obtained, the unknown imaginary component of the d-term on the reference antenna's X feed (arbitrarily set to zero in CASA, and propagated over the array) will translate to an unknown offset in circular polarization. External calibration is required to determine this offset, in the same way that an interferometer cannot self-calibrate the absolute flux density scale. Ideally this would be accomplished using an observation of an absolute circularly polarized flux density calibrator. However, no such sources are known. Rather than attempt to identify and monitor such sources, an alternative is to apply a statistical constraint by observing a sample of circularly polarized sources (per frequency band) and assuming that the Universe has no preferred handedness for circular polarization [e.g. RD32]. If this is the case (or, if not, assuming that any systematic handedness is at a level below the accuracy required here for the imaginary leakage component), then the imaginary component can be set by the mean level (zero-point) of circular polarization over the sample. The required accuracy in band-averaged imaginary leakage offset is 0.01% to yield unbiased 40 dB circular polarization dynamic range. Therefore, a sample of ~ 100 sources exhibiting $\sim 0.1\%$ fractional circular polarization (typical level for sources investigated by RD32) will be required to yield an uncertainty in their mean (zero-point) of 0.01%. This does not seem unreasonable for an observatory program.

For completeness, it should be noted that absolute leakages will deliver more accurate absolute position angle alignment than relative leakages, although unlike above this is not a key motivation for seeking absolute leakages. If relative leakages are obtained, the unknown real component of the d-term on the reference antenna's X feed (arbitrarily set to zero in CASA, and propagated over the array) will translate to an unknown offset in absolute position angle given by the magnitude of the true $\mathrm{Re}(d_{X,\mathrm{ref}})$ [e.g. RD15]. For example, assuming 2% band-averaged leakages, the resulting absolute position angle uncertainty when using relative leakage solutions will be $\sim 1^{\circ}$. This is unlikely to be significant for scientific position angle measurements. This error will be systematic for any given observation. Changes

[14] Strictly, as discussed by RD36, there are circumstances in which dynamic range will not be limited, but rather fidelity (i.e. a systematic difference between the reconstructed and true sky). Absolute leakages are therefore further motivated by the desire to avoid such subtleties between the types of errors incurred.

[15] If channelized leakage amplitudes are 2% and there are minimal frequency-dependent variations in leakage phase across the band, then the band-averaged systematic leakage will be of the same magnitude.

in absolute position angle alignments between observations in a multi-epoch dataset will degrade polarimetric image dynamic to ~ 30 dB (see calculation below assuming $\Delta\theta = 1^\circ$ and neglecting the factor $1/\sqrt{N}$), though this can be mitigated in software by ensuring that the selected reference antenna is available in each observation. However, whether relative or absolute leakages are recovered, accuracy in the d-term solutions for each epoch will also produce differences in absolute position angle alignment between epochs. To illustrate, consider effective gain errors in Stokes U that will lead to degraded polarimetric dynamic range. Assuming fractional linear polarization $L/I = \sqrt{Q^2+U^2}/I = 5\%$ where $\vec{L} = Q + iU = Le^{i2\theta}$ with position angle θ, observations at zero parallactic angle and nominal Stokes $U = 0$ without loss of generality, $\sigma_d = 0.07\%$ (as above), $N = 123$ antennas, and absolute position angle variation between observations $\Delta\theta = 0.004^\circ$ arising from systematic offset $\sigma_d/\sqrt{N} = 0.006\%$, variations in Stokes U in the combined dataset will be $\Delta U/I = \sin(2\Delta\theta)\, L/I = 0.007\%$. Assuming these differences are randomized over at least 4 observations (following motivation in Section 6.3.2.1 for ~ 4 hour scheduling blocks over a total of 15 hours), the effective dynamic range limit in linear polarization will be ~ 55 dB. This is sufficient to satisfy CAL0124.

An additional systematic position angle offset will be present, even if absolute leakages are obtained, even if these leakages are known with zero error, and indeed even if these leakages are identically zero, because each antenna in the array will exhibit a nonzero error in mechanical feed alignment about their design orientation (i.e. even if the dipoles on any given antenna are perfectly aligned with respect to each other, they may be misaligned with respect to a neighbouring antenna; antenna leakages are antenna-based and do not capture this information). This will lead to an offset between the assumed and true sky frames. In principal, external absolute position angle calibration is required to account for this offset. However, if mechanical offsets are sufficiently small, then external position angle calibration will be unnecessary. From an engineering perspective, it is very difficult (and therefore costly) to set the alignment of each feed to better than 1° rms. An uncertainty of 2° rms is considered to be a reasonable target (e.g. as demonstrated by ALMA; RD38). For an array with $N = 123$ antennas, 2° rms implies a systematic position angle offset of 0.2°, which exceeds any reasonable scientific expectations for position angle accuracy. However, differences in feed alignments across the array will also produce gain errors that will limit image dynamic range. Following notation from RD15, incorporating characteristic difference $\alpha = \sqrt{2}\beta$ in the otherwise common parallactic angles viewed by two antennas over a baseline where β is the rms feed alignment uncertainty per antenna, ignoring leakages, and assuming (without loss of generality) observation at zero parallactic angle, the relationship between the four reconstructed Stokes parameters (primed) and the Stokes parameters that would be measured from ideal visibilities (unprimed) is given by[16]

$$I' = I\cos\alpha - iV\sin\alpha \qquad (21)$$

$$Q' = Q\cos\alpha + U\sin\alpha \qquad (22)$$

$$U' = U\cos\alpha - Q\sin\alpha \qquad (23)$$

$$V' = V\cos\alpha - iI\sin\alpha\ . \qquad (24)$$

[16] See also RD37 for a derivation of these equations, though note errors in sign and in the interpretations of the equations.

The effects are as follows. Amplitude calibration will offset antenna-based gains by mean $\cos\alpha$, but the scatter in these solutions will yield antenna-based gain errors[17] $(1-\cos\beta)$ that will limit image dynamic range to approximately $\sqrt{N}/(1-\cos\beta) \approx 43$ dB (using Equation 1) for $\beta = 2°$ and $N = 123$ antennas (or 49 dB for engineering minimum $\beta = 1°$). Feed alignment errors must be within $0.6°$ to deliver 53 dB and in turn satisfy CAL0122 and CAL0123. Equations 22 and 23 indicate that linearly polarized intensity will be unaffected (i.e. $L' = \sqrt{(Q')^2 + (U')^2} = L$). Similarly, the mean polarization position angle over all baselines will be unaffected, though position angles measured along all baselines to any given antenna will exhibit scatter with magnitude[18] $\beta/2$. This scatter will lead to errors in linear polarization entering Equations 16–19 and in turn degrade image dynamic range in all Stokes parameters. A worst-case dynamic range limit can be estimated using the relationship for $\Delta L/I$ above and assuming a target with fractional linear polarization $\sim 10\%$, giving $\sqrt{N}/(L/I \times \sin\beta) \approx 35$ dB for $\beta = 2°$ and $N = 123$ antennas (or 38 dB for engineering minimum $\beta = 1°$). Feed alignment errors must be within $0.03°$ to deliver 53 dB and in turn satisfy CAL0122 and CAL0123. Finally, Equation 24 indicates that $I\sin\alpha$ will contaminate the real part of the cross-hand visibilities (Equations 17 and 18), namely linear polarization (Stokes V will be unaffected), with zero systematic mean offset (due to the odd function of $\sin\alpha$) and non-zero scatter. The scatter will yield effective antenna-based gain errors that will lead to dynamic range limitations when imaging linear polarization. These gain errors can be estimated by $\sqrt{N}/(\sin\beta) \approx 25$ dB for $\beta = 2°$ and $N = 123$ antennas (or 28 dB for engineering minimum $\beta = 1°$). Feed alignment errors must be within $0.03°$ to deliver 43 dB and in turn satisfy CAL0124.

It will not be possible to deliver mechanical feed alignment accuracy within $\beta = 0.03°$. However, this can be accomplished using celestial calibration. Engineering mechanical feed alignment can then be relaxed to a realistic target of $2°$ rms. Feed alignment calibration requires a linearly polarized source with antenna-based SNR $(2\beta)^{-1} \approx 30$ dB (RD07 Equation 9.67 with factor 2 for position angles). Assuming a target calibrator with fractional linear polarization no less than 6%, this implies a calibrator with antenna-based total SNR 42 dB. This is at the approximate polarization dynamic range limits described earlier, and will therefore require careful examination to determine if more accurate leakage calibration is required (though this may be satisfied automatically using the calibration database leakages described below; database narrow channel leakages can be averaged together over wider channels relevant here, further improving the polarization dynamic range limit). The thermal noise of the ngVLA using $N = 123$ antennas in a 1 hour period with 50% fractional bandwidth is anticipated to be no worse than 2 μJy/beam. A calibrator with total flux density greater than 0.4 Jy is therefore required. The absolute position angle of the calibrator does not need to be known. However, the calibrator must be spatially unresolved on all baseline lengths of interest so that they all see the same position angle. This may be challenging to ensure over short baselines; however, this can be overcome by specifying a minimum baseline length for the calibration and extending the time period for the observation accordingly. Calibrators exhibiting variability over hourly timescales must be avoided.

[17] Gain errors scale with β rather than α because the former is the typical misalignment that an antenna will see against the average misalignment from all other antennas (i.e. against $\beta/\sqrt{N-1} \approx 0°$).

[18] The factor of 2 arises because position angles are periodic in $180°$.

Feed alignments must remain stable indefinitely, accommodating in particular any quasi-static systematic antenna deformations (e.g. thermal deformation) that could lead to systematic rotation in the feed platform. It is reasonable to expect (and require) that this can be satisfied by antenna design, which must support blind pointing under normal conditions within $< 0.01^\circ$ (see requirements in Section 6.2.1). Note the alternative: if feed alignment stability cannot be maintained, calibration will need to be performed regularly during science observations (e.g. tracking antenna deformations sampled by offset pointing calibration), resulting in an unacceptable decrease in observing efficiency (CAL0112). Short-term instability may be acceptable as long as it integrates down to within 0.01° over the time period of interest (e.g. wind loading, and perhaps sunrise/sunset where differential heating/cooling may temporarily 'inflate'/'deflate' the structure in an unpredictable manner before settling within a steady state). CAL0610 highlights this issue in a formal requirement.

The absolute leakages will need to be supplied to science observations through a calibration database, with sufficient spectral resolution to support Standard Observing Mode projects. There are no requirements on this spectral resolution, so 10 km/s over all ngVLA frequency space will be assumed (33 kHz at 1 GHz, 3.3 MHz at 100 GHz); this may be subject to change in the future. The various filter responses (baseband, subband) will need to be taken into account so that stored solutions can be averaged as required to supply science observations with channel widths greater than 10 km/s. Such averaging will also improve leakage accuracy, but only down to the level of atmospheric and pointing limitations associated with the leakage calibrator observations. Interpolation may be used to support narrower widths, though reduced accuracy will need to be accepted in these cases. Should these derived products be insufficient for some Standard Observing Mode projects, it may be necessary to consider the creation of 'enhanced' polarization calibration procedures in which justified proposals can request suitable observations of polarimetric calibrators.

To deliver leakage amplitude accuracy $\sigma_{dc} = 1\%$ per channel with $N = 123$ antennas, the signal to noise on the leakage calibrator must be $\sqrt{2N}/\sigma_{dc} \approx 1600$ (32 dB). The thermal noise of the ngVLA using $N = 123$ antennas in a 20 min integration is anticipated to be no worse than 0.75 mJy/beam within a 10 km/s channel in any frequency band. A calibrator with flux density $S_{cal} > 1.2$ Jy will therefore be required for leakage calibration. This should not be problematic.

Additional requirements for the observatory-managed procedure to measure absolute leakages are as follows. Only (ideally strongly) linearly polarized calibrators can be accepted for absolute leakage calibration; position angle calibration (solving for the real component of the d-term on the reference feed) cannot be performed with an unpolarized source (as intuitively expected). Selected leakage calibrators must contain a compact polarized component that is detectable over all baseline lengths. Any selected leakage calibrator must be observed with sufficiently wide parallactic angle coverage so that intrinsic source structure (i.e. baseline dependence) will be taken into account in the solutions (similar to CAL0702). It will be necessary to account for (and ideally utilize for improved constraints) differential parallactic angle coverage over long baselines and the likely resolved fractional polarization structure of calibrators (see related comments in Section 6.6.1). To enable efficient calibration over all frequency space, 20 min integration time per bandwidth range (as above) can be interleaved over a multi-hour observing block. This will also need to include a circular polarization calibrator survey (as above). Care will need to be taken to account for, or avoid, sources that exhibit variability on short timescales, possibly minutes (e.g. see the polarimetric intraday variable in Figure 2 in RD32); variability on timescales associated with gathering parallactic angle coverage (hours) may be prevalent in the bright source population used to measure leakages and circular polarization. Polarization properties of leakage and circular polarization calibrators should be stored in a calibrator database, though only for the purpose of identifying variability (and thus potentially avoiding them in the future; see also comment at end of Section 6.6.1); quantitative details from these records should not be used when obtaining any new calibration solutions. Stability requirements for leakage solutions are addressed futher below.

The leakage solutions will be affected by Faraday rotation in the lower frequency bands. When linearly polarized radiation traverses a birefringent medium such as a magnetized thermal plasma, it will undergo Faraday rotation, resulting in a rotation of the position angle of linear polarization. The rotation arising from signal passage through the plasmasphere and ionosphere (dominated by the latter; see Section 6.3.2.2) is given by

$$\Delta\theta_f = \frac{e\,c\,r_0}{2\pi m_e \nu^2}\int B_{los}(l)\,n_e(l)\,dl \tag{25}$$

$$\approx \frac{1.35}{\nu^2}\,B_{los}\,N_e \;\;\mathrm{deg}\;\;, \tag{26}$$

where e is the electron charge, c is the speed of light, r_0 is the classical electron radius, and m_e is the electron mass. The approximation in Equation 26 is for a thin shell ionized atmosphere with representative line of sight magnetic field B_{los} in units of gauss (positive when pointed toward the observer, and which can be suitably estimated by taking the Earth's $B_{los}(l)$ at the height of the weighted-column thin-shell; RD18), where ν is the observing frequency in units of GHz and N_e is the STEC in units of TECU (recall definitions from Equation 10). Alternatively, Equation 26 can be written in terms of rotation measure,

$$RM \approx 0.26\,B_{los}\,N_e \;\;\mathrm{rad/m^2}\;\;. \tag{27}$$

The STEC above each antenna can be estimated by combining GPS-derived VTEC maps, available from external sources such as the IGS, with a model of the Earth's magnetic field, such as that provided by the International Geomagnetic Reference Field (IGRF). The IGS 'Final' maps aggregate results from several analysis centers worldwide with 2 hour time resolution that are published with ~ 2 week latency. The Jet Propulsion Laboratory (JPL) Global Differential GPS System (GDGPS[19]) publishes real-time VTEC maps every 5 mins. Similarly, the Massachusetts Institute of Technology (MIT) Automated Processing of GPS (MAPGPS[20]) service publishes VTEC maps every 5 mins, but these differ from the sources above in that data are only provided along slightlines where satellites were present rather than interpolating to produce standardized TEC maps that are regularly sampled in latitude and longitude. Diurnal variations

[19] http://www.gdgps.net/products/tec-maps.html
[20] https://www.haystack.mit.edu/atm/arrays/gps/index.html

in VTEC at the VLA site typically range from a maximum of ~ 50 TECU to a third of this value at night (with further modulation from various dynamics highlighted in Section 6.3.2.2). STEC values rise with increasing zenith angle to within factor 5, or ~ 250 TECU, at $\sim 80^\circ$. VTEC data such as that provided by the IGS typically exhibit uncertainties within ~ 2 TECU (best-case ~ 1 TECU, worst-case ~ 5 TECU). STEC uncertainties are then typically within ~ 10 TECU. The Earth's line of sight magnetic field at the VLA site ranges between 0 G to $+0.4$ G with typical value $+0.2$ G over the sky at the IGS-assumed 450km height of the thin-shell ionosphere [RD18]. The equations above indicate that changes in STEC and B_{los} throughout a long observation could lead to antenna-based variations as large as ~ 20 rad/m^2 in rotation measure, or equivalently $\sim 1^\circ$ in position angle when observing at 10 GHz (band 2, relevant for CAL0123 and CAL0124). If GPS-derived VTEC data with 10 TECU STEC uncertainties are used to remove these variations when calibrating the telescope data, the residual errors could be as large as 1 rad/m^2, or respectively 0.4° and 0.04° at the lower (3.5 GHz) and upper (12.3 GHz) ends of band 2.

Variability in ionospheric Faraday rotation will cause position angles to be rotated above each antenna as a function of time, leading to scatter in Stokes Q and U and in turn degrading image dynamic range in all Stokes parameters. This is analogous to feed misalignment errors described earlier, characterized by Equations 22 and 23. The dynamic range limit arising from antenna-based rms fluctuations in position angle γ is then given by $\sqrt{MN}/(L/I \times \sin\gamma)$ where M is the number of statistically independent samples throughout the observation. This implies worst-case $\gamma < 0.1^\circ$ to satisfy the 50 dB total intensity imaging requirement from CAL0123 (and automatically the 40 dB polarization imaging requirement from CAL0124), assuming $N = 123$ antennas, a target with 10% fractional linear polarization, and worst-case $M = 7$ for a 15 hour observation (recall Section 6.3.2.1 for the motivation behind 15 hours) over which the ionosphere deviates from a given VTEC model (e.g. IGS) with 2 hour coherence timescale. However, in reality, the ionosphere will exhibit a power spectrum of TEC fluctuations that will extend to much shorter timescales. Assuming a 5 min coherence timescale ($M = 60$), and assuming that this is tracked by GPS VTEC data that is sampled on a similar timescale (so that fluctuations on longer timescales will be removed), the requirement becomes $\gamma < 0.8^\circ$. These results indicate that to satisfy CAL0123 and CAL0124, the ngVLA data reduction pipeline will need to ingest VTEC data to correct for ionospheric Faraday rotation. The results also indicate that the typical ~ 2 TECU accuracy of external GPS-derived VTEC data will be sufficient to satisfy CAL0123 and CAL0124; ionospheric Faraday rotation will not need to be measured using array observations of polarized calibrators, in turn avoiding the need for calibrator polarization selection criteria and associated monitoring and database overheads. Access to VTEC data with low latency at 5 min time resolution (e.g. GDGPS or MAPGPS, latter with improved spatial resolution) is required in order to minimize deviations between the true STEC values and the GPS-derived model, and more importantly to eliminate complications for ngVLA data reduction scheduling that would arise from the need to accommodate the 2 week latency of the IGS data. Careful commissioning will be required to ensure that any systematic biases in the ingested VTEC data are identified and removed, for example by comparing VTEC data with band 1 observations of a calibrator with known position angle (e.g. 3C286); it is known that there are systematic differences (~ 2 TECU) between the IGS, GDGPS, and MAPGPS reconstructed VTEC values. This is important for interpretation of the dynamic range calculations above, which assume fluctuations that integrate down with time, as well as the following. If fluctuations integrate down like white noise, then any residual leakage offset per observation along the real axis will be given by $\gamma/\sqrt{MN} \approx 0.005°$ when assuming $M = 60$, $N = 123$, and $\gamma = 0.4°$ (i.e. the worst-case value at 3.5 GHz). Following the calculation presented earlier for dynamic range limitations arising from absolute position angle differences between 4 observations, the dynamic range limit in linear polarization will be ~ 54 dB. This is sufficient to satisfy CAL0124. Finally, note that errors of 1 rad/m^2 arising from STEC uncertainties of 10 TECU imply position angle errors $\sim 4°$ at 1.2 GHz. The associated dynamic range limit in total intensity is then ~ 43 dB. Celestial calibration may help to improve this limit, though note the similar 45 dB limit at 1.2 GHz arising from phase calibration (Equation 12).

If the true leakages are sufficiently stable with time, then calibration database solutions will remain valid for an extended period of time and re-calibration overheads can be minimized (CAL0107, CAL0115). Ideally, leakages should only need to be measured once, with results valid for years, or at minimum over the time period between antenna/receiver maintenance. Leakage solutions are expected to be stable with time because their origins are rooted in antenna and feed geometry (and good engineering). Variations arising from antenna deformation (e.g. differential heating, which gives rise to the need for offset pointing) or elevation changes (e.g. changing aperture illumination) are not expected to be significant within the leakage accuracy required here (systematic $\sigma_d = 0.07\%$). CAL0604 states this in a formal requirement. This stability will need to be demonstrated during the ngVLA commissioning phase. RD39 found that leakages on the Very Long Baseline Array (VLBA) were stable over a period of 16 months. Similarly, RD40 examined calibration stability for the Jansky Very Large Array (JVLA) at L-band over a period of 5.5 years, finding that leakages for each antenna remained stable over multiple years unless affected by a receiver change.

Some forms of antenna maintenance, and particularly changes in an antenna's IRD package, will result in new leakages for that antenna. When such events occur, the leakages (and other antenna-based calibration parameters) will need to be recalibrated. Several antennas may be serviced in any given week. A detailed service-mode calibration schedule will need to be developed to optimize the approach for re-calibrating these antennas and returning them to science observations (including ensuring compatibility with the needs of other calibrations like absolute amplitude and bandpass; recall Sections 6.4.2 and 6.5). For example, the highest overall efficiency may be achieved by targeting IRD replacements early in the week followed by a weekly 'calibration day', even if this means that one or two antennas could remain idle for up to a few days. A multi-hour (e.g. 10 hour) calibration run (which may not require the full array) could be performed every Wednesday with the aim to (automatically) process the data overnight and subsequently (semi-automatically) assess the results and update the calibration database on Thursday. This would provide regularity for personnel, and sufficient observing time to ensure that factors such as parallactic angle and frequency space can be sufficiently sampled without significantly affecting overall science observing efficiency. Alternatively, if absolute leakages can be calibrated using a very short observation (e.g. by taking into account the constraints provided by the majority of unaffected antennas with unchanged leakages), then antennas could be rapidly returned to science observations after completion of their maintenance visit.

Relative gain amplitude stability between polarization pairs on any given antenna is required to ensure that Stokes parameters and polarization calibration parameters can be accurately calculated. Stability is also required to satisfy image dynamic range limits, so that all correlation products can be calculated within the same levels of uncertainty. The requirement for crosshand gain amplitude stability is therefore the same as for noise diode stability (CAL0401).

The crosshand phase frame must remain stable to prevent corruption of the recovered Stokes parameters and leakages. To maximize observing efficiency (CAL0111, CAL0112, CAL0115), crosshand bandpass phase calibration must be performed using an instrument-generated calibration signal rather than repetetive observations of celestial calibrators. This can be accomplished by installing a pulsed harmonic comb generator [e.g. RD07 Sec. 9.5.7] in every receiver on every antenna. This system will inject an RF test signal as early as possible in each signal path. The injected signal can be sampled approximately every second to track changes in crosshand phase on the nominated reference antenna. This system must be installed on all antennas to minimize complexities associated with reference antenna changes within observations and between multi-epoch observations, and also for simplicity in design, scaling for production, and maintenance (e.g. IRD swapping). The inclusion of this hardware in all receivers on all antennas will also be invaluable for remote testing of system integrity; indeed, a requirement for pulsed comb generators on all receivers and antennas may be justified solely by the need to accurately diagnose problems over the full signal path prior to arranging (expensive) antenna maintenance visits (CAL0110). For this solution to be viable, it must be possible to build a comb generator with significant output at RF frequencies up to 116 GHz. Historically this has not been feasible, but recently the ngVLA project has become aware of a promising commercial vendor. If the pulsed comb generator approach remains unachievable in band 6, then the proposed strategy above will need to be reassessed, for example falling back to celestial calibration using a polarized source (with acceptable unknown position angle).

Crosshand phase measurement errors will behave similarly to leakage errors, leading to image dynamic range limitations (CAL0123, CAL0124). Equation 20 can therefore be rewritten as

$$\frac{\mathcal{L}_\epsilon}{\mathcal{I}} \approx \frac{\sigma_\rho}{\sqrt{M}} \approx \frac{\sigma_{\rho c}}{\sqrt{M N_c}} \ , \tag{28}$$

where $\sigma_\rho = \sigma_{\rho c}/\sqrt{N_c}$ is the residual crosshand phase error on one antenna after band-averaging statistically-independent channelized crosshand phase errors $\sigma_{\rho c}$ over N_c channels, M is the number of statistically independent time samples, and the number of antennas in the array (N) is not present (unlike Equation 20) because crosshand phase is propagated from the reference antenna over the array. For consistency with the leakage accuracy calculation presented earlier, it will be assumed here (conservatively) that $N_c = 200$ channels are sufficient to sample all crosshand bandpass features across a frequency band. Assuming 1 second sampling with errors that will integrate down over a 5 min. period (conservatively $M = 300$) so that accurate calibration may be achieved over a short observation (e.g. relevant for any rapid calibrations such as the leakage re-calibration approach described above), $\sigma_{\rho c} < 0.5^\circ$ is required to satisfy CAL0124. Therefore each pulsed comb generator should ideally deliver channelized uncertainty 0.5° on a ~ 1 second timescale. This calculation will need to be reassessed if any of these assumptions are inappropriate, for example if channelized phase errors will not be statistically independent.

Finally, it is worth noting that the ngVLA could offer parallel-hand only observations (XX and YY only; e.g. see L4 calibration strategy in RD31, as used by ALMA), for example to reduce data rates or trade full cross-product correlation for increased spectral resolution. The ngVLA's amplitude stability, crosshand gain stability, and database leakages could be used facilitate this strategy (see also e.g. RD41).

6.7 Calibrator Structure

Parameter	Req. #	Value	Traceability
Calibrator Search and Characterization	CAL0701	Facilitate rapid (∼minutes) blind search and characterization (e.g. histogram of amplitude ratios over binned baseline lengths) of complex gain calibrators within $3°$ of any (accessible) sky coordinate. Prioritize re-detection of promising (minimally-variable) previously known calibrators from the calibration database.	CAL0102, CAL0108, CAL0704
Modeling of Calibrator Structure	CAL0702	Facilitate rapid (∼minutes) modeling of calibrator internal structure in total intensity (with a goal to perform this in full polarization).	CAL0102, CAL0108
Array Configuration Snapshot Performance	CAL0703	Ensure ngVLA antenna configuration is optimized to support robust snapshot calibrator modeling.	CAL0702
Calibrator Database: Source Ingest	CAL0704	Ingest new calibrator models into the calibrator database, noting that these will likely be time-dependent and so must be stored in a manner suitable for examining light curves and changes in source structure.	CAL0111, CAL0702

The wide range of baseline lengths proposed for the ngVLA will make it necessary to take into account the likely resolved structure of any given calibrator prior to using it for complex gain referencing or other purposes. Fortunately, the ngVLA's excellent snapshot uv coverage (arising from a rather random, non-geometric distribution of antenna locations) should enable rapid calculation of robust models of source internal structure from snapshot observations. CAL0701 requires the ability to quickly scan around a target region of sky to find a suitable calibrator. This will be of use in the automated preparation of both standard observing modes and triggered modes. CAL0702 requires the ability to rapidly derive a model of the calibrator's internal structure in total intensity, with a goal to perform this in full polarization (a side benefit of this effort will be a scientifically interesting database). CAL0703 is defined to ensure that the ability to derive a robust calibrator model from a snapshot observation is accounted for when optimizing the final fixed ngVLA antenna configuration. CAL0704 requires calibrator models to be compiled within a calibrator database so as to improve observational efficiency for future observations. Note however that this will likely only minimize the time required for calibrator search. Modeling of calibrator structure will likely need to take place every time a calibrator is used, to account for variability (particularly at higher frequencies).

6.8 Summary

The key L2 requirements are summarized as follows:

Pointing:	$3''/7''$ offset, $18''/42''$ blind, in precision/normal conditions
Primary Beam:	0.1% of boresight response within -10 dB power contour
Surface:	170 μm precision conditions, 400 μm normal conditions
Motion:	Slew $3°$ in 7 seconds including time to settle within offset pointing error
Baseline:	125 μm
Timing Accuracy:	0.2 μs over array
Feed Basis:	Linear feeds in all frequency bands with common alignment over array
Bandpass:	1% in 0.1 km/s channels
Polarization:	0.01% leakage and $< 0.2°$ angle on-axis; snapshot polarimetry supported
Amplitude:	Absolute flux density accuracy 1% best-case, 6% worst-case
Phase:	$0.7°$ in 1 second at 10 GHz (scaling $\propto \nu$ troposphere, $\propto 1/\nu$ ionosphere)
Amplitude Stability:	Internal switched power amplitude scale tied $\leq$monthly to celestial scale
Phase Stability:	Troposphere: WVRs on all antennas; Ionosphere: frequency switching
Crosshand Stability:	Amplitude: Switched power; Phase: Pulsed harmonic comb generators
Calibration Overheads:	Observatory maintained calibration database for maximal efficiency
Dynamic Range:	50 dB image at 10 GHz, 50 dB spectral in all bands
Automation:	Automated scheduling and pipeline data processing for standard modes
Antenna Reintegration:	Regular 'calibration day' to reintegrate antennas following maintenance

7 APPENDIX

7.1 Abbreviations & Acronyms

Acronym	Description
ALMA	Atacama Large Millimeter/submillimeter Array
CASA	The Common Astronomy Software Applications package
DIXSG	Disturbance ionosphere index spatial gradient
EVLA	Expanded Very Large Array
FWHM	Full-width at half-maximum
GDGPS	Global Differential GPS System
GPS	Global Positioning System
HPBW	Half-power beam-width
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IF	Intermediate frequency
IGRF	International Geomagnetic Reference Field
IGS	International Global Navigation Satellite System Service
IRD	Integrated receiver and digitizer
JPL	Jet Propulsion Laboratory
JVLA	Jansky Very Large Array
MAPGPS	MIT Automated Processing of GPS
MIT	Massachusetts Institute of Technology
RF	Radio frequency
RFI	Radio frequency interference
rms	Root mean square
ROTI	Rate of TEC index
SNR	Signal to noise ratio
STEC	Slant total electron content
TEC	Total electron content
TECU	Total electron content unit
uv	Spatial frequency plane coordinates
VTEC	Vertical total electron content
VLBA	Very Long Baseline Array
VLBI	Very long baseline interferometry
WVR	Water vapor radiometer/radiometry