Antenna Preliminary Technical Requirements

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Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	04/18/2017	R. Selina	All	Started first draft. Used ngVLA System Requirements as a template, and pulled in 'Strawman' requirements by P. Napier. Also incorporates text and structure from ALMA-34.00.00.00-006-C-SPE Version C.
0.2	04/24/2017	R. Selina	Appendix	Added coordinate system diagram by S. Sturgis.
0.3	05/02/2017	R. Selina	All	Updated efficiency tables. Added Verification and Documentation sections. Revisions & elaborations throughout.
0.4	05/08/2017	R. Selina	5.3, 5.14, 5.17	Incorporated feedback from T. Beasley. Updated close packing text. Added serviceability requirement. Updated lifecycle text.
0.5	05/09/2017	R. Selina	5.5, 5.6, 9	Incorporated feedback from W. Grammer. Revised aperture efficiency requirements. Added beam subtended half angle requirement. Updated verification text, etc.
0.6	06/05/2017	R. Selina	5.9, 5.13, 5.14	Updated MTBF, maintenance interval, slew rates and environmental specifications.
0.7	07/07/2017	R. Selina	1.1, 2.1, 2.2, 3.2, 3.3, 5, 9, 10, 11.	Updated post June Workshop. Revised aperture diameter to 18m. Updated associated parameters to match. Updated optical parameters consistent with Granet. Added Requirements for Design and Safety sections. Added Requirements Summary. Other minor additions.
0.8	07/24/2017	R. Selina	9, 13	Revised EMC requirements. Added EM performance simulation requirements as suggested by D. Chalmers. Updated coordinate system narrative to match Granet. Added representative optical sketch. Other misc. corrections throughout.
0.9	08/28/2017	R. Selina, D'Addario	All	Incorporated input from NRAO-Internal (Napier, Jackson, Grammer, Sturgis, Kern, Walker, etc.) and TAC (Tetsuo, Lamb, Kantor, and D'Addario) review. Struck path-length change requirements. Added focus stability requirements. Rescoped EM analysis and requirements.
0.91	09/06/2017	R. Selina	4.2	Struck mount geometry req. ANT0212.
0.92	09/11/2017	R. Selina, M. McKinnon	All	Incorporated comments from McKinnon and Beasley. Edits to narrative throughout. Added Design Life to KPP list.

Version	Date	Author	Affected Section(s)	Reason
1	2017-09-12	R. Selina, M. McKinnon	N/A	First Release for Antenna Reference Design contract.
1.1	2017-10-12	R. Selina	4.2, 4.5, 4.9, 4.13, 4.15, 4.16, 7.3.2, 10.	Updated to address requested corrections and questions from GDMS. Clarified MTBF and M&C requirements. Corrected irregularities in references.
2	2018-01-23	R. Selina	N/A	Second Release. Updated for the Antenna Reference Design Contract.
2.1	2018-11-06	D. Dunbar	Doc number and Title, 3.4, 4.14.1, 4.14.2	Updated document number (SPE to REQ) to conform to System Engineering protocol. Updated Precision and Normal wind velocities to match System Level Spec.
2.2	2018-11-14	D. Dunbar	2.1, 2.2, 4.13, 4.14, 8.1.4, 10	Added additional reference docs. Updated Environment Conditions to trace back to ENV requirements (and not SYS Req). Updated Electromag table and requirements to match/point to EMC requirement doc. Added additional applicable environmental requirements. Updated Load Case Table (precision) wind loads to match lower velocity (5 m/s).
2.3	2019-05-29	R. Selina	3.2	Updated introduction materials to reflect LBA inclusion in project scope.
A	2019-07-29	A. Lear	All	Prepared PDF for signatures and release.

Table of Contents

1 Introduction

1.1 Purpose

This document presents a preliminary set of technical specifications for the ngVLA antenna. Many requirements flow down from the preliminary ngVLA System Requirements [AD01], which in turn flow down from the preliminary ngVLA Science Requirements.

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

NRAO desires a cost-effective solution for the antenna that can be manufactured in volume and installed at remote locations. The optimization for value requires flexibility in key requirements until the cost and technical impact of the parameters are understood. These requirements are therefore considered preliminary until refined through feedback with the antenna designer.

1.2 Scope

The scope of this document is the ngVLA antenna element. This consists of the foundation, mounting structure that provides for motion in azimuth and elevation, reflectors and their supporting structures, drive system, and associated motion control electronics. All other instrumentation, including feed antennas and receiving electronics, are outside the scope of this element, though interfaces must be considered. This specification establishes the performance, functional, design, and test requirements applicable to the ngVLA antennas.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	International Standard: Protection Against Lightning	IEC 62305:2010
AD03	Protection Against Electric Shock: Common Aspects for Installation and Equipment	IEC 61140:2016
AD04	Electrical Standards for Industrial Machinery	NFPA 79
AD05	Safety of Machinery: Electrical Equipment of Machines	IEC 60204:2016
AD06	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD07	Hydraulic and Pneumatic Fluid Power Safety	ISO 4413
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
AD09	Occupational Safety and Health Standards for Construction	29 CFR Part 1926
AD10	Military Handbook, Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
AD11	Non-Electronic Parts Reliability Data	NPRD-95
AD12	Electromagnetic Compatibility	IEC 61000-3-5
AD13	Offset Dual Reflector Antenna	Mitsuguch et al., IEEE APS 1976, DOI 10.1109/APS.1976.1147539

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Essential Radio Astronomy	http://www.cv.nrao.edu/course/astr534/2DApertures.html
RD02	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106. Perley, Brundage, Mertely.
RD03	Designing Classical Offset Cassegrain or Gregorian Dual-Reflector Antennas from Combinations of Prescribed Geometric Parameters	Christophe Granet, *IEEE Antennas and Propagation Magazine*, Vol. 44, No. 3, June 2002
RD04	USGS Coterminous US Seismic Hazard Map – PGA 2% in 50 Years	ftp://hazards.cr.usgs.gov/web/nshm/conterminous/2014/2014pga2pct.pdf
RD05	System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements	020.10.15.10.00-0002-REQ
RD06	System Environmental Specifications	020.10.15.10.00-0001-SPE

3 Overview of Antenna Technical Specifications

3.1 Document Outline

This document presents the technical specifications of the ngVLA antenna element. These parameters determine the overall form and performance of the antenna.

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification procedures.

In many cases, the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the required analysis and trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA antenna concept.

Requirements pertinent to interfacing systems are described in Section 5. Initial requirements are noted by interface, along with identified parameters for Interface Control Documents (ICDs) that will fully define the interfaces as the design progresses.

Safety requirements applicable to both the design phase and the functional antenna are described in Section 7. Additional requirements for the design phase are described in Section 8. Documentation requirements for both technical design documentation and software are provided in Section 9.

Requirements for the Verification and Test of the antenna, from the conceptual design through to prototype, are described in Section 10.

Section 11 identifies Key Performance Parameters (KPP) that should be estimated and monitored throughout the design phase. These are metrics to assist in the trade-off analysis of various concepts, and help identify and resolve tensions between requirements as the design progresses.

3.2 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The ngVLA will be a synthesis radio telescope composed of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The array's signal processing center will be located at the Very Large Array site on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

3.3 General Antenna Description

The antennas will operate in free air, during daytime and nighttime, as long as the atmospheric conditions remain within the specified operating limits. When not in an operating condition, the antenna will be put in a safe "stow" configuration.

The antennas will be constituted of a shaped paraboloidal reflector with a subtended circular aperture of 18 m diameter. The optical configuration shall be an offset Gregorian feed-low design supported by an Altitude-Azimuth mount.

The subreflector shall be supported so that neither it nor any of its supporting structure obstructs the aperture of the primary reflector. If necessary to meet the performance requirements, the position of the subreflector may be remotely adjusted with a controlled mechanism. Space is required near the secondary focal point for installation of feed antennas, receivers, and other electronics. Additional space is required near ground level for electronics and instruments.

3.4 Summary of Antenna Requirements

The following table provides a summary of the major antenna requirements in order to provide the reader with a high-level view of the desired antenna. Should there be a conflict between the requirements listed here and the descriptions in Sections 4 through 10, the latter shall take precedence.

Parameter	**Summary of Requirement**	**Reference Reqs.**
Frequency Range	1.2–116 GHz	ANT0101 ANT0102 ANT0103
Diameter	18 m	ANT0202
Number of Antennas	244	ANT0401
Surface Accuracy	**Precision Operating Conditions** 160 μm RMS (λ/16 @ 116 GHz), primary & subreflector combined **Normal Operating Conditions** 300 μm RMS, primary and subreflector combined	ANT0501 ANT0502
Pointing Accuracy	**Precision Operating Conditions**: Absolute pointing: 8 arc sec RMS Referenced pointing: 3 arc sec RMS (4 deg angle, 15 min time) **Normal Operating Conditions** Absolute pointing: 35 arc sec RMS Referenced pointing: 5 arc sec RMS (4 deg angle, 15 min time)	ANT0611 ANT0612 ANT0621 ANT0622
Tracking Range	**Azimuth:** ±270 deg **Elevation:** 12 deg to 88 deg	ANT0801 ANT0802
Movement Rate	**Slew:** Azimuth 90 deg/min, Elevation 45 deg/min. **Tracking:** Azimuth 7.5 deg/min, Elevation 3.5 deg/min	ANT0901 ANT0902 ANT0906
Antenna Geometry	Offset Gregorian, satisfying Mizuguch-Dragone polarization condition, with focal point on bottom.	ANT0201 ANT0206 ANT0211
Environmental Conditions	**Survival Conditions at Stow Position:** wind ≤50 m/s, temperature ≥–40 C, 2.5 cm radial ice, 25 cm snow in dish, 2.0 cm dia hailstones **Precision Operating Conditions:** Nighttime only, wind ≤5 m/s, temperature ≥–15 C, no precipitation **Normal Operating Conditions**: Day and night, wind ≤7 m/s, temperature ≥–15 C, no precipitation	ANT1411 through ANT1447

4 Antenna Functional and Performance Requirements

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

4.1 Operating Frequency Range

Parameter	Req. #	Value	Traceability
Upper Operating Frequency	ANT0101	116 GHz	SYS0801
Lower Operating Frequency	ANT0102	1.2 GHz	SYS0801
Optimized Operating Frequencies	ANT0103	8 GHz–50 GHz	SYS0801

The upper and lower operating frequencies for the antenna flow down directly from the system requirements. However, operation above 8 GHz is of higher importance, and the lower operating frequency should not be permitted to significantly increase the design cost or compromise performance at higher frequencies.

For example, optimizing performance at 1.2 GHz may necessitate a large subreflector, perhaps 4–5 m in diameter. Such a subreflector may increase the structural requirements on the feed/subreflector arm and make meeting the pointing specification more difficult due to increased wind loads. Therefore, subreflector size should be a compromise to provide minimal wind loading at high frequencies, with spillover temperature optimized for 8 GHz and up.

4.2 Optical and Mounting Geometry

Parameter	Req. #	Value	Traceability
Optical Configuration Type	ANT0201	Offset Gregorian	SYS0701 SYS0601
Primary Aperture Diameter and Shape	ANT0202	18m, circular	SYS0501 SYS0601
Secondary Reflector Aperture Diameter	ANT0203	3.2m minimum	SYS0501 SYS0701
Secondary Angle of Illumination	ANT0204	From the focal point, the aperture of the secondary reflector shall subtend an angle of 110°	
Reflector Offset	ANT0205	There shall be no overlap of the physical secondary reflector with the projected aperture of the main reflector	
Focal Ratio, Primary	ANT0206	The closest paraboloid to the main reflector shall have a focal ratio of 0.40 ±0.05	
Cross Polarization	ANT0207	The secondary reflector tilt angle (β in Figure 1) shall be chosen to satisfy the Mizuguch condition [AD13]	SYS0501
Reflector Shapes	ANT0208	The shapes of the main and secondary reflectors will deviate no more than 0.25m from the classical Gregorian conic sections (paraboloid and ellipsoid). For the main reflector, deviations will be azimuthally symmetric about the paraboloid axis	

Parameter	Req. #	Value	Traceability
Secondary Reflector Extension	ANT0209	The secondary reflector shall be extended on its outside edge by 0.5 m as a shield against ground radiation. This part of the reflector is outside its defined aperture and its shape is not specified; it is not shown in Figure 1. The extension may be integral with the reflector or constructed as a separate component.	
Main Reflector Extensions	ANT0210	The main reflector may extend beyond the defined aperture to facilitate efficient fabrication (e.g., assembly from hexagonal panels).	
Mounting Configuration	ANT0211	The focal point shall be closest to the ground at the minimum elevation angle.	

The optical configuration for classical conic section reflectors is fully specified by requirements ANT0202 through ANT0207 (except that ANT0205 and ANT0207 specify only minimum values). Figure 1 (next page) conforms to these requirements using the minimum secondary reflector size and 10 cm offset ($d_{sr\text{-}mr}$ = 10 cm).

The primary aperture diameter is measured in the plane perpendicular to its axis. The physical reflector's largest dimension, given the offset geometry, is appreciably larger.

The secondary reflector aperture (ANT0203 and ANT0205) is measured in the plane perpendicular to the geometrical optics ray from focal point to main aperture center. The secondary reflector's physical edge (not including the extension described in ANT0209) shall be circular when projected into this plane.

The final shapes of the reflectors have not been determined (NRAO responsibility), but they are expected to deviate from the classical paraboloid and ellipsoid. Whereas the deviation will be small (ANT0208), the classical shapes should be used for the preliminary design.

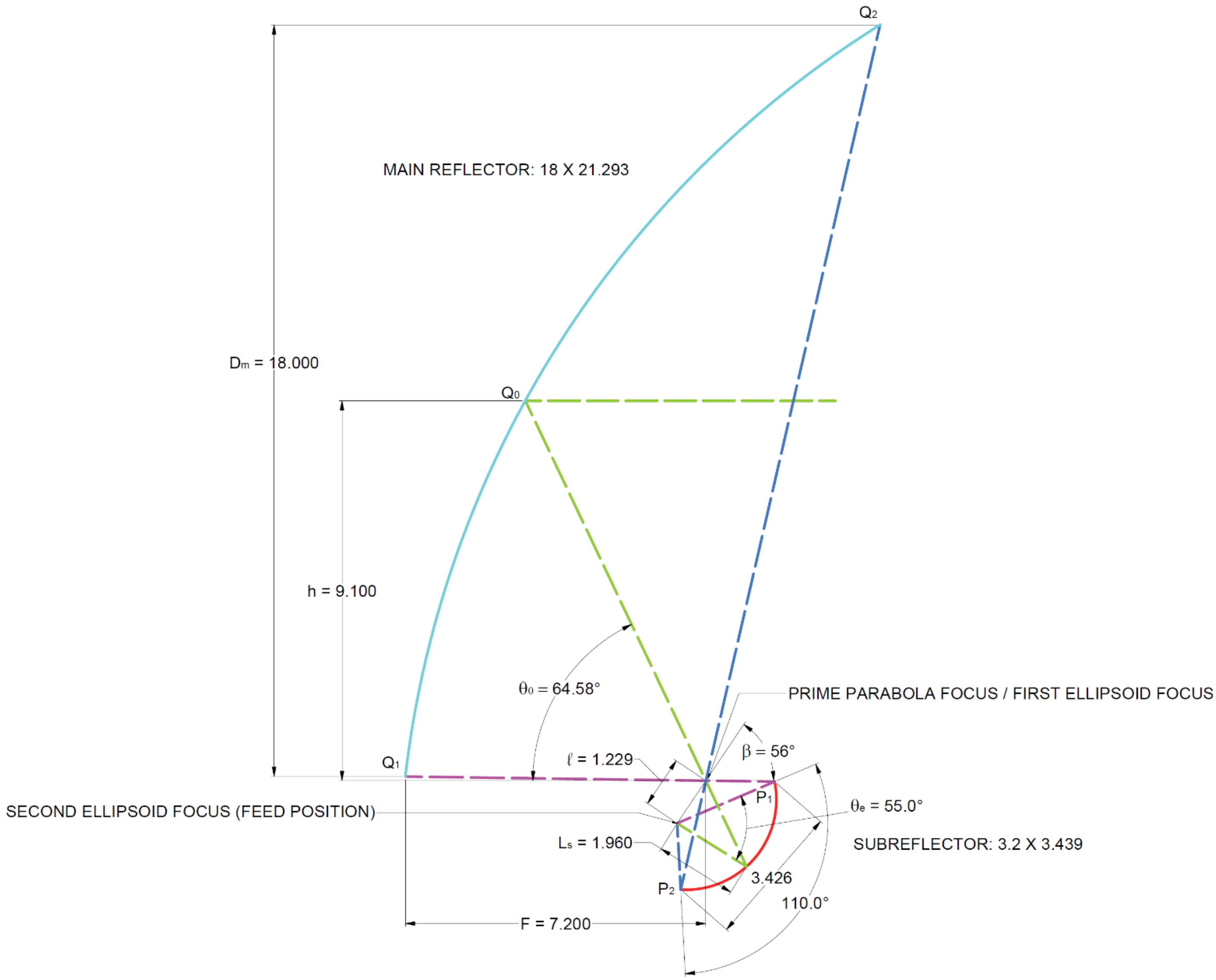

Figure 1 - Cross-section of the optical geometry through the plane of symmetry for unshaped (paraboloid ellipsoid) reflectors. Values may be refined in the design.

4.3 *Allowable Design Volume & Mass*

Parameter	Req. #	Value	Traceability
Minimum Spacing	ANT0301	Antennas whose azimuth axes are separated by 30 m shall not collide for any combination of their orientations.	
Height	ANT0302	At the lower limit of normal elevation motion, no part of the movable structure shall be closer than 1.0 m to the nearest point on the ground.	
Mass	ANT0303	Unconstrained.	

If the minimum spacing requirement proves difficult to accommodate, NRAO may evaluate a revision to this requirement. The height of the pedestal is limited to provide adequate clearance for snow. For service, a low feed arm is desirable, but the design height should also consider equipment and personnel safety concerns. The mass is an unconstrained free parameter, but lower mass is preferred in order to minimize cost. The envelopes of NRAO-supplied equipment will be defined in the ICDs described in Section 5.

4.4 Number of Antennas

Parameter	Req. #	Value	Traceability
Number of Antennas	ANT0401	244	SYS0501

Additional antennas would be desirable. In practice, this requirement is set by construction cost constraints.

4.5 Reflector Construction & Accuracy

Parameter	Req. #	Value	Traceability
Surface Accuracy, Precision	ANT0501	Surface errors shall not exceed 160 µm RMS, for the primary and secondary reflector combined when operating in the Precision operating environment.	SYS0501
Surface Accuracy, Normal	ANT0502	Surface errors shall not exceed 300 µm RMS, for the primary and secondary reflector combined, when operating in the Normal operating environment.	SYS0501
Reflector Construction	ANT0503	Each reflector shall be a solid metal surface (not a mesh or perforated sheet). Each may be constructed as a single piece or as multiple panels. If constructed of multiple panels, gaps between panel edges shall not exceed 1 mm.	

The surface error at each point is defined to be the deviation of the actual surface from the nominal surface, measured normal to the nominal surface. The RMS is computed by integrating over the main aperture (not across the reflector's local surface) with uniform weighting. The limits apply to the RMS of the sum of the main and secondary reflector errors, but that value may be estimated by taking the root-sum-squared of the main and secondary RMS errors measured separately.

The aim with the reflector construction specification is to ensure high reflector efficiency over the operating frequencies (Section 4.1) with minimal transmission through gaps from electro-magnetic interference (EMI) or ground emission. If alternate designs and provisions ensure that the system maintains aperture efficiency and noise temperature, NRAO may revise this requirement.

4.6 Pointing Accuracy

Pointing error is defined as the difference between the commanded orientation of the antenna and the actual direction of its RF beam. Pointing errors are classified as repeatable and non-repeatable. Pointing accuracy is specified by the maximum allowable Non-Repeatable Pointing Error and Referenced Pointing Error. The absolute error may be larger provided it is repeatable over the specified range of environmental conditions (mainly temperature and wind). Repeatable errors will be calibrated and removed in the control software.

To further correct the non-repeatable errors, referenced pointing will be used. This involves astronomical measurement of the pointing error using observations of a known object near the desired pointing direction. The Referenced Pointing Error specifications then limit the difference in pointing error at a given angular separation from the desired direction and the change in that difference over a given time. Pointing requirements apply over the full operational range of motion.

4.6.1 Pointing Accuracy in Precision Operating Environment

Parameter	Req. #	Value	Traceability
Non-Repeatable Pointing Error	ANT0611	18 arc sec RMS	SYS0801
Referenced Pointing Error	ANT0612	3 arc sec RMS, within 4° of the target position and 15 mins time	SYS0701, SYS0801

The non-repeatable pointing specification is equivalent to full width half maximum over ten (FWHM/10) at 20 GHz, while the referenced pointing requirement is equivalent to the FWHM/10 at 116 GHz. The control loop used for referenced pointing within 4° should not be unique—performance at larger angles is expected to degrade in a manner roughly proportional to slew distance. Note that systematic pointing errors are more damaging than random errors, and this RMS value assumes a random distribution of errors after application of the pointing model.

4.6.2 Pointing Accuracy in the Normal Operating Environment

Parameter	Req. #	Value	Traceability
Non-Repeatable Pointing Error	ANT0621	35 arc sec RMS	SYS0801
Referenced Pointing Error	ANT0622	5 arc sec RMS within 4°; must maintain spec for ≥15 mins time	SYS0701, SYS0801

The absolute pointing specification is equivalent to FWHM/10 at 10 GHz, while the referenced pointing requirement is equivalent to the FWHM/15 at 50 GHz. The latter specification ensures that the array operates effectively at frequencies below 50 GHz during typical good daytime environmental conditions.

4.7 Focus Stability

Parameter	Req. #	Value	Traceability
Secondary Focus Position Stability in Precision Operating Environment	ANT0701	125 µm over full range of elevation	
Secondary Focus Position Stability in Normal Operating Environment	ANT0702	300 µm over full range of elevation	

The focus position stability in the precision environment is equivalent to $\lambda/20$ at 116 GHz, while the specification in the normal operating environment is equivalent to $\lambda/20$ at 50 GHz. This specification may be met by active compensation (e.g., moving the subreflector).

4.8 Range of Motion

Parameter	Req. #	Value	Traceability
Azimuth Tracking Range	ANT0801	+/–270° minimum, where zero is towards true south	
Elevation Tracking Range	ANT0802	12° to 88° minimum from the local horizon	SYS1201
Elevation Movement Range	ANT0803	TBD	

The Azimuth tracking range specified has a zero-degree fiducial vector pointing towards the celestial south pole. The elevation range is relative to the local horizon. The coordinate system is further explained in Section 12.2.

The lower elevation permits observations over large portions the southern hemisphere. A lower elevation limit of 12 degrees allows observations of order –40 declination near the meridian (given the latitude of the ngVLA Core). However, this limit in particular may prove to be a driving requirement with the feed low optical design, as the backup and feed support structure may interfere with a pedestal at lower elevations. Should this requirement prove to be a significant cost or complexity driver, it can be reviewed.

The movement range should be larger than the tracking range. A margin should be provided for the normal limits of motion before limit switches are reached. The hard mechanical limits should be slightly wider still. (See Section 4.17 for additional information.) Maintenance and safety stow positions may also be outside the elevation tracking range.

4.9 Axis Rates

Parameter	Req. #	Value	Traceability
Slew: Azimuth	ANT0901	90 deg/min. minimum	SYS1107
Slew: Elevation	ANT0902	45 deg/min. minimum	SYS1107
Acceleration: Azimuth	ANT0903	4.5 deg/sec^2 minimum	
Acceleration: Elevation	ANT0904	2.25 deg/sec^2 minimum	
Slew + Settle Time	ANT0905	Move 4-deg on sky and settle to within Referenced Pointing Specification within 10 sec for elevation angles <70°	SYS1107
Tracking: Azimuth	ANT0906	7.5 deg/min. minimum	
Tracking: Elevation	ANT0907	3.5 deg/min. minimum	

The slew speeds and accelerations specified attempt to minimize time spent slewing between targets or calibrators, without significantly driving the antenna design. They also allow for rapid response to transient events, reaching anywhere on sky within approximately two minutes. The slew + settle time specification aims to reduce phase calibration overheads. The 70-degree elevation angle constraint is given so as not to drive the specification for azimuth slew rates at higher elevation. Should this specification prove to be a driving requirement it may be reviewed, as there are alternative approaches to phase calibration at the system level.

The tracking specifications give the rates at which the specified pointing error limits must be maintained. In general, tracking error that contributes to the pointing error must be included in the pointing error budget for both Precision and Normal conditions. The azimuth tracking rate corresponds to approximately ten times sidereal at an elevation of 70 degrees. Tracking at super-sidereal rates will be important for multiple observation modes, such as on-the-fly mosaicking, or tracking objects that move across the celestial sphere, such as planets, asteroids, and satellites.

4.10 Stow Positions

Parameter	Req. #	Value	Traceability
Stow Position: Survival	ANT1001	Survival stow position shall limit wind load on the antenna while ensuring water and snow accumulation does not exceed safe structural allowances.	
Stow Position: Maintenance	ANT1002	Maintenance stow position shall place the receiver enclosure as close to horizontal as possible.	

It shall be possible to stow the antenna in two different positions, one used for occurrence of the survival atmospheric conditions, the other for specific maintenance to be performed. The Maintenance position aims to provide a level working platform around the receiver enclosure mounted on the feed arm. In practice, this may be unattainable in some designs and will be constrained by the lower elevation limit. In Survival position, the antenna shall withstand the survival conditions described in Section 4.14.4. The designer shall determine a single survival position that minimizes stress from wind and snow/ice loading.

4.11 System Noise Contributions

Parameter	Req. #	Value	Traceability
Resistive Losses	ANT1101	The primary and secondary reflector shall each have a surface resistive loss of less than 1.0% over the operating frequency range.	

Contributions to system noise from the antenna, due to resistive loss of the primary and secondary reflector surfaces and scattering of ground noise into the feed, shall be minimized as much as possible without compromising the surface accuracy and pointing requirements. Should this requirement prove difficult to meet at the upper operating frequency, NRAO may review the requirement.

4.12 Solar Observations

Parameter	Req. #	Value	Traceability
Solar Observations	ANT1201	Direct solar observations allowed. System will meet specifications for the normal operating environment.	FUN0006

The specifications for pointing and surface accuracy for the Normal operating environment must be met when pointed directly at the Sun.

4.13 Spurious Signals/Radio Frequency Interference Generation

Parameter	Req. #	Value	Traceability
Spurious Signal Level	ANT1301	Not to exceed the equivalent isotropic radiated power limits in Table 1	EMC0310

The electronics within the antenna must be shielded to avoid radio frequency interference (RFI) being received by the Front End electronics, degrading system sensitivity. Table 1 is based on the analysis presented in RD02, updated for longer integrations consistent with SCI0116.

Freq. (GHz)	**1**	**2**	**4**	**6**	**8**	**10**	**20**	**30**
F_h (w/m²)	1.5E-19	1.1E-18	8.9E-18	2.9E-17	6.3E-17	1.2E-16	1.2E-15	4.3E-15
$EIRP_h$ (W)	1.9E-16	1.4E-15	1.1E-14	3.7E-14	7.9E-14	1.5E-13	1.6E-12	5.4E-12
$EIRP_h$ (dBm)	**–127**	**–119**	**–110**	**–104**	**–101**	**–98**	**–88**	**–83**

Table 1 - Allowable radiation power for electronic components.

The table is based on unity gain, assuming the RFI enters through a sidelobe of the antenna. F_h is the harmful power flux density level, and $EIRP_h$ is the harmful effective isotropic radiated power. The ratio of the emitting device EIRP to the harmful EIRP ($EIRP_h$) is the shielding required. For example, a device with an EIRP of 1nW @ 2GHz would require of order 59dB of shielding.

Table 1 assumes the radiator is 10 m from the antenna feed. For other distances, the $EIRP_h$ can be calculated as follows:

$$EIRP_h = \frac{4\pi r^2 S F_h}{G}$$

where *r* is the distance in meters, *S* is the device shielding ratio, *G* is equal to *1*, and F_h is from Table 1.

Radiated Power shall be computed over a bandwidth that corresponds to a spectral resolution of 100 m/s. This can be calculated as 333 Hz * *vG*, where *vG* is the RF frequency in GHz.

4.14 Environmental Conditions

Based on historical weather data of the VLA site and other public weather databases, the following definitions of environmental conditions are adopted. These requirements are verbatim from the environmental specification outlined in [AD01].

4.14.1 Precision Operating Conditions

Parameter	Req. #	Value	Traceability
Solar Thermal Load	ANT1411	Nighttime only; no solar thermal load within last 2 hours.	ENV0311
Wind Speed	ANT1412	0 ≤ W ≤ 5 m/s average over 10 min time. 7 m/s peak gusts.	ENV0312
Temperature	ANT1413	–15 C ≤ T ≤ 25 C	ENV0313
Temperature Rate of Change	ANT1414	1.8°C/Hr	ENV0314
Precipitation	ANT1415	No precipitation	ENV0315

The Precision operating environment defines the conditions under which the system is expected to meet the most stringent requirements and provide optimal system performance.

The solar thermal load requirement limits this environment to two hours after sunset through sunrise, so long as the other requirements of this section are met. The two-hour restriction is intended to allow sufficient time for the system to equilibrate.

4.14.2 Normal Operating Conditions

Parameter	Req. #	Value	Traceability
Solar Thermal Load	ANT1421	Exposed to full sun, 1200W/m^2	ENV0321
Wind Speed	ANT1422	W ≤ 7 m/s average over 10 min time; 10 m/s peak gusts	ENV0322
Temperature	ANT1423	–15 C ≤ T ≤ 35 C	ENV0323
Temperature Rate of Change	ANT1424	3.6°C/Hr	ENV0324
Precipitation	ANT1425	No precipitation	ENV0325

When the environment meets the constraints of normal operating conditions, system performance requirements are relaxed but still expected to provide adequate performance for operation below 50 GHz.

4.14.3 Limits to Operating Conditions

Parameter	Req. #	Value	Traceability
Solar Thermal Load	ANT1430	Exposed to full sun, 1200W/m^2	ENV0330
Wind	ANT1431	W ≤ 15 m/s average over 10 mins; W ≤ 20 m/s gust.	ENV0331
Temperature	ANT1432	–20 C ≤ T ≤ 45 C	ENV0332
Precipitation	ANT1433	5 cm/hr over 10 mins	ENV0333
Ice	ANT1434	No ice accumulation on structure	ENV0334

A third categorization will establish hard limits to the operating conditions. While outside the bounds of the normal operating environment but within this regime, no performance guarantees are expected, but the system shall still be capable of safe operation. Once these limits are exceeded, the antenna will be moved to its "stow-survival" orientation to prevent damage.

4.14.4 Survival Conditions at Stow Position

Parameter	Req. #	Value	Traceability
Wind	ANT1441	0 m/s ≤ W ≤ 50 m/s average	ENV0341
Temperature	ANT1442	–30 C ≤ T ≤ 50 C	ENV0342
Radial Ice	ANT1443	2.5 cm	ENV0343
Rain Rate	ANT1444	16 cm/hr over 10 mins	ENV0344
Snow Load—Antenna	ANT1445	25 cm	ENV0345
Hail Stones	ANT1446	2.0 cm	ENV0347
Antenna Orientation	ANT1447	Stow-survival, as defined by designer	ENV0348

The survival conditions describe the environment that the antenna should be able to withstand without damage when placed in its least-vulnerable state. The designer must specify the orientation that will result in minimum stress to the structure at the maximum wind speed and maximum snow and ice loading. Note that 50 m/s survival wind is not high enough to survive tornadoes in eastern New Mexico and Texas. This issue should be considered in the Hazard Analysis described in Section 7.2.

The temperature limits, radial ice, snow load and hail stone requirements are based on experience at the VLA site and a survey of conditions throughout the extent of the array. Should these requirements prove onerous or constraining, a risk versus loss analysis may be performed to evaluate the likely cost and time for repair, and the frequency of expected repairs, compared to the cost impact of meeting the requirement over the lifetime of the facility. This would be executed as part of the analysis described in Section 7.2.

4.14.5 Lightning Protection Requirements

Parameter	Req. #	Value	Traceability
Lightning Protection: Structure	ANT1451	The antenna and housed equipment shall be protected from both direct and nearby lightning strikes, achieving Protection Level 1 as defined in in IEC 62305-1/3 [AD02]	ENV0511
Lightning Protection: Electronics	ANT1452	The antenna electrical and electronics systems shall be protected against Lightning Electromagnetic Impulse (LEMP) in accordance with IEC 62305-4. [AD02]	ENV0512
Lightning Protection: Personnel	ANT1453	A safety hazard analysis shall be performed for anticipated preventive maintenance tasks that may place personnel at risk in the event of direct or nearby lightning strikes.	ENV0513

Given the array's extent and the prevailing environmental conditions, direct and nearby lightning strikes causing a lightning electromagnetic pulse (LEMP) should be anticipated and mitigated in the antenna design.

The antenna and housed equipment shall be protected in any antenna orientation. The requirements for the antenna grounding electrode, provided as part of the antenna foundation, shall be documented in the relevant interface control document (ICD) as described in Section 5.1. All bearings shall have bypass grounding connections. The grounding system shall be designed to minimize ground loops.

The lightning protection system shall be designed to achieve Protection Level I as defined by [AD02] "IEC 62305-1 – Protection against lightning." This level assures protection against 99% of strikes, with a residual risk of damage for strikes with parameters outside the defined range.

4.14.6 Seismic Protection Requirements

Parameter	Req. #	Value	Traceability
Seismic Protection	ANT1461	The antenna and foundation shall be designed to withstand a low probability earthquake with up to 0.2g peak acceleration in either the vertical or horizontal axis.	ENV0521

Low probability has been defined as a 2% probability of an event exceeding this magnitude over a 50-year period, consistent with data available from the USGS Seismic Hazard Model [RD04]. Equipment shall be designed to survive this standard in any operational condition and orientation.

4.14.7 Site Elevation

Parameter	Req. #	Value	Traceability
Altitude Range	ANT1471	The antenna and foundation shall be designed for survival and operation at altitudes from sea level to 2500 m.	ENV0351

4.14.8 Vibration

Parameter	Req. #	Value	Traceability
Wind Vibration	ANT1481	Exposed equipment, including within the antenna, shall be designed to withstand persistent wind-induced vibration.	ENV0531

The vibration mitigation requirement is especially applicable to all mechanical connectors. All cables shall be mechanically supported to mitigate vibration loosening of connectors.

4.15 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Preventive Maintenance Cycle	ANT1502	Preventive maintenance shall not be required at intervals shorter than 12 months.	SYS2301
Preventive Maintenance Effort	ANT1502	Periodic preventive maintenance shall require no more than a 2-person team and no more than 2 8-hour workdays.	SYS2301
Mean Time Between Failures	ANT1503	MTBF ≥35,000 hrs.	SYS2302

The maintenance and reliability requirements support high-level requirements that limit total array operating cost. The preventive maintenance effort is intended to be averaged over the array design life and need not be equal on all 12-month cycles.

The MTBF requirement corresponds to an annual failure rate of 25% for the antenna electro-mechanical systems alone. Monitor points/sensors should be included in the MTBF/MTTR analysis, but sensors and other components that can be reasonably deemed to be ancillary to operation may be removed from the determination of compliance with the MTBF requirement (ANT1503).

"Failure" will be defined as a condition which places the system outside of its performance specifications (pointing, slew, tracking, etc.), or into an unsafe state, requiring repair. For example, a malfunction on one of three redundant anemometers would not meet the standard for failure in the MTBF analysis, and should not factor into compliance with ANT1503. Similarly, the malfunction of a gearbox temperature sensor would not be considered a failure for the purposes of ANT1503. However, the malfunction of a metrology sensor required for pointing model corrections would be considered a failure.

4.16 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Antenna Control Unit (ACU)	ANT1601	The antenna shall be equipped with an electronic control unit that will drive the azimuth and elevation axis motions according to commands received from either the Monitor and Control system (see Interfaces) or from a local manual interface(s).	
Servo Loops	ANT1602	The ACU shall include servos with position and rate control loops on each axis, and the servo design shall account for the structure's dynamic behavior.	SYS2601
Self-Monitoring	ANT1603	The antenna shall measure, report, and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures.	SYS2601
Weather Monitoring	ANT1604	The antenna shall be equipped with anemometers and thermometers to determine when safe operating conditions have been exceeded and to stow the antenna.	
Network Hardening/ Authentication	ANT1605	System remote control shall require an authentication process, and only respond to commands from authorized sources.	SYS2602
Remote Reset	ANT1606	It shall be possible to remotely reset each antenna, including a reboot of the antenna control unit, and return the antenna to operational status.	

For maintenance purposes, local control of the ACU near the point of service is desirable.

The expectation with self-monitoring (ANT1603) is that the antenna control system will expose lower-level sensors to the monitor and control system when queried. The cadence of access is flexible and not expected at high rates (typical access might be on second to minute scales). Any high-cadence monitoring should generally be internal to the antenna control system with summary output on the interface.

Exclusions from the remote reset requirement are hardware interconnects for safety, the disconnection of the power in the case of a fire alarm activation, and recovery from axis in hard stop. Other features of the ACU interface are to be specified in the Monitor and Control ICD.

4.17 Motion Limiting Features

Parameter	Req. #	Value	Traceability
Software Limits	ANT1701	The antenna shall include logic to prevent motion beyond programmable limits in azimuth and elevation during normal operation.	
Hardware Limits	ANT1702	The antenna shall be equipped with mechanically driven switches to inhibit operation outside its safe operating limits.	
Hard Stops	ANT1703	The antenna shall be equipped with hard mechanical stops that physically prevent the antenna from exceeding operating limits when damage is imminent.	
Safety Lock-Out	ANT1704	The antenna shall be equipped with a safety lock-out that inhibits motion of the antenna during service.	
Fire Alarm	ANT1705	The antenna shall be equipped with fire alarms in any equipment compartments. The fire alarm shall disconnect power to the antenna when triggered.	
Fail Safe Brakes	ANT1706	The drive brakes shall engage when the antenna experiences a loss of power.	

Fire alarms may be necessary at additional locations as determined by the designer.

4.18 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	ANT1801	The antenna shall be designed to require no major overhaul work for 20 years.	
Lifecycle Optimization	ANT1802	The antenna design shall minimize its lifecycle cost for 20 years of operation.	
Country of Origin	ANT1803	The antenna should meet US federal procurement regulations for country of origin content.	

An exception to the design life is painting, which should not be required for 10 years or more. Lifecycle costs include manufacturing, transportation, construction/assembly, operation and decommissioning.

The ngVLA will be designed and constructed with a large contribution of federal funds. Provisions to "buy American" are expected, and the design and costing should presume the use of US steel (if steel is included in the design) and limits on total foreign content.

5 Interface Requirements

This section provides information about the interfaces of the antenna. ICDs are required between the antenna and all connecting systems. In many cases, specifications for the interfaces are not yet available, but the broad scope of the ICD can be defined.

These interfaces shall be developed and documented by the antenna designer and approved by ngVLA as part of the antenna conceptual design effort, then updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Foundation/Station

The conceptual design of the foundation is within the scope of the antenna element. Final design and delivery of the foundation will be the responsibility of others.

The foundation refers to all stations where an antenna can be mounted, irrespective of its location. Antenna stations will be available at the VLA antenna test facility (ATF) site for assembly and testing purposes.

The ICD between the antenna and foundation shall define the geometry of the attachment and the mechanical characteristics of the foundation. Furthermore, it will define the position and geometry of the vaults for the electric power and for the signals routed to the antenna through or adjacent to the foundation.

Note that contributions from the foundation at the antenna stations shall be taken into account in the performance of the antenna and included in the error budgets to demonstrate compliance with the specifications. The antenna designer must ensure that the antenna in conjunction with the foundation provides the performance required by his/her error budget.

The minimum stiffness and load capability of the foundation shall be defined in the ICD. The finite stiffness of the combined soil and foundation shall be included in the dynamic analysis of the antenna.

5.2 Interface to the Electrical Infrastructure

Electrical power will be provided to the antenna through a vault adjacent to or integrated into the antenna foundation. Most locations are expected to be connected to the commercial power grid, but some remote sites may use locally generated power. For the preliminary design, it should be assumed that three-phase, 208V, 60 Hz power will be provided at this interface.

Loads shall be protected from brown-out conditions where one or two phases of the distribution system are lost. Any shunt trip device shall be remotely resettable, and shall have a programmable automatic reset sequence.

The ICD should describe both the mechanical and electrical specifications of the electrical interfaces. Circuit sizing and load estimates should include allocations for NRAO-supplied systems housed within the antenna, defined in Sections 5.3 and 5.6. NRAO will provide load estimates for NRAO-supplied equipment.

5.3 Interface to the Fiber Optic Transmission System

A number of fibers will be distributed to each antenna for monitor and control, data transmission, and time and frequency distribution. The fiber optic cables will be physically routed through a vault adjacent to or integrated into the antenna foundation and should terminate at a splice box within the base electronics enclosure. The conduit or cable wrap may need to be thermally insulated or regulated.

The ICD should describe the mechanical specifications of the fiber optic interface. Note that the antenna has no direct optical connection to the Fiber Optic Transmission System. The communications interface to the antenna shall be considered part of the monitor and control system interface.

5.4 Interface to Other External Cables and Piping

HVAC and cryogenic equipment may be located on or adjacent to the antenna. Other calibration equipment may also be located in close proximity. The interfaces to all other external systems (excluding the fiber optic transmission system and electrical infrastructure) will be described in this ICD.

5.5 Interface to the Receiver Enclosure/Front End Electronics

The receiver enclosure will house the complement of feeds, cryogenic receivers and ancillary equipment necessary for signal recovery at the secondary focus of the antenna. These components will be collectively referred to as the antenna Front End electronics. The Front End electronics will be connected to the antenna back-end electronics, located in the pedestal room.

Note that the receiver selection mechanism (indexer) and focus adjustment mechanism are the responsibility of the antenna designer. It is expected that a two-axis stage, providing adjustment in the Z_F and Y_F axes (see coordinate system in Section 12.2.4), will be required at a minimum. Adjustment in the X_F range may be necessary depending on the degree of gravitational deformation.

The range of adjustment required in each axis is TBD, as it depends on antenna parameters as well as the Front End electronics. Adjustment ranges of $Z_F \geq 20$ mm (focus) and $Y_F \geq 1000$ mm (translation for band selection) are expected given the current Front End design. Antenna-based contributions (thermal, gravitational deformation, etc.) should be added to these allocations. In terms of speed, the Y_F translation rate is most important. It should traverse its range of motion in 20 seconds or less (allowing for typical band switching in a 10-second period).

The receiver enclosure, an NRAO responsibility, will be a shielded enclosure constituted of a durable continuous metallic surface. Durable RFI shielding will be provided on the access panels and on all other penetrations and discontinuities (seams, apertures, vents, cable and pipe penetrations, screws, etc.). The mounting method between the enclosure and two-axis stage shall ensure proper grounding.

The ICD should define the masses and volumes of the Front End electronics. The requirements in terms of mechanical positioning and stability, electrical loads, and environmental control shall be included. Requirements for personnel access for maintenance shall also be considered.

5.6 Interface to the Back End Electronics

The Base electronics enclosure shall house the antenna Back End electronics, which provide local time and frequency references, and a digital Back End that formats the signal collected by the Front End for distribution back to the central correlator. It also provides an interface to the Monitor and Control system, described in Section 5.9. The nature of the enclosure and its interface will be dependent on the mount design. NRAO will supply volumes, mass, and other interface requirements.

5.7 Interface to Internal Cables and Piping

Fiber optic cables, multi-conductor electrical cables, cryogenic piping and other cooling system piping will distribute signals and fluids to customer-supplied equipment in the base electronics enclosure, receiver enclosure and cryogenic platform. While the cables and piping are supplied by other systems, the antenna must provide suitable routing spaces and wrap protection.

The ICD will describe the point-to-point connections, cable cross sections, bend radii, and other mechanical parameters necessary for internal cable and piping distribution.

Cable wraps shall be provided in azimuth and elevation that will accommodate all antenna cables as well as interfacing system cables and hoses. The cable wraps shall permit full angular rotation of the antenna. The cable wraps shall be such that cables are neither excessively stressed by twisting or bending, nor damaged by pulling over edges of a fixed structure. Specific requirements on bending radii shall be documented in the ICD. The minimum bending radius of the elevation and azimuth cable wrap shall be in any case larger than 200 mm.

Possible limitations in amount of torsion which can be sustained by cables and hoses (e.g., helium lines) shall also be considered. The cable wrap design shall be optimized for durability and reliability taking into account the lifetime requirements of Section 4.14.7 and 4.18.

5.8 Interface to the Cryogenic System

Space must be available for a cryogenic compressor on the antenna yoke, below the elevation axis but above the azimuth axis. A combination of rigid and flex lines will provide the supply and return lines between the compressor and the refrigerators within the receiver enclosure. The ICD should describe the point-to-point connections, bend radii, platform size, compressor mass and volume, ancillary connections, and access requirements for maintenance.

5.9 Interface to the Monitor and Control System

The Antenna Control Unit (ACU) will govern the local control of the antenna, processing higher-level commands into lower level commands suitable for each axis drive and ancillary mechanisms. Pointing trajectories will be supplied to the antenna through a series of time-tagged azimuths and elevations. Suitable interpolation and damping shall be provided in the servo control system to achieve required tracking accuracy.

The vendor-supplied antenna control unit shall operate in three pointing modes:

- Raw or Encoder Mode: The servo system shall be controlled such that the encoder values match the commanded values.
- Metrology Mode: The servo system shall apply any corrections to the input coordinates based on the values of metrology sensors located in the antenna system.
- Active Mode: The servo system may include a pointing model containing the seven classic terms (additional terms may be added through mutual agreement). The antenna must be able to pass a site acceptance test (SAT) based on the application of this pointing model.

The focus indexer/positioner shall follow a similar design philosophy with three modes of operation (encoder, metrology correction only, full model). Philosophically, any terms or operations which require modelling of the antenna structure should be corrected for in the metrology mode. Terms that only depend on sky position can be accommodated in the pointing or focus model.

In all cases, no action or inaction of the monitor and control system can cause incorrect or dangerous conditions in the covered hardware.

In addition, the ACU shall provide monitor data defining the current condition of key monitor points that describe the overall health and status of the antenna. The physical interface between the ACU and M&C system shall be multimode fiber using TCP/IP over Ethernet.

6 Subsystem Requirements

Derivation of subsystem requirements shall be included as part of the antenna conceptual design effort and updated throughout the design. Post CDR/FDR, subsystem requirements shall only be updated through formal project change control processes that will include the designer, manufacturer, and NRAO.

The expected main elements of the antenna include, at a minimum:

- Antenna Mount
- Reflector Panels
- Panel Adjusters
- Backup Structure
- Subreflector
- Subreflector Support Arm/Structure
- Receiver Selection Mechanism
- Cables & Cable Wraps
- Antenna Control System

7 Safety

7.1 General

To achieve protection against all possible hazards, the antenna shall be considered a piece of machinery, and its design and construction shall comply with the requirements set forth in this section.

Parameter	Req. #	Value	Traceability
Code Compliance	ANT7001	The design shall comply with all relevant federal, State of New Mexico, and State of Texas building codes.	
Safety of Personnel	ANT7002	The design shall allow the Observatory to comply with all relevant federal and state occupational health and safety regulations for personnel servicing the antenna.	

7.2 Hazard Analysis

7.2.1 Hazard Severity

Hazard severity categories are defined (Table 2) to provide a qualitative measure of the mishap.

Category	Description	Definition
I	Catastrophic	Death, severe injury, or system loss
II	Critical	Major injury, major occupational illness, major system damage
III	Marginal	Minor injury, minor occupational illness, minor system damage
IV	Negligible	Less than minor injury/occupational illness and minor system damage

Table 2 - Hazard severity categories.

System loss: the antenna and/or the housed systems cannot be recovered at reasonable costs.

Major system damage: the antenna and/or the housed systems can be recovered but extensive industrial support is necessary and/or the system is out of operation for more than three weeks.

Minor system damage: the antenna and/or the housed systems can be repaired by ngVLA without any support from industry and/or the system is less than three weeks out of operation.

7.2.2 Hazard Probability

Table 3 shows the probability classification of hazards occurring during the 20 years of expected antenna lifetime.

Level	Definition	Description
A	Frequent	Likely to occur frequently (typically once a year)
B	Probable	Will occur several times (6 to 10 times in 20 years)
C	Occasional	Likely to occur (2 to 5 times in 20 years)
D	Remote	Unlikely but possible to occur (typically once in 20 years)
E	Improbable	So unlikely that occurrence can be assumed not to be experienced (>20 years)

Table 3 - Probability levels.

7.2.3 Hazard Risk Acceptability Matrix

The following two matrices (Table 4 and Table 5) define the degree of acceptability of the various hazard categories:

Frequency of Occurrence	I Catastrophic	II Critical	III Marginal	IV Negligible
Frequent	I A	II A	III A	IV A
Probable	I B	II B	III B	IV B
Occasional	I C	II C	III C	IV C
Remote	I D	II D	III D	IV D
Improbable	I E	II E	III E	IV E

Table 4 - Hazard classification matrix.

Hazard risk index	Assessment criteria
I A to I D, II A, B; III A	Unacceptable
II C, D; III B; IV A	Undesirable (ngVLA decision required)
I E; II E; III C; IV B	Acceptable with review by ngVLA
III D, E; IV C, IV D, IV E	Acceptable without review by ngVLA

Table 5 - Hazard acceptability matrix.

7.2.4 Requirements on Operational Hazards

None of the items in the following list (not meant to be exhaustive) shall lead to an unacceptable or undesirable hazard risk for the antenna or human beings:

- One or two independent operator errors;
- One operator error plus one hardware failure;
- One or two hardware failures;
- One or two software failures;
- Partial or complete loss of energy, reference signals, or control communications to the antenna;
- Emergency braking of the antenna;
- Earthquakes happening for whatever position of the antenna; or
- Wind loads.

7.2.5 Hazard Analysis

The purpose of a Hazard Analysis is to identify safety critical areas, evaluate hazards, and identify the safety measurement to be used. A Hazard Analysis shall list all possible hazards, including an assessment of their severity and probability, and shall show that safety considerations are included in all stages of the project including assembly, training, maintenance, etc.

Safety provisions and alternatives needed to eliminate hazards or reduce their associated risk to a level acceptable to ngVLA shall be described. As the design of the system progresses, the Hazard Analysis shall be kept up to date reflecting new considerations, data, and/or information. The following issues shall be considered:

1. Safety-related interface considerations among various system elements, e.g., material compatibility, electromagnetic interference, inadvertent activation, fire initiation and propagation, hardware and software controls, etc.
2. Environmental hazards including handling and operating environments.
3. All hazards related to operating, testing, maintenance and emergency procedures.
4. Any other identified hazards.
5. A description of any risk reduction methods employed for each hazard like safety-related equipment, safeguards, interlocks, system redundancy, hardware or software fail-safe design considerations, etc., taking into account the design requirements noted in Section 4.17.

7.3 Safety Design Requirements

7.3.1 Fire Safety

Smoke detectors are required in any equipment compartment and shall be interlocked to shunt trip all electric power in the antenna. When smoke is detected the detector shall immediately close a contact used by ngVLA for a remote fire alarm and will energize a local audible alarm. The shunt trip of all power shall occur five seconds after smoke detection. Emergency power for the smoke detectors and local alarm shall utilize “Gel-cells” with a minimal reserve of six hours and less than a 24-hour recharge cycle.

7.3.2 Mechanical Safety

For each component under design, all the possible criteria of mechanical failure relevant to the component under examination shall be considered (strength, fatigue, buckling, etc.). Unless otherwise required by the Standards applicable to this specification or by any applicable standard the minimum safety margins to be used are those provided herein.

- A minimum stress safety factor of 1.5 with respect to the yield point shall be used in the design of all mechanical components which in case of a failure lead to an unacceptable or undesirable hazard risk.
- This stress safety factor shall be reduced to 1.1 in case of survival and accidental conditions.
- For metallic materials where the relevant failure criteria is not linked to plasticity (e.g., fatigue), an equivalent stress safety factor of 1.5 shall be used in the design of all those mechanical components, which in case of a failure lead to an unacceptable or undesirable hazard risk.
- For CFRP parts, the equivalent stress safety factor shall be applied to the relevant failure mode to be considered for the part under examination. All relevant failure criteria shall be considered (delamination, fatigue, cracking, gluing failure, etc.). An equivalent stress safety factor of 1.5 shall be used in the design of all those components, which in case of a failure lead to an unacceptable or undesirable hazard risk. This value applies also in case of accidental and survival conditions.

7.3.3 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard. The Antenna as a whole shall be in conformity with either IEC 60204-1:2016 [AD15] or NFPA 79 [AD14] and with IEC 61140 [AD13].

Electrical installations and equipment shall be specifically built and/or derated in order to safely perform their intended functions under the applicable environmental conditions. Insulation shall be coordinated in conformity with IEC 60664 [AD17] while taking into account the altitude of up to 2500 m above sea level.

The antenna shall be designed, manufactured and erected to exhibit functional safety with regard to electromagnetic phenomena. Influence onto the antenna safety of sources of electromagnetic disturbances internal to the antenna itself shall be considered in relation with the antenna design.

7.3.4 Hydraulic & Pneumatic Safety

Any hydraulic or pneumatic systems shall be designed in accordance with ISO 4413 [AD18].

7.3.5 Handling, Transport, and Storage Safety

The design of the antenna shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation.

7.3.6 Toxic Substances

No use of toxic substance (asbestos, formaldehyde, lead, etc.) and of their derivatives shall be permitted in the antenna. Insulation materials and paints specifications shall be reviewed by ngVLA.

7.3.7 Confined Space

Considerations of confined space in the sense of OSHA Standards 29 CFR Part 1910 and 1926 shall be taken into account in the design where applicable (e.g., base, yoke, etc.).

7.4 Physical Security

Reasonable protection against unauthorized personnel access and theft shall be provided in the antenna by means of lockable and caged access ladder, locks on cabinets, doors and similar design provisions. Sensors shall be installed to monitor the condition “door open” and to relay the information to the ACU in order to detect unauthorized intrusion.

8 Requirements for Design

8.1 Analyses and Design Requirements

8.1.1 Finite Element Structural Analyses

All the Finite Element Analyses (FEA) necessary for the verification of the performance of the antenna must be performed with an internationally recognized numerical code. The structural models used shall be adapted to the particular analysis for which they are going to be used and shall be accurate enough to provide a good description of the behavior of the structure under examination in terms of displacements, stress and frequencies.

The analysis error due to mesh discretization shall be $\leq$10% in terms of finite element internal criteria like the "Percentage error in energy norm." Alternatively, this type of error can be evaluated by mesh refining. The analyses which are required to be performed are listed and specified below. In case during the design phase it appears that other analyses are necessary, the list below shall not be considered exhaustive. The FEA analysis must also support the EM Analysis (by others). Relevant scenarios are described in Table 6 and Table 7 of Section 8.1.4.

8.1.1.1 Static Analysis

Static analyses shall be used in the calculation of the effect of:

- Gravity loads (stress and deflection)
- Sudden braking (stresses)
- Thermal deformation (input loads derived from the thermal analysis)
- Wind under precision and normal operating conditions (deflections)
- Wind under survival conditions (stresses).

8.1.1.2 Modal Analysis

A modal analysis shall be performed in order to obtain accurate information concerning the Eigen frequencies and the Eigen modes of the antenna, when integrated in the antenna station, i.e. the combined stiffness of the soil and foundation of the antenna stations shall be adequately represented in the dynamic FE Model. The number of degrees of freedom shall be such as to have a good representation of the frequency range required. Care must be exerted to correctly represent the boundary conditions of the system under examination.

8.1.1.3 Seismic Analysis

The structural model used for the seismic analysis shall adequately represent the distribution of stiffness and mass so that all significant deformation shapes and inertia forces are properly accounted for under the seismic action considered. Non-structural elements,[1] which may influence the response of the main resisting structural system, shall also be accounted for. The response of all vibration modes contributing significantly to the global response shall be taken into account. This may be demonstrated by either of the following:

- the sum of the effective modal masses for the modes, taking into account at least 80% of the total mass of the structure, or
- all frequencies below 50 Hz are taken into account.

[1] An architectural, mechanical or electrical element, system or component which, whether due to lack of strength or the way it is connected to the structure, is not considered in the seismic design as load carrying element.

The above conditions have to be verified for each spatial direction. The seismic analysis shall be based on the modal response spectrum technique, using a linear-elastic model of the structure. It shall be assumed that the structural damping is 1.5 % of critical damping.

The Square Root Sum of the Square method (SRSS) may be used in order to combine the contribution of the various modal responses. The three spatial components of the response may also be combined with the SRSS method. Alternatively, the designer may propose combination rules for the modal and spatial components consistent with a relevant international earthquake resistance standard.

8.1.1.4 Wind Analysis

The force distribution on the antenna caused by precision and normal operating conditions can be derived by either of the following:

- Adequate Computational Fluid Dynamic (CFD) analysis, or
- extrapolated wind tunnel measurement results of similar structure.

The force distribution caused by survival wind loads may be derived from a CFD analysis. These forces may be applied as quasi-static.

8.1.2 Thermal Modeling and Analysis

A thermal model of the antenna shall be used to compute the temperature distribution in the antenna during daytime Precision and Normal operating conditions. The model shall also be used to determine the equilibration period duration from sunset. The thermal model shall be able to simulate adequately the effects of thermal conduction, convection and radiation (solar flux). The calculated temperature distribution shall be applied as thermal load to the structural finite element model to predict the thermal error contribution to the pointing and surface error budgets.

8.1.3 Stress Analysis and Load Combination

A detailed stress analysis of the Antenna shall be performed. The stress analysis shall combine the individual design loads and conditions specified under Section 8.1.1.1. In general, the load combinations to be verified are given herein, whereby for specific components different load combinations may apply.

Load Combination: Operational Condition
Gravity + Thermal (secondary) + Wind (10 m/sec)
Gravity + Thermal (primary)+ Wind (7 m/sec) + Fast Switching
Load Combination: Accidental Condition
Gravity + Thermal (secondary) + Wind (20 m/sec) + Emergency braking
Load Combination: Survival Condition
Gravity + Wind (50 m/sec)
Gravity + Thermal (–30 °C) + Wind (30 m/sec)
Gravity + Wind (30 m/sec) + Icing + Snow
Gravity + Seismic + Wind (20 m/s)

8.1.4 Antenna EM Analysis Support

Surface deformations shall be computed for the loads shown in Table 6 and Table 7. The set of load cases is extensive but intended to provide a full representation of antenna performance in the precision operating environment. The results shall be provided to NRAO for electromagnetic performance analysis (by others).

Load Case	Name	Az. angle (deg)	El. angle (deg)
L.01	Gravity	0	15
L.02	Gravity	0	30
L.03	Gravity	0	60
L.05	Gravity	0	90
L.07	Wind 5 m/s	0	15
L.08	Wind 5 m/s	0	30
L.09	Wind 5 m/s	0	60
L.10	Wind 5 m/s	0	90
L.11	Wind 5 m/s	45	30
L.12	Wind 5 m/s	90	30
L.13	Wind 5 m/s	135	30
L.14	Wind 5 m/s	180	15
L.16	Wind 5 m/s	180	90
L.17	Thermal ΔTu= 10 °C (Uniform over structure)		
L.18	Thermal gradient ΔTx= 3.6 °C along X_{MR} axis		
L.19	Thermal gradient ΔTy= 3.6 °C along Y_{MR} axis		
L.20	Thermal gradient ΔTz= 3.6 °C along Z_{MR} axis		

Table 6 - Load cases for antenna efficiency analysis.

Combined load cases are shown in Table 7. Combined cases may be calculated from results of the individual load case analyses. Load combinations L.C.01 through L.C.10 are representative of the precision operating conditions described in Section 4.14.1, while L.C.11 through L.C14 pertain to the normal operating conditions of Section 4.14.2. These cases are not fully defined, as they depend on the results of the analysis of L.C.01 through L.C.10. Only the worst-case gravity and wind scenarios are subject to combination with the thermal gradients in order to limit the number of load permutations to be analyzed.

Load Case Combination	Name	Note
L.C. 01	L.01+L.07	Precision Operating Conditions
L.C. 02	L.02+L.08	Precision Operating Conditions
L.C. 03	L.03+L.09	Precision Operating Conditions
L.C. 04	L.05+L.10	Precision Operating Conditions
L.C. 05	L.01+L.11	Precision Operating Conditions
L.C. 06	L.01+L.12	Precision Operating Conditions
L.C. 08	L.01+L.13	Precision Operating Conditions
L.C. 09	L.01+L.14	Precision Operating Conditions
L.C. 10	L.05+L.16	Precision Operating Conditions
L.C. 11	L. <worst gravity>+L.<worst wind>+ L.17	Normal Operating Conditions
L.C. 12	L. <worst gravity>+L.<worst wind>+ L.18	Normal Operating Conditions
L.C. 13	L. <worst gravity>+L.<worst wind>+ L.19	Normal Operating Conditions
L.C. 14	L. <worst gravity>+L.<worst wind>+ L.20	Normal Operating Conditions

Table 7 - Combined load cases for antenna efficiency analysis.

8.1.5 Control loop design and analysis

For each function to be controlled, the stability margins shall be computed. Dynamic simulations of the control loops shall be performed, including nonlinear effects like friction, stick-slip, sensor noise, etc.

8.1.6 Reliability, Availability, Maintainability Analysis

A Reliability, Availability, Maintainability analysis shall be performed to locate weak design points and determine whether the design meets the Maintenance and Reliability requirements. ngVLA suggests to apply the Parts Count Method for predicting the reliability of the system as described in the MIL-HDBK-217F, but the designer may propose to use other methods. For non-electronic parts, the values of NPRD-95 [AD22] or data from manufacturers or other databases may be used.

Another, but more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in MIL-HDBK-217F. This may be used if the result of the Parts Count Method does not comply with the Maintenance and Reliability requirements.

Some ngVLA antennas will be operated at an elevation up to 2500m above sea level, where temperature and pressure might decrease the MTBF relative to that at low elevations. These conditions shall be taken into specific account in the reliability prediction by using the environmental factor given in MIL-HDBK-217F. The analysis shall result in estimates of the Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR), assuming that scheduled preventive maintenance is performed.

8.2 Electromagnetic Compatibility Requirements

The ngVLA antenna element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility). Preventing electromagnetic interference (EMI) between the antenna and other subsystems (inter-system electromagnetic compatibility) is also critical.

The following requirements shall be fulfilled as a minimum to achieve both intra- and inter-system EMC, but the antenna designer may propose alternatives if quantitative evidence is provided that they are at least as effective as those specified. Shielding requirements may be computed as described under Radio Frequency Interference Generation (Section 4.13).

- Control circuits, drive motor amplifiers, and switching devices shall be designed and constructed taking into account requirements concerning radiated and conducted electromagnetic energy. In particular, all motor leads, both power and control, shall be filtered.
- All relay contacts and actuators shall be properly bypassed with snubber circuits, shielded, and/or filtered.
- All amplifiers and oscillators shall be mounted in shielded enclosures that provide effective shielding of radio frequency energy.
- Silicon-controlled rectifier switching devices shall not be used unless phase-controlled and zero-current cross switching techniques are used.
- No gaseous discharge devices, except noise sources for test, shall be employed.
- Means shall be employed to reduce static electricity and the consequent radio frequency noise generated in any rotating machinery.
- All displays (LCD, plasma, LED, CRT) shall have an RFI shield in front to avoid radiated RFI. This requirement may be waived if the screen is powered off during typical operation and is used for maintenance only. It must be possible to monitor and turn off such emitting devices remotely.
- All digital equipment, whether a simple logic circuit, embedded CPU, or rack-mounted PC, shall be shielded and have its AC power line and communication line(s) filtered at the chassis.

The frequency range to be covered by these design measures for radiated radio-frequency interference (RFI) suppression shall extend from 50 MHz up to 12 GHz. Demonstration of EMC above 12 GHz is not required because mitigation at 12 GHz and below is expected to be adequate at higher frequencies.

8.3 *Materials, Parts and Processes*

8.3.1 Type of Steel

The steel used in the antenna mount shall be a carbon or a low-alloy steel. The selection of the steel shall take into account the low temperature to be expected during antenna operation and stow, under the point of view of embrittlement. In particular, the nil-ductility transition temperature of the selected steel shall not exceed –45°C. The nil-ductility transition temperature is that at which the material starts to exhibit cleavage fracture with very little evidence of notch ductility.

When necessary (e.g., gears and pinions, if applicable) materials with suitable hardness or surface hardened shall be used, in order to ensure the life of the system.

8.3.2 Stress relieving

All structural welded parts shall be stress-relieved by means of an appropriate method to reduce stresses and ensure dimensional stability (unless proven by the antenna designer to be unnecessary).

8.3.3 CFRP

If Carbon Fiber Reinforced Plastic (CFRP) is used, the material and fabrication processes shall be selected, examined, and if necessary qualified with respect to strength, fatigue, and life. All CFRP structures shall be protected against solar radiation and humidity with suitable paints and or sunshades.

8.3.4 Fasteners

All fasteners shall be metric except those on off-the-shelf units. The use of standard metric cross-sections for construction materials is preferred but not required.

8.3.5 Paints

To limit the effect of solar heating and associated differential expansion of structural members and to protect the structure against atmospheric corrosion, the antenna structure shall be painted with white solar reflecting paint. The paint shall be chosen to last at least 10 years without repainting.

8.3.6 Surface Treatment

Unpainted surfaces shall be treated against corrosion.

8.3.7 Thermal Insulation

Thermal insulation when used in an exterior application by the antenna designer shall be protected with a metal cover.

8.3.8 Rodent Protection

Antennas shall be designed to prevent rodent damage. At a minimum, this may involve protecting all cables with flexible or rigid conduit or equivalent. Any penetrations within enclosures and raceways shall mitigate the risk of rodent damage.

8.3.9 Name Plates and Product Marking

As a general rule, the main parts and all exchangeable units shall be equipped with nameplates which are visible after installation of the part/unit and which contain the following information:

- Part/unit name
- Drawing number including revision
- Serial number
- Manufacturing month and year
- Name of manufacturer

Alternatively, a system of marking based on barcodes or similar system may be used upon approval by ngVLA. For Line Replaceable Units (LRUs; see Section 12.3), it is highly desirable that the LRU serial number be ascertainable over the monitor and control interface (see Section 5.9).

8.3.10 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled. Electrical cabinets, switch panels, UPS, and all electrical equipment that can be manually operated or is relevant for safety shall be labeled in English and Spanish.

9 Documentation Requirements

9.1 Technical Documentation

All documentation related to the antenna shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units.
- Layouts of electronic circuits and printed circuit boards shall also be provided in electronically readable form. The ngVLA preferred formats are Altium Designer files for electronic circuit diagrams and printed circuit board layouts.
- The electronic document formats are Microsoft Word and Adobe PDF.
- The preferred CADsystem used is AutoDesk Inventor and/or AutoCAD.
- The preferred FEA modeling software is Siemens FeMAP NASTRAN.

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

9.2 Software and Software Documentation

The ACU software and any other specially developed software (SW), are deliverables. The SW shall be delivered in source and object form, together with all procedures and tests necessary for compilation, installation, testing, upgrades and maintenance.

- Software must be tagged with suitable version numbers that allow identification (also online remotely) of a Release.
- User manuals of software developed under this specification and of any other commercial software used (controllers embedded software, special tools, etc.) shall be provided.
- Software maintenance and installation upgrade documentation shall be provided.
- Full Test and Acceptance procedures shall be documented.

10 Verification and Quality Assurance

The design may be verified to meet the requirements by design (D), analysis (A), inspection (I), a factory acceptance test (FAT), or a site acceptance test (SAT). The definitions of each are given below.

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

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

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

Verification by Factory Acceptance Test: The compliance of the developed item/assembly/unit with the specified performance shall be demonstrated by tests. A FAT is performed w/o integration with interfacing systems.

Verification by Site Acceptance Test: The compliance of the developed item/assembly/unit with the specified performance shall be demonstrated by tests. SAT is performed on-site with the equipment as installed.

Multiple verification methods are allowed.

Table 8 summarizes the expected verification method for each requirement. This degree of verification applies to the prototype antenna(s) only. Separate verification procedures should be developed as part of the verification plan to ensure all production antennas conform to the design specification (mfg. to print).

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
ANT0101	Upper Operating Frequency	*				
ANT0102	Lower Operating Frequency	*				
ANT0103	Optimized Operating Frequencies	*				
ANT0201	Optical Configuration Type	*				
ANT0202	Primary Aperture Diameter and Shape	*				
ANT0203	Sub-Reflector Aperture Diameter	*				
ANT0204	Secondary Angle of Illumination	*				
ANT0205	Reflector Offset	*				
ANT0206	Focal Ratio, Primary	*				
ANT0207	Cross Polarization	*	*			
ANT0208	Reflector Shapes	*				
ANT0209	Secondary Reflector Extension	*		*		
ANT0210	Main Reflector Extensions	*				
ANT0211	Mounting Configuration	*				
ANT0301	Minimum Spacing	*	*			
ANT0302	Height	*		*		
ANT0303	Mass	*				
ANT0401	Number of Antennas	*				
ANT0501	Surface Accuracy, Precision	*	*		*	*
ANT0502	Surface Accuracy, Normal	*	*		*	*
ANT0503	Reflector Construction	*		*		
ANT0611	Non-Repeatable Pointing Error, Precision		*			*

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
ANT0612	Referenced Pointing Error, Precision		*			*
ANT0621	Non-Repeatable Pointing Error, Normal		*			*
ANT0622	Referenced Pointing Error, Normal		*			*
ANT0701	Focus Stability, Precision		*			*
ANT0702	Focus Stability, Normal		*			*
ANT0801	Azimuth Tracking Range	*		*		
ANT0802	Elevation Tracking Range	*		*		
ANT0803	Elevation Movement Range	*				
ANT0901	Slew: Azimuth	*	*			*
ANT0902	Slew: Elevation	*	*			*
ANT0903	Acceleration: Azimuth	*	*			*
ANT0904	Acceleration: Elevation	*	*			*
ANT0905	Slew + Settle Time		*			*
ANT0906	Tracking: Azimuth		*			*
ANT0907	Tracking: Elevation		*			*
ANT1001	Stow Position - Survival	*		*		
ANT1002	Stow Position - Maintenance	*		*		
ANT1101	Resistive Losses	*				*
ANT1201	Solar Observations	*	*			*
ANT1301	Spurious Signal Level	*	*		*	
ANT1411	Precision Env.: Solar Thermal Load		*			
ANT1412	Precision Env.: Wind		*			
ANT1413	Precision Env.: Temperature		*			
ANT1414	Precision Env.: Temp. Rate of Change		*			
ANT1415	Precision Env.: Precipitation		*			
ANT1421	Normal Env.: Solar Thermal Load		*			
ANT1422	Normal Env.: Wind		*			
ANT1423	Normal Env.: Temperature		*			
ANT1424	Normal Env.: Temp. Rate of Change		*			
ANT1425	Normal Env.: Precipitation		*			
ANT1430	Ops. Limit: Solar Thermal Load		*			
ANT1431	Ops. Limit: Wind		*			
ANT1432	Ops. Limit: Temperature		*			
ANT1433	Ops. Limit: Precipitation	*	*			
ANT1434	Ops. Limit: Ice		*			
ANT1441	Survival: Wind		*			
ANT1442	Survival: Temperature		*			
ANT1443	Survival: Radial Ice		*			
ANT1444	Survival: Rain Rate		*		*	
ANT1445	Survival: Snow Load - Antenna		*			
ANT1446	Survival: Hail Stones		*			
ANT1447	Antenna Orientation	*				
ANT1451	Lightning Protection: Structure	*	*			
ANT1452	Lightning Protection: Electronics Systems	*	*			
ANT1453	Lightning Protection: Personnel	*	*			
ANT1461	Seismic Protection		*			

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
ANT1471	Site Elevation		*			
ANT1481	Wind Vibration		*			
ANT1501	Preventive Maintenance Cycle	*	*			
ANT1502	Preventive Maintenance Effort	*	*			
ANT1503	Mean Time Between Failure		*			
ANT1601	Antenna Control Unit (ACU)	*		*		
ANT1602	Servo Loops		*			
ANT1603	Self-Monitoring	*		*		
ANT1604	Weather Monitoring	*		*		
ANT1605	Network Hardening/Authentication	*				
ANT1606	Remote Reset	*				
ANT1701	Software Limits	*			*	
ANT1702	Hardware Limits	*			*	
ANT1703	Hard Stops	*				
ANT1704	Safety Lock-Out	*		*		
ANT1705	Fire Alarm	*		*		
ANT1706	Fail Safe Brakes	*				
ANT1801	Design Life	*	*			
ANT1802	Lifecycle Optimization		*			
ANT1803	Country of Origin	*		*		
ANT7001	Code Compliance	*				
ANT7002	Safety of Personnel	*	*			

Table 8 - Expected requirements verification method.

11 Key Performance Parameters

This section provides Key Performance Parameters that should be estimated by the designer and monitored by NRAO throughout the design phase of the project. These parameters have a large influence on the eventual effectiveness of the facility, and are useful high-level metrics for trade-off decisions.

These parameters are of higher importance to NRAO. Improved performance above the requirement is desirable on these parameters. The impact on system-level performance is often discussed in the narrative in Section 4.

NRAO's expectation is that the specified technical requirements will not push technical boundaries. Rather, the key challenge of this antenna design is to deliver a design that can be manufactured in volume and delivered affordably. A second challenge is reducing the maintenance burden and total lifecycle cost.

Given these expectations, the technical requirements are generally specified as minimum values. The goal is to give the designer some latitude in optimization for a balanced design. Understanding the anticipated performance of the antenna (not just its specified minimum) on these parameters is of value for system-level analysis and performance estimation.

These parameters may also be useful for determining the relative priority of the requirements documented in Section 4 and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

The Key Performance Parameters that have been identified for monitoring are described in Table 9. Note that the order in the table reflects the order in the document, and is not indicative of relative importance or priority.

Key Performance Parameter	Req. #
Minimum Spacing	ANT0301
Surface Accuracy, Precision Environment	ANT0501
Surface Accuracy, Normal Environment	ANT0502
Non-Repeatable Pointing Error, Precision Environment	ANT0611
Referenced Pointing Error, Precision Environment	ANT0612
Non-Repeatable Pointing Error, Normal Environment	ANT0621
Referenced Pointing Error, Normal Environment	ANT0622
Elevation Range (Lower Elevation Limit)	ANT0802
Slew: Azimuth	ANT0901
Slew: Elevation	ANT0902
Acceleration: Azimuth	ANT0903
Acceleration: Elevation	ANT0904
Slew + Settling Time	ANT0905
Tracking: Azimuth	ANT0906
Tracking: Elevation	ANT0907
Preventive Maintenance Cycle	ANT1501
Preventive Maintenance Effort	ANT1502
Mean Time Between Failures	ANT1503
Design Life	ANT1801

Table 9 - Key performance parameters for monitoring during design.

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
ACU	Antenna Control Unit
AD	Applicable Document
ATF	Antenna Test Facility (at the VLA Site)
CDR	Critical Design Review
CoDR	Conceptual Design Review
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Plastic
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
EIRP	Equivalent Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
EMP	Electro-Magnetic Pulse
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FWHM	Full Width Half Max (of Primary Beam Power)
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LO	Local Oscillator
LRU	Line Replaceable Unit
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SAT	Site Acceptance Test
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

12.2 Coordinate System

12.2.1 Antenna Pad Coordinate System

The Antenna Pad Coordinate System (or Foundation Coordinate System) is indicated by O_p, X_p, Y_p, $Z_{p.}$ to denote the origin and three Cartesian coordinate vectors, as shown in Figure 2.

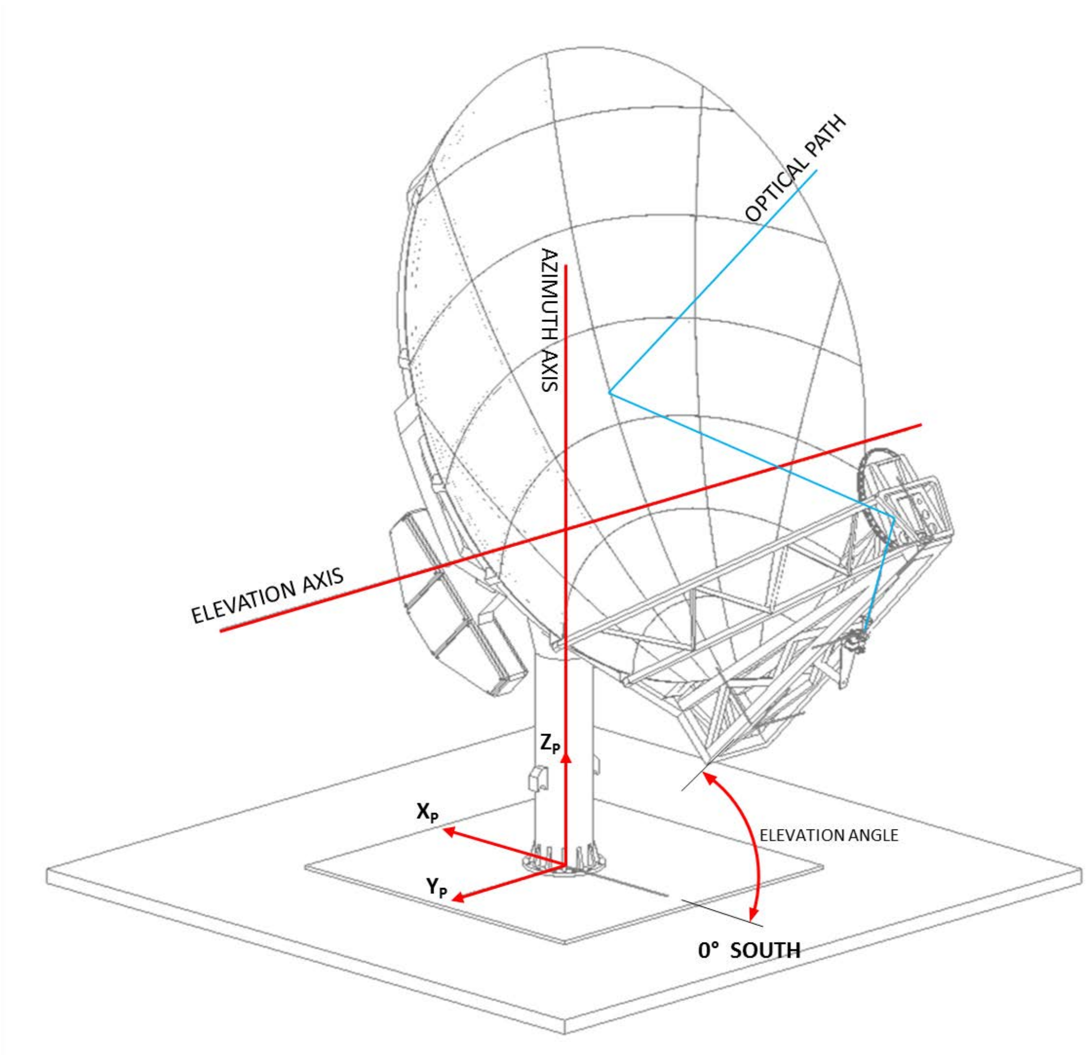

Figure 2 - Cartoon of the antenna pad coordinate system and major axes. Separate Cartesian reference frames define each mirror surface, the focus, and the pad respectively. Antenna design is diagrammatic only.

The Pad Coordinate system is based on the right-hand rule, with the Z_p corresponding to the local vertical, positive direction toward zenith, X_p axis pointing to the geographical North, and the Y_P axis pointing to geographical West. The origin of the system is in the plane of the embedded flanges at the antenna pad, at the nominal center of the as-built pad, as defined by the kinematic mount of the antenna.

12.2.2 Main Reflector (MR) Coordinate System

The MR coordinate system is a Cartesian coordinate system, based on the right hand rule, fixed to the focus of the reflector. This system of coordinates is indicated by O_{MR}, X_{MR}, Y_{MR} ,Z_{MR} as shown in Figure 3.

The X–Y plane is perpendicular to the antenna beam, with the X_{MR} axis perpendicular to the elevation axis, the Z_{MR} axis is parallel to the nominal boresight of the antenna, positive toward the source, and the Y_{MR} axis according to the right hand rule. As such, when the azimuth of the antenna is equal to zero, the Y_{MR} axis is parallel, to the Y_p axis.

12.2.3 Secondary Reflector (SR) Coordinate System

The SR coordinate system is a Cartesian coordinate system, based on the right hand rule, fixed to the focus of the main reflector ($O_{SR} = O_{MR}$). This system of coordinates is indicated by O_{SR}, X_{SR}, Y_{SR} ,Z_{SR} as shown in Figure 3.

The Y-axis is shared with the MR coordinate system. The X_{SR}-axis and Z_{SR}-axis are rotated from the MR axes by the tilt angle beta (β).

12.2.4 Focal Plane Coordinate system

The focal plane coordinate system is defined in Figure 3.

This coordinate system is also a Cartesian coordinate system, with coordinates indicated by F_0, X_F, Y_F, $Z_{F.}$

The position of the origin, F_0, is the nominal secondary focus of the antenna. Z_F is towards the projected midpoint of the secondary mirror as seen from O_F. The Y_F axis is parallel to Y_{MR} and Y_{SR}, and the X_F axis according to the right hand rule.

12.2.5 Azimuth of the Antenna

The Azimuth angle shall be zero when the antenna is rotated so that Y_{MR} is pointing toward West. The Azimuth angle origin is then counted from the negative X_P (South), positive direction when the antenna moves in the clockwise direction (Azimuth angle = 90 when Y_{MR} is pointing toward North).

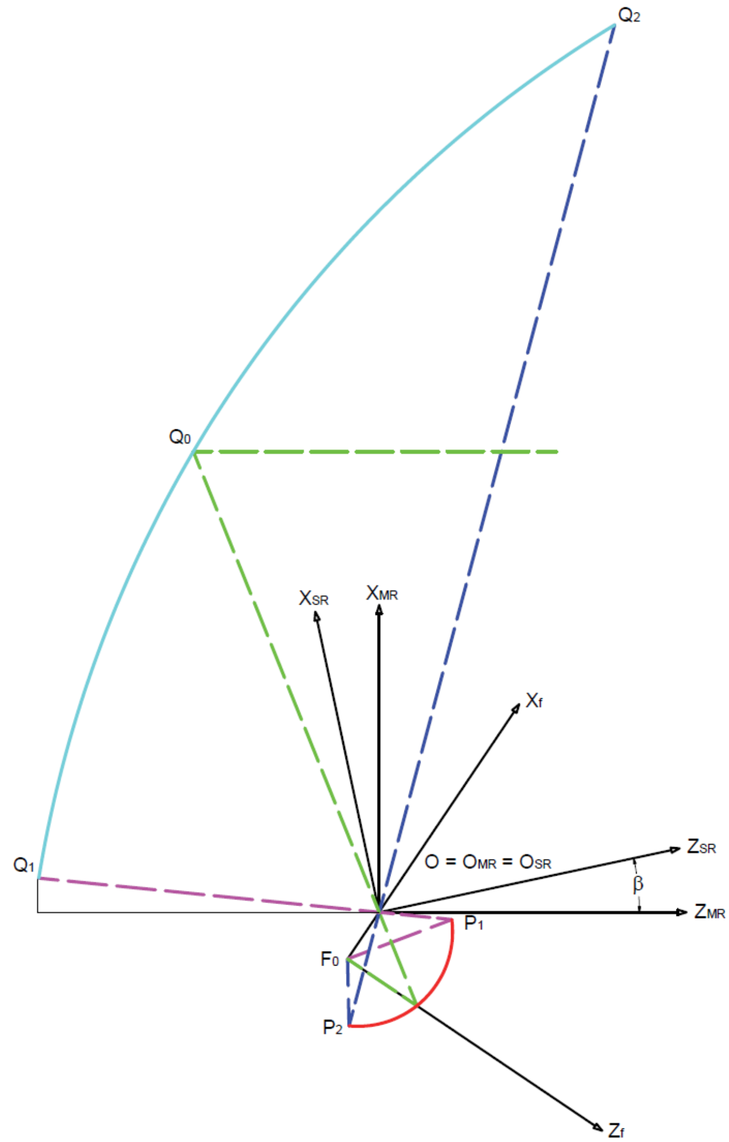

Figure 3 - Antenna optical coordinate system. Separate Cartesian reference frames define each reflector surface and the secondary focus.

12.2.6 Elevation of the Antenna

The Elevation shall be set to zero when the Z_{MR} axis is pointing to horizon and to +90 when the Z_{MR} axis is pointing toward zenith.

12.3 Maintenance Definitions

12.3.1 Maintenance Approach

Required maintenance tasks shall be minimized. Maintenance shall be mainly performed at assembly and subassembly level by exchange of Line Replaceable Units (LRUs). LRUs are defined as units which can be easily exchanged (without extensive calibration, of sufficient low mass and dimension for easiness of handling, etc.) by maintenance staff of technician level.

LRU exchange shall be possible by 2 trained people within 4 working hours on the installed antenna. It is desirable that LRU replacement be possible without a boom truck, basket or scissor lift, using only standard tools and special tools identified in the antenna maintenance manual. A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual. The following equipment shall be considered an LRU as a minimum:

- Subreflector mechanism (if provided)
- Elevation encoder(s)
- Azimuth encoder(s)
- Drive Motors
- Electronic cards and drives
- Stow pin assemblies (if provided)
- End stops
- Elevation cable wrap parts (excluding cables and cable installation)
- Locking pins
- Lightning arrestors
- Temperature sensors
- Anemometers
- Additional metrology sensors (if provided)
- Limit switches

Other LRUs shall be defined by the antenna designer, depending on the design. The LRUs will be maintained by the ngVLA project (with or without industrial support).

12.3.2 Periodic Preventive Maintenance

Preventive maintenance is performed at planned intervals in order to maintain the antenna operational and within its specified performance. This includes checking, greasing, substitution of consumables, visual inspection, etc. All maintenance operations shall be planned in a Programmed Check and Intervention List (PCIL) of the Maintenance Manual, which shall list the tools, the procedures and the time necessary for their execution and their periodicity.

The antenna design shall enable these maintenance activities to be performed with the antenna stowed in the "maintenance stow" position as defined in Section 4.10. The normal preventive maintenance shall not exceed the requirements established in Section 4.14.7. Any greasing operation or lubrication activity that needs to be performed at interval shorter than 12 months shall be automatic.

12.3.3 Overhaul

Overhaul is a planned major maintenance operation that is performed at the antenna site. The following applies:

- No overhaul operation shall last longer than three weeks.
- No overhaul operation shall be required at intervals shorter than 20 years.
- Periodic painting and surface protection shall not be necessary more often than every ten years.
- Overhaul activities, including painting and possible exchange of azimuth and elevation bearings, shall be described in the Maintenance Manual.