Short Baseline Array Antenna: Preliminary Technical Requirements

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2017-09-25	R. Selina	All	Started first draft. Used ngVLA Antenna Preliminary Technical Specifications 020.25.00.00.00-0001-SPE as a base.
02	2017-09-26	R. Selina	3, 4, 7	Updated requirement IDs, changed language to SBA0503. Minor title and text changes for clarity.
03	2018-11-06	D. Dunbar	Doc no., Doc Title, 3.3, 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.
04	2018-11-14	D. Dunbar	2.1, 2.2, 4.13, 4.14, 8.1.4, 10	Added new reference documents. 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)
05	2019-04-15	D. Dunbar	All	Updated antenna count to 244 18m and 19 6m
A	2019-07-23	A. Lear	All	Incorporated edits by M. McKinnon and R. Selina. Prepared PDF for signatures and release.

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1 Introduction

1.1 *Purpose*

This document presents a preliminary set of technical specifications for the ngVLA Short Baseline Array (SBA) 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. This document reflects a preliminary analysis of these use cases, and the flow down recursively to the system and subsystem requirements.

NRAO desires a cost-effective solution for the antenna that can be manufactured in volume and operated affordably. 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 SBA 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 SBA 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.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	V1.0, 3/30/2017 Doc: 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

Reference No.	Document Title	Rev/Doc. No.
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:

Reference 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	ngVLA System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements	Doc: 020.10.15.10.00-0002-REQ
RD06	ngVLA System Environmental Specifications	Doc: 020.10.15.10.00-0001-SPE

3 Overview of SBA Antenna Technical Specifications

3.1 Document Outline

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

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes elaborate on 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 explain or analyze 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 SBA 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 metrics 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 observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter, operating in a phased or interferometric mode.

The design will also include a compact Short Baseline Array (SBA) composed of approximately 19 reflector antennas each of 6 meters diameter. These antennas will be spaced randomly but closely, providing information necessary to recover large-scale source structure. The SBA may be operated in conjunction with the 18m array in an interferometric mode, or independently.

The array 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. Operations will be conducted from both the VLA Control Building and the Domenici Science Operations Center in Socorro, NM.

3.3 General SBA Antenna Description

The SBA 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 SBA antennas will be constituted of a shaped paraboloidal reflector, with a subtended circular aperture of 6 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 SBA Antenna Requirements

The following table summarizes the major SBA antenna requirements to give the reader a high-level view of the desired antenna. Should a conflict exist 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	SBA0101, SBA0102, SBA0103
Diameter	6m	SBA0202
No. of Antennas	19	SBA0401
Surface Accuracy	**Precision Operating Conditions:** 160 μm RMS (λ/16 @ 116 GHz), primary and subreflector combined. **Normal Operating Conditions:** 300 μm RMS, primary and subreflector combined.	SBA0501, SBA0502
Pointing Accuracy	**Precision Operating Conditions**: Absolute pointing: 54 arc sec RMS Referenced pointing: 9 arc sec RMS (4 deg angle, 15 min time) **Normal Operating Conditions:** Absolute pointing: 105 arc sec RMS Referenced pointing: 15 arc sec RMS (4 deg angle, 15 min time)	SBA0611, SBA0612, SBA0621, SBA0622
Tracking Range	**Azimuth:** ±270 deg **Elevation:** 12 deg to 88 deg	SBA0801, SBA0802
Movement Rate	**Slew:** Azimuth 90 deg/min, Elevation 45 deg/min. **Tracking:** Azimuth 7.5 deg/min, Elevation 3.5 deg/min.	SBA0901, SBA0902, SBA0906
Antenna Geometry	Offset Gregorian, satisfying Mizuguch-Dragone polarization condition, with focal point on bottom.	SBA0201, SBA0206, SBA0211
Environmental Conditions	**Survival Conditions at Stow Position:** Wind ≤50 m/s, temp ≥–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.	SBA1411 through SBA1446

4 SBA 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	SBA0101	116 GHz	SYS0801
Lower Operating Frequency	SBA0102	1.2 GHz	SYS0801
Optimized Operating Frequencies	SBA0103	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 cost of the design or compromise the performance at higher frequencies.

For example, optimizing performance at 1.2 GHz may necessitate a large subreflector, perhaps 4–5m in diameter. Such a subreflector may increase the structural requirements on the feed/subreflector arm and may 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 8GHz and up.

4.2 Optical and Mounting Geometry

Parameter	Req. #	Value	Traceability
Optical Configuration Type	SBA0201	Offset Gregorian	SYS0701, SYS0601
Primary Aperture Diameter and Shape	SBA0202	6m, circular	SYS0501, SYS0601
Secondary Reflector Aperture Diameter	SBA0203	2.5m minimum	SYS0501, SYS0701
Secondary Angle of Illumination	SBA0204	From the focal point, secondary reflector aperture shall subtend an angle of 110°.	
Reflector Offset	SBA0205	There shall be no overlap of the physical secondary reflector with the projected aperture of the main reflector.	
Focal Ratio, Primary	SBA0206	The closest paraboloid to the main reflector shall have a focal ratio of 0.40 ±0.05.	
Cross Polarization	SBA0207	The secondary reflector tilt angle (β in Figure 1) shall be chosen to satisfy the Mizuguch condition [AD13].	SYS0501
Reflector Shapes	SBA0208	The shapes of the main and secondary reflectors will deviate no more than 0.25m from the classical Gregorian conic sections (paraboloid and hyperboloid). For the main reflector, deviations will be azimuthally symmetric about the paraboloid axis.	

Parameter	Req. #	Value	Traceability
Secondary Reflector Extension	SBA0209	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	SBA0210	The main reflector may extend beyond the defined aperture if that facilitates efficient fabrication (e.g., assembly from hexagonal panels).	
Mounting Configuration	SBA0211	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 SBA0202 through SBA0207 (except that SBA0205 and SBA0207 specify only minimum values), and Figure 1 conforms to these requirements using the minimum secondary reflector size and 10 cm offset.

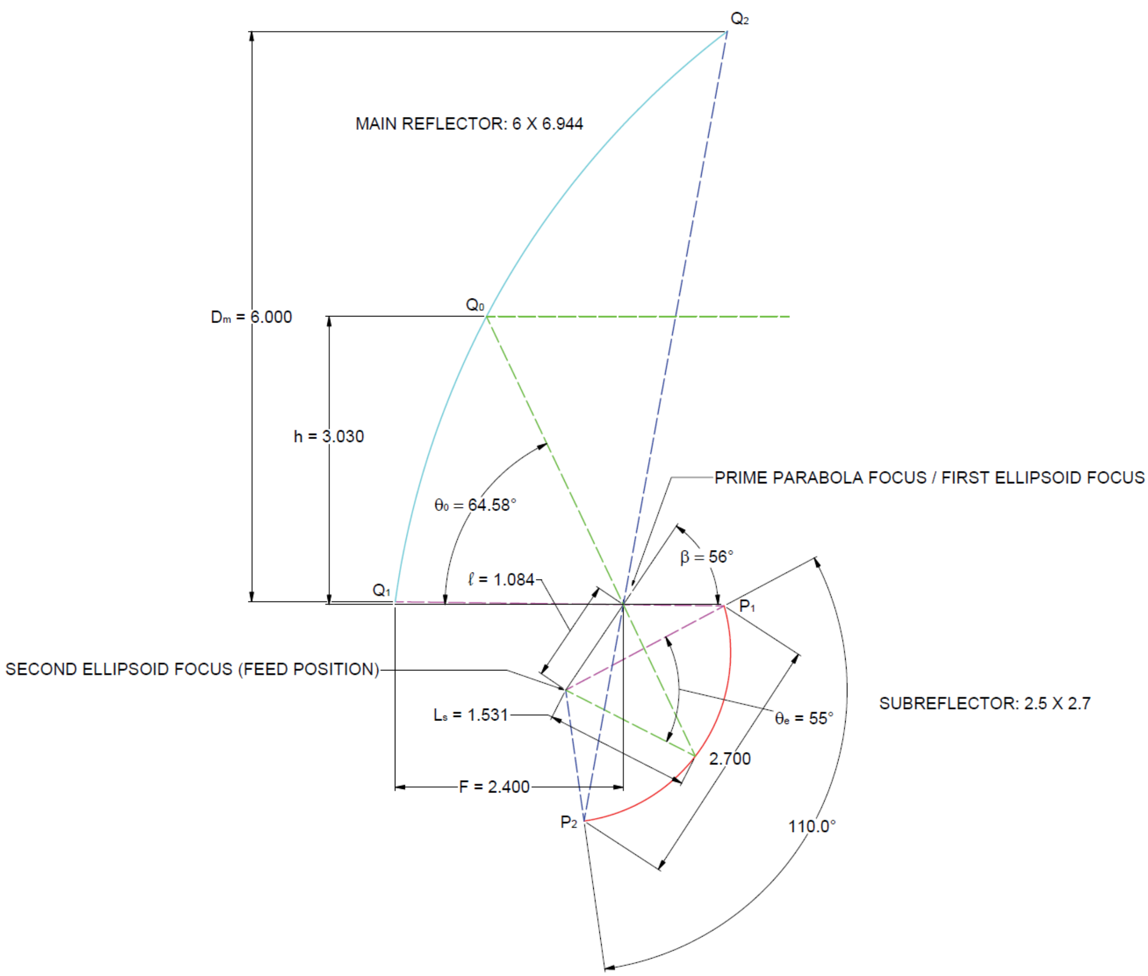

Figure 1 - Cross-section of the optical geometry through the plane of symmetry for unshaped (paraboloid ellipsoid) reflectors. Values may be refined in the design.

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 (SBA0203 and SBA0205) is measured in the plane perpendicular to the geometrical optics ray from the focal point to the center of the main aperture. The secondary reflector's physical edge (not including the extension described in SBA0208) 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 (SBA0208), the classical shapes should be used for the preliminary design.

4.3 Allowable Design Volume and Mass

Parameter	Req. #	Value	Traceability
Minimum Spacing	SBA0301	Antennas whose azimuth axes are separated by 11m shall not collide for any combination of their orientations.	
Height	SBA0302	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	SBA0303	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
No. of Antennas	SBA0401	19	SYS0501

The final number of antennas will depend on the configuration design for both the 18m main array and the SBA. Values of 16–20 have been adequate in preliminary studies but should be revisited as the configuration design matures.

4.5 Reflector Construction and Accuracy

Parameter	Req. #	Value	Traceability
Surface Accuracy, Precision	SBA0501	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	SBA0502	Surface errors shall not exceed 300 μm RMS, for the primary and secondary reflector combined, when in the Normal operating environment.	SYS0501
Reflector Construction	SBA0503	Each reflector may be constructed as a single piece or 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 reflector construction method is not intended to preclude innovative composite layups. The goal is that the reflector surface provide high reflectivity and minimal transmission over the operating frequency range.

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 that 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	SBA0611	54 arc sec RMS	SYS0801
Referenced Pointing Error	SBA0612	9 arc sec RMS, within 4° of target position and 15 minutes of 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	SBA0621	105 arc sec RMS.	SYS0801
Referenced Pointing Error	SBA0622	15 arc sec RMS, within 4°. Must maintain spec for 15 mins minimum.	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	SBA0701	125 µm over full elevation range	
Secondary Focus Position Stability in Normal Operating Environment	SBA0702	300 µm over full elevation range	

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	SBA0801	+/– 270° minimum, where zero is towards true South.	
Elevation Tracking Range	SBA0802	12° to 88° minimum from local horizon.	SYS1201
Elevation Movement Range	SBA0803	As required to support operation over the elevation tracking range. (TBC)	

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

The lower elevation permits observations over large portions of 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 SBA). However, this lower elevation 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). At the discretion of the designer, maintenance and safety stow positions may be outside the elevation tracking range.

4.9 Axis Rates

Parameter	Req. #	Value	Traceability
Slew: Azimuth	SBA0901	90 deg/mins minimum	SYS1107
Slew: Elevation	SBA0902	45 deg/mins minimum	SYS1107
Acceleration: Azimuth	SBA0903	4.5 deg^2/sec minimum	
Acceleration: Elevation	SBA0904	2.25 deg^2/sec minimum	
Slew + Settle Time	SBA0905	Move 4-deg on sky and settle to within Referenced Pointing Specification within 10 seconds for elevation angles <70°.	SYS1107
Tracking: Azimuth	SBA0906	7.5 deg/mins minimum	
Tracking: Elevation	SBA0907	3.5 deg/mins 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 alternative approaches to phase calibration exist at the system level.

The tracking specifications give the rates at which the specified pointing error limits must be maintained. In general, there is a tracking error that contributes to the pointing error and must be included in the pointing error budget for both Precision and Normal conditions. The azimuth tracking rate corresponds to approximately 10 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	SBA1001	The survival stow position shall limit the wind load on antenna while ensuring water and snow accumulation does not exceed safe structural allowances.	
Stow Position: Maintenance	SBA1002	The 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, and the other for specific maintenance to be performed on the antenna.

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 the 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	SBA1101	The primary and secondary reflector shall each have a surface resistive loss of <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	SBA1201	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	SBA1301	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 lists the allowable radiation for electronic components as a function of frequency, and 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/m^2)	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 Fh 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 * νG, where νG 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	SBA1411	Nighttime only; no solar thermal load within last 2 hours.	ENV0311
Wind Speed	SBA1412	0 ≤ W ≤ 5 m/s average over 10 min time. 7 m/s peak gusts.	ENV0312
Temperature	SBA1413	–15°C ≤ T ≤ 25°C	ENV0313
Temperature Rate of Change	SBA1414	1.8°C/Hr.	ENV0314
Precipitation	SBA1415	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	SBA1421	Exposed to full sun, 1200W/m^2	ENV0321
Wind Speed	SBA1422	W ≤ 7 m/s average over 10 min time. 10 m/s peak gusts.	ENV0322
Temperature	SBA1423	–15°C ≤ T ≤ 35°C	ENV0323
Temperature Rate of Change	SBA1424	3.6°C/Hr.	ENV0324
Precipitation	SBA1425	No precipitation.	ENV0325

When the environment meets the constraints of the normal operating conditions, system performance requirements are relaxed but are 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	SBA1430	Exposed to full sun, 1200W/m^2	ENV0330
Wind	SBA1431	W ≤15 m/s average over 10 mins. W ≤20 m/s gust.	ENV0331
Temperature	SBA1432	–20°C ≤ T ≤ 45°C	ENV0332
Precipitation	SBA1433	5 cm/hr over 10 min	ENV0333
Ice	SBA1434	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.

If these limits are exceeded, the antenna will be moved to "stow-survival" orientation to prevent damage.

4.14.4 Survival Conditions at Stow Position

Parameter	Req. #	Value	Traceability
Wind	SBA1441	0 m/s ≤ W ≤ 50 m/s average.	ENV0341
Temperature	SBA1442	–30°C ≤ T ≤ 50°C	ENV0342
Radial Ice	SBA1443	2.5 cm	ENV0343
Rain Rate	SBA1444	16 cm/hr. over 10 min	ENV0344
Snow Load – Antenna	SBA1445	25 cm	ENV0345
Hail Stones	SBA1446	2.0 cm	ENV0347
Antenna Orientation	SBA1447	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	SBA1451	The antenna and housed equipment shall be protected from both direct and nearby lightning strikes, achieving Protection Level 1 as defined in IEC 62305-1/3. [AD02]	ENV0511
Lightning Protection: Electronics Systems	SBA1452	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	SBA1453	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 extent of the array 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 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	SBA1461	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	SBA1471	The antenna and foundation shall be designed for operation and survival at altitudes ranging from sea level to 2200 m.	ENV0531

4.14.8 Vibration

Parameter	Req. #	Value	Traceability
Wind Vibration	SBA1481	Exposed equipment, including all equipment 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	SBA1502	Preventive maintenance shall not be required at intervals shorter than 12 months.	SYS2301
Preventive Maintenance Effort	SBA1502	Periodic preventive maintenance shall require no more than a two-person team and no more than two 8-hour workdays.	SYS2301
Mean Time Between Failures	SBA1503	MTBF ≥ 35,000 hrs	SYS2302

The maintenance and reliability requirements support high-level requirements that limit total operating cost of the array. The preventive maintenance effort is intended to be averaged over the design life of the array, and needn't 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)	SBA1601	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	SBA1602	The ACU shall include servos with position and rate control loops on each axis, and the design of these servos shall account for the dynamic behavior of the structure.	SYS2601
Self-Monitoring	SBA1603	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	SBA1604	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	SBA1605	System remote control shall require an authentication process, and only respond to commands from authorized sources.	SYS2602
Remote Reset	SBA1606	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 required. 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.

The weather-monitoring requirement can be met centrally if preferred by the designer. The SBA antennas are expected to be located within a geographically compact area (less than a square km in extent) so uniform weather may be assumed. Other features of the ACU interface are specified in the M&C ICD.

4.17 Motion Limiting Features

Parameter	Req. #	Value	Traceability
Software Limits	SBA1701	The antenna shall include logic to prevent motion beyond programmable limits in azimuth and elevation during normal operation.	
Hardware Limits	SBA1702	The antenna shall be equipped with mechanically driven switches to inhibit operation outside its safe operating limits.	
Hard Stops	SBA1703	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	SBA1704	The antenna shall be equipped with a safety lock-out that inhibits motion of the antenna during service.	
Fire Alarm	SBA1705	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	SBA1706	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	SBA1801	The antenna shall be designed to require no major overhaul work for 20 years.	
Lifecycle Optimization	SBA1802	The antenna design shall minimize its lifecycle cost for 20 years of operation.	

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

5 Interface Requirements

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

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

Note that some consistency between the SBA antenna interfaces and 18m antenna interfaces is desirable, in order to promote reuse of equipment.

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 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 in order 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 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 to the antenna.

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 range 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 (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 5.7.

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 which 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 the amount of torsion that can be sustained by cables and hoses (e.g., helium lines) shall also be considered. The design of the cable wrap shall be optimized for durability and reliability taking into account the lifetime requirements of Sections 4.17 and 4.18.

5.8 Interface to the Cryogenic System

Space must be available for one (1) 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 the required tracking accuracy. The vendor supplied antenna control unit shall operate in three pointing modes:

- Raw or Encoder mode: In this mode, the servo system shall be controlled such that the encoder values match the commanded values.
- Metrology mode: In this mode, the servo system shall apply any corrections to the input coordinates based on the values of any metrology sensors located in the antenna system (if included in the design).

- Active mode: In this 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 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 modeling 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, the 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 and 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	SBA7001	The design shall comply with all relevant Federal and state building codes. When in conflict, the most stringent code shall apply.	
Safety of Personnel	SBA7002	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 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 defines classification of the probability 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 the occurrence can be assumed not to occur (>20 years)

Table 3 - Probability levels.

7.2.3 Hazard Risk Acceptability Matrix

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 supplied to the antenna
- Emergency braking of the antenna
- Earthquakes happening for whatever position of the antenna
- 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 elements of the system, 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 which ngVLA will use for a remote fire alarm and will energize a local audible alarm. The shunt trip of all power shall occur 5 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 margin of 1.5 with respect to the yield point shall be used in 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 (example fatigue), an equivalent stress safety factor of 1.5 shall be used in the design of all 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 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 and 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 paint 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 FE internal criteria like the "Percentage error in energy norm." Alternatively, this type of error can be evaluated by mesh refining.

The required analyses are listed and specified below. If 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). Table 6 and Table 7 of Section 8.1.4 describe relevant scenarios.

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 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 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
- All frequencies below 50 Hz are taken into account.

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

The above conditions must 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
- 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 FE 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 Conditions
Gravity + Thermal (secondary) + Wind (10 m/sec)
Gravity + Thermal (primary)+ Wind (7 m/sec) + Slew
Load Combination Accidental Conditions
Gravity + Thermal (secondary) + Wind (20 m/sec) + Emergency braking
Load Combination Survival Conditions
Gravity + Wind (50m/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 the antenna performance in the precision operating environment. The results shall be provided to NRAO for electromagnetic performance analysis (by others).

Load Case	Name	Azimuth angle (deg)	Elevation 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.

Table 7 shows combined load cases. Combined cases may be calculated from results of the individual load case analyses. Load combinations L.C.01 through L.C.10 represent 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 analysis results for L.C.01 through L.C.10. Only the worst-case gravity and wind scenarios are subject to combination with the thermal gradients 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 of function to be controlled, the stability margins shall be computed. Dynamic simulations of the control loops shall be performed, including non-linear 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 the Parts Count Method for predicting system reliability as described in MIL-HDBK-217F, but the designer may propose 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.

ngVLA SBA antennas will operate at an elevation of 2200m 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 SBA 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 motors amplifiers, and switching devices shall be designed and constructed taking into account the 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 will provide effective shielding of radio frequency energy.
- Silicon-controlled rectifier switching devices shall not be used unless phase controlled and zero current crossing 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 a RFI shield in front of the display to avoid radiated RFI. This requirement may be waived if the screen is powered off during typical operation, and is used for maintenance purposes 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 shall account for the lowest temperature to be expected during antenna operation and stow to minimize embrittlement. In particular, the nil-ductility transition temperature (at which the material starts to exhibit cleavage fracture with very little evidence of notch ductility) of the selected steel shall not exceed –45°C. When necessary (e.g., gears and pinions, if applicable), materials with suitable hardness or surface hardened shall be used to ensure system life.

8.3.2 Stress Relieving

All structural welded parts shall be stress relieved using 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 ten years without repainting.

8.3.6 Surface Treatment

Unpainted surfaces shall be treated against corrosion.

8.3.7 Thermal Insulation

Thermal insulation used in an exterior antenna application 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 contain the following information:

- Part/unit name
- Drawing number including revision

- Serial number
- Manufacturing month and year
- Name of manufacturer

Alternatively, a marking system based on barcodes or similar system may be used upon ngVLA approval.

For Line Replaceable Units (LRUs, Section 12.3), it is highly desirable that the LRU serial number be ascertainable over the monitor and control interface (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 which 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. Altium Designer files are the ngVLA preferred formats 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

Deliverables include ACU software and any other specially developed software. The software 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 the ngVLA project office may check during the design phase by design documentation review.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which the ngVLA project office may check 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 without 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
SBA0101	Upper operating frequency	*				
SBA0102	Lower operating frequency	*				
SBA0103	Optimized operating frequencies	*				
SBA0201	Optical configuration type	*				
SBA0202	Primary aperture diameter and shape	*				
SBA0203	Sub-reflector aperture diameter	*				
SBA0204	Secondary angle of illumination	*				
SBA0205	Reflector offset	*				
SBA0206	Focal ratio, primary	*				
SBA0207	Cross polarization	*	*			
SBA0208	Reflector shapes	*				
SBA0209	Secondary reflector extension	*		*		
SBA0210	Main reflector extensions	*				
SBA0211	Mounting configuration	*				
SBA0301	Minimum spacing	*	*			
SBA0302	Height	*		*		
SBA0303	Mass	*				
SBA0401	Number of antennas	*				
SBA0501	Surface accuracy, precision	*	*		*	*
SBA0502	Surface accuracy, normal	*	*		*	*
SBA0503	Reflector construction	*		*		
SBA0611	Non-repeatable pointing error, precision		*			*

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
SBA0612	Referenced pointing error, precision		*			*
SBA0621	Non-repeatable pointing error, normal		*			*
SBA0622	Referenced pointing error, normal		*			*
SBA0701	Focus stability, precision		*			*
SBA0702	Focus stability, normal		*			*
SBA0801	Azimuth tracking range	*		*		
SBA0802	Elevation tracking range	*		*		
SBA0803	Elevation movement range	*				
SBA0901	Slew: Azimuth	*	*			*
SBA0902	Slew: Elevation	*	*			*
SBA0903	Acceleration: Azimuth	*	*			*
SBA0904	Acceleration: Elevation	*	*			*
SBA0905	Slew + settle time		*			*
SBA0906	Tracking: Azimuth		*			*
SBA0907	Tracking: Elevation		*			*
SBA1001	Stow position, survival	*		*		
SBA1002	Stow position, maintenance	*		*		
SBA1101	Resistive losses	*				*
SBA1000	Solar observations	*	*			*
SBA1001	Spurious signal level	*	*		*	
SBA1411	Precision env.: Solar thermal load		*			
SBA1412	Precision env.: Wind		*			
SBA1413	Precision env.: Temperature		*			
SBA1414	Precision env.: Temp. rate of change		*			
SBA1415	Precision env.: Precipitation		*			
SBA1421	Normal env.: Solar thermal load		*			
SBA1422	Normal env.: Wind		*			
SBA1423	Normal env.: Temperature		*			
SBA1424	Normal Env.: Temp. rate of change		*			
SBA1425	Normal env.: Precipitation		*			
SBA1430	Ops. limit: Solar thermal load		*			
SBA1431	Ops. limit: Wind		*			
SBA1432	Ops. limit: Temperature		*			
SBA1433	Ops. limit: Precipitation	*	*			
SBA1434	Ops. limit: Ice		*			
SBA1441	Survival: Wind		*			
SBA1442	Survival: Temperature		*			
SBA1443	Survival: Radial ice		*			
SBA1444	Survival: Rain rate		*		*	
SBA1445	Survival: Snow load, antenna		*			
SBA1446	Survival: Hail stones		*			
SBA1447	Survival: Antenna orientation	*				
SBA1451	Lightning protection: Structure	*	*			
SBA1452	Lightning protection: Electronics systems	*	*			
SBA1453	Lightning protection: Personnel	*	*			
SBA1461	Seismic protection		*			

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
SBA1471	Site elevation		*			
SBA1481	Wind vibration		*			
SBA1501	Preventive maintenance cycle	*	*			
SBA1502	Preventive maintenance effort	*	*			
SBA1503	Mean time between failure		*			
SBA1701	Antenna control unit (ACU)	*		*		
SBA1702	Servo loops		*			
SBA1703	Self-monitoring	*		*		
SBA1704	Weather monitoring	*		*		
SBA1705	Network hardening/authentication	*				
SBA1706	Remote reset	*				
SBA1701	Software limits	*			*	
SBA1702	Hardware limits	*			*	
SBA1703	Hard stops	*				
SBA1704	Safety lock-out	*		*		
SBA1705	Fire alarm	*		*		
SBA1706	Fail safe brakes	*				
SBA1801	Design life	*	*			
SBA1802	Lifecycle optimization		*			
SBA7001	Code compliance	*				
SBA7002	Safety of personnel	*	*			

Table 8 - Expected requirements verification method.

11 Key Performance Parameters

This section provides key performance parameters that the designer should estimate and NRAO should monitor throughout the project design phase. These parameters have a large influence on the eventual facility effectiveness and are useful high-level metrics for trade-off decisions. These parameters are of higher importance to NRAO, making improved performance above the requirement desirable. The impact on system-level performance is discussed in depth in Section 4.

NRAO's expectation is that the specified technical requirements will not push technical boundaries. Rather, the key challenge 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 antenna performance (not just its specified minimum) on these parameters facilitates 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 capability reductions be required to fit within cost constraints.

Table 9 lists key performance parameters identified for monitoring. Note that their order reflects the order in the document, and is not indicative of relative importance or priority.

Req. #	Key Performance Parameter
SBA0301	Minimum spacing
SBA0501	Surface accuracy, precision environment
SBA0502	Surface accuracy, normal environment
SBA0611	Non-repeatable pointing error, precision environment
SBA0612	Referenced pointing error, precision environment
SBA0621	Non-repeatable pointing error, normal environment
SBA0622	Referenced pointing error, normal environment
SBA0802	Elevation range (lower elevation limit)
SBA0901	Slew: Azimuth
SBA0902	Slew: Elevation
SBA0903	Acceleration: Azimuth
SBA0904	Acceleration: Elevation
SBA0905	Slew + settling time
SBA0906	Tracking: Azimuth
SBA0907	Tracking: Elevation
SBA1501	Preventive maintenance cycle
SBA1502	Preventive maintenance effort
SBA1503	Mean time between failures
SBA1801	Design life

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
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
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, and 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
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.

The pad coordinate system is based on the right-hand rule, with the Z_P corresponding to the local vertical, positive direction toward zenith, and X_p axis pointing to the geographical north and the Y_P axis pointing to geographical west. The system origin 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 antenna's kinematic mount.

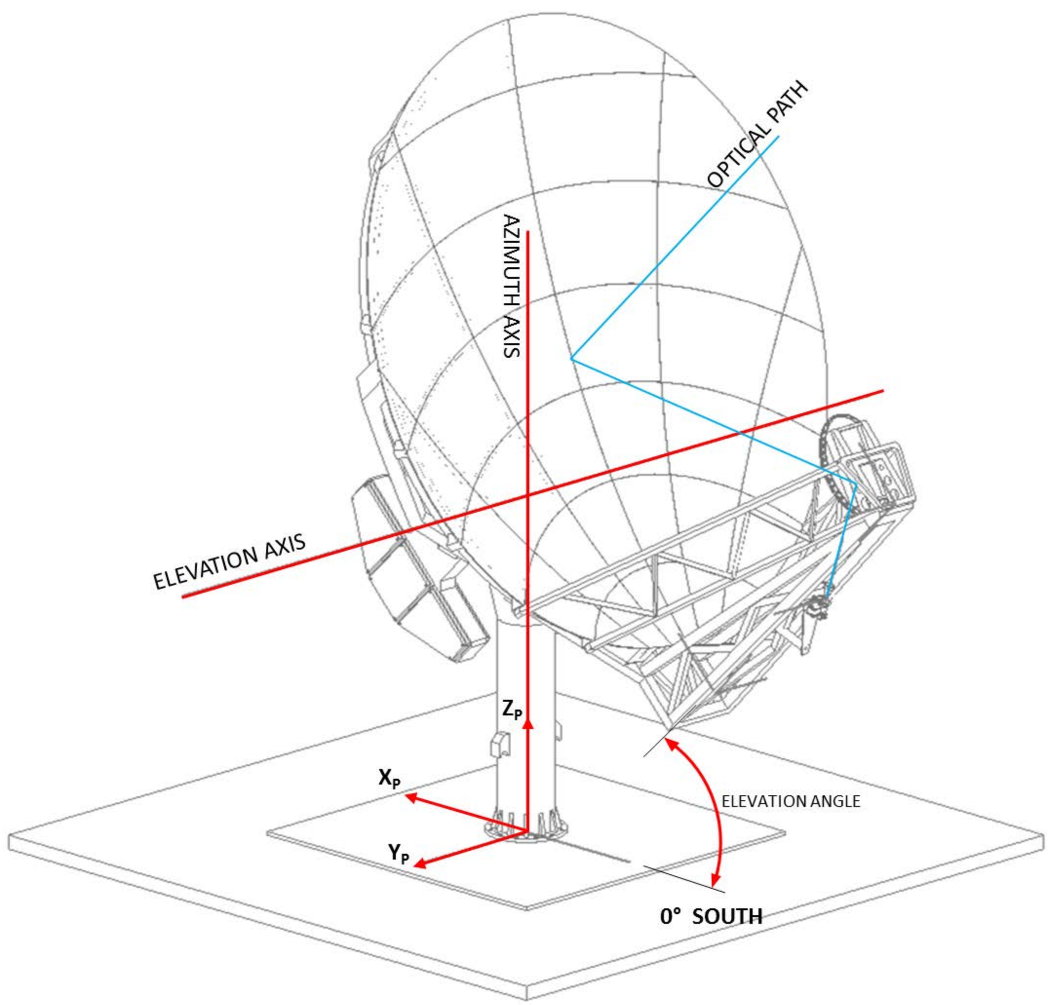

Figure 2 - Diagram of the antenna pad coordinate system and major axes. Separate Cartesian reference frames define each mirror surface, the focus, and the pad respectively. Antenna design is diagrammatic only.

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 reflector focus. This coordinate system 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 antenna azimuth equals 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).

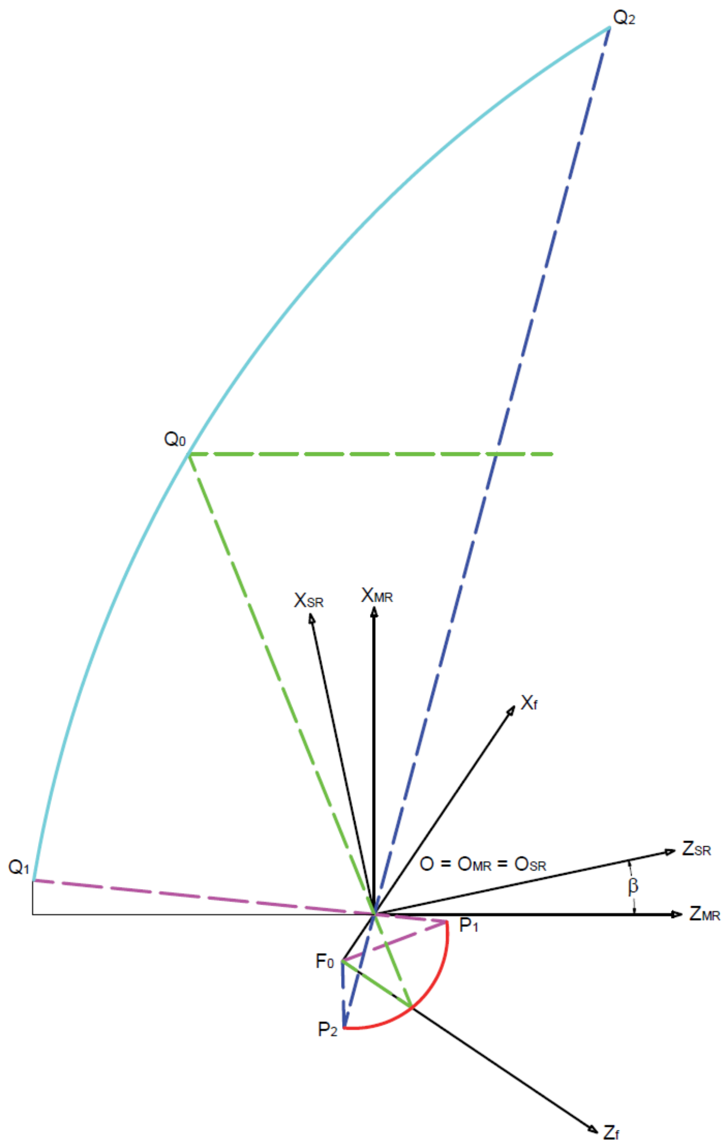

Figure 3 - Antenna optical coordinate system. Separate Cartesian reference frames define each reflector surface and the secondary focus.

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 Antenna Azimuth

The azimuth angle shall be zero when the antenna is rotated so that Y_{MR} is pointing 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 north).

12.2.6 Antenna Elevation

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 that can be easily exchanged (without extensive calibration, of sufficient low mass and dimension for handling ease, etc.) by technician-level maintenance staff. LRU exchange shall be possible by two trained people within four 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 a LRU as a minimum:

- Sub-reflector 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 to keep 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 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 4.15. Any greasing operation or lubrication activity that must be performed at intervals shorter than 12 months shall be automatic.

12.3.3 Overhaul

Overhaul is a planned major maintenance operation 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.