2

ngvla

Next Generation Very Large Array

SYSTEM REFERENCE DESIGN

Volume 2: Antennas & Antenna Electronics

Preface

The ngVLA Science Book describes the frontiers of discovery enabled by a next-generation centimeter-wavelength interferometer with unprecedented sensitivity and angular resolution. Realizing such a facility will require a substantial financial investment, and the commitment of these funds comes with a responsibility upon the project to fulfill this vision within funding and time constraints. At this stage of the project, it is incumbent upon us to develop our facility concept to a degree where the investment required and the associated risks can be understood by both decision makers and the project team.

This three-volume compendium describes the ngVLA Reference Design. The reference design is a low-technical-risk, costed concept that supports the key science goals for the facility, and forms the technical and cost basis of the ngVLA Astro2020 Decadal Survey proposal. The compendium includes a total of 55 technical documents and represents the work of more than 54 engineers and scientists contributing to the project. While led by the project team at the National Radio Astronomy Observatory, the author list includes many collaborators from the US and international radio astronomy community who have contributed their expertise to the project. Many more have contributed to the definition of the science case and science requirements, or contributed through critical review.

This technical compendium describes the system from end to end, and provides a snapshot of the technical development of the facility concept as of August, 2019. As the first technical baseline, it has gaps and minor inconsistencies that will be addressed in advance of the system conceptual design review, but it presents the clear and substantive progress that has been made in defining a realizable ngVLA facility concept.

What is most important at this juncture is to have a viable concept for each subsystem that supports the overall system and science requirements, enabling robust performance and cost estimates, and a technical baseline for future trade studies. Alternate concepts that improve performance to key parameters or reduce cost can, and will, be revisited as part of the conceptual design activities.

The volume of this compendium is indicative of the effort invested and the technical maturation of the project. It is only through the documentation of our ideas that we identify the inconsistencies and gaps in our thinking, and the act of writing forces us to make multiple small decisions that sharpen our concepts and produce a realizable design. The development of this reference design gives us confidence in our performance and cost estimates, the technical readiness of the design, and our ability to achieve the transformational science described in the ngVLA Science Book.

With the realization of this technical concept, the ngVLA will uniquely tackle a broad range of high-priority scientific questions in modern astronomy, physics, chemistry, and biology, dramatically extending the scientific frontiers that are within reach of existing facilities. In doing so, the ngVLA will transform our understanding of planet formation, the initial conditions for life, galaxy formation and evolution, and the physics of black holes, and will ultimately advance humanity's understanding of the cosmos and our place within it.

Robert J. Selina
ngVLA Project Engineer
August, 2019

For more information and updates, please see the digital version of this book that is available on the ngVLA website.

Use the QR Code above, or visit us at ***https://ngvla.nrao.edu/page/projdoc***.

Volume II

Preface
R. Selina

Part V: Antennas

Antenna: Preliminary Technical Requirements
020.25.00.00.00-0001-REQ-A
R. Selina

ngVLA Optical Reference Design: Analysis of the ngVLA Antenna Optical Design #6 with Ideal and Actual Feed
020.25.01.00.00-0001-REP-A
L. Baker

ngVLA 18m Antenna: Preliminary Design Document
101-0000-001-PDD-001
D. Chalmers

Short Baseline Array Antenna: Preliminary Technical Requirements
020.47.05.00.00-0001-REQ-A
R. Selina and D. Dunbar

ngVLA 6m Antenna: Concept Design Document
102-0000-001-CDD-001
D. Chalmers

Part VI: Antenna Electronics

Front End: Technical Requirements
020.30.03.01.00-0001-REQ-A
W. Grammer

Front End: Reference Design Description
020.30.03.00.00-0002-DSN-A
W. Grammer

Cryogenic Subsystem: Requirements
020.30.10.00.00-0001-REQ-A
D. Urbain

Cryogenic Subsystem: Reference Design Description
020.30.10.00.00-0002-DSN-A
D. Urbain

Integrated Receiver and Downconverters: Preliminary Technical Requirements
020.30.15.00.00-0001-REQ-A
M. Morgan

Integrated Downconverters and Digitizers: Design Description
020.30.15.00.00-0002-DSN-A
M. Morgan

Digital Back End/Data Transmission System: Technical Requirements
020.30.25.00.00-0001-REQ-A
J. Jackson

Digital Back End/Data Transmission System: Reference Design Description
020.30.25.00.00-0002-DSN-A
J. Jackson, M. Luce, A. Erickson, E. Ford, and R. Selina

DC Power Supply: Preliminary Technical Requirements
020.30.50.00.00-0001-REQ-A
P. Lopez

DC Power Supply: Reference Design Description
020.30.50.00.00-0002-DSN-A
P. Lopez

Bins, Modules, and Racks: Preliminary Technical Requirements
020.30.55.00.00-0001-REQ-A
D. Gerrard, S. Sturgis, and J. Allison

Bins, Modules, and Racks: Reference Design Description
020.30.55.00.00-0002-DSN-A
D. Gerard, S. Sturgis, and J. Allison

Antenna Electronics Environmental Control System: Preliminary Technical Requirements
020.30.60.00.00-0001-REQ-A
S. Sturgis and J. Allison

Antenna Electronics Environmental Control System: Reference Design Description
020.30.60.00.00-0002-DSN-A
D. Gerrard, S. Sturgis, and J. Allison

Independent Phase Calibration System: Preliminary Requirements
020.45.00.00.00-0001-REQ-A
A. Erickson

Water Vapor Radiometer: Design Description
020.45.00.00.00-0002-DSN-A
A. Erickson

Antenna Preliminary Technical Requirements

020.25.00.00.00-0001-REQ-A-ANTENNA_PRELIM_TECH_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
R. Selina	Electronics Div., NRAO	2019-05-29
D. Dunbar, ngVLA Antenna IPT Lead	ngVLA/NM-Ops, NRAO	2019-03-29

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.29 12:20:42 -06'00'	Electronics Div., NRAO	2019-07-29
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.29 12:53:03 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-29

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.29 12:53:18 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-29

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 7
1.1 Purpose 7
1.2 Scope 7
2 Related Documents and Drawings 8
2.1 Applicable Documents 8
2.2 Reference Documents 8
3 Overview of Antenna Technical Specifications 9
3.1 Document Outline 9
3.2 Project Background 9
3.3 General Antenna Description 9
3.4 Summary of Antenna Requirements 10
4 Antenna Functional and Performance Requirements 11
4.1 Operating Frequency Range 11
4.2 Optical and Mounting Geometry 11
4.3 Allowable Design Volume & Mass 13
4.4 Number of Antennas 14
4.5 Reflector Construction & Accuracy 14
4.6 Pointing Accuracy 14
4.6.1 Pointing Accuracy in Precision Operating Environment 15
4.6.2 Pointing Accuracy in the Normal Operating Environment 15
4.7 Focus Stability 15
4.8 Range of Motion 15
4.9 Axis Rates 16
4.10 Stow Positions 16
4.11 System Noise Contributions 17
4.12 Solar Observations 17
4.13 Spurious Signals/Radio Frequency Interference Generation 17
4.14 Environmental Conditions 18
4.14.1 Precision Operating Conditions 18
4.14.2 Normal Operating Conditions 18
4.14.3 Limits to Operating Conditions 19
4.14.4 Survival Conditions at Stow Position 19
4.14.5 Lightning Protection Requirements 19
4.14.6 Seismic Protection Requirements 20
4.14.7 Site Elevation 20
4.14.8 Vibration 20
4.15 Maintenance and Reliability Requirements 20
4.16 Monitor and Control Requirements 21
4.17 Motion Limiting Features 22
4.18 Lifecycle Requirements 22
5 Interface Requirements 23
5.1 Interface to the Foundation/Station 23
5.2 Interface to the Electrical Infrastructure 23
5.3 Interface to the Fiber Optic Transmission System 23
5.4 Interface to Other External Cables and Piping 24
5.5 Interface to the Receiver Enclosure/Front End Electronics 24

5.6 Interface to the Back End Electronics 24
5.7 Interface to Internal Cables and Piping 24
5.8 Interface to the Cryogenic System 25
5.9 Interface to the Monitor and Control System 25
6 Subsystem Requirements 26
7 Safety 26
7.1 General 26
7.2 Hazard Analysis 26
7.2.1 Hazard Severity 26
7.2.2 Hazard Probability 27
7.2.3 Hazard Risk Acceptability Matrix 27
7.2.4 Requirements on Operational Hazards 27
7.2.5 Hazard Analysis 28
7.3 Safety Design Requirements 28
7.3.1 Fire Safety 28
7.3.2 Mechanical Safety 28
7.3.3 Electrical Safety 29
7.3.4 Hydraulic & Pneumatic Safety 29
7.3.5 Handling, Transport, and Storage Safety 29
7.3.6 Toxic Substances 29
7.3.7 Confined Space 29
7.4 Physical Security 29
8 Requirements for Design 30
8.1 Analyses and Design Requirements 30
8.1.1 Finite Element Structural Analyses 30
8.1.2 Thermal Modeling and Analysis 31
8.1.3 Stress Analysis and Load Combination 31
8.1.4 Antenna EM Analysis Support 31
8.1.5 Control loop design and analysis 33
8.1.6 Reliability, Availability, Maintainability Analysis 33
8.2 Electromagnetic Compatibility Requirements 33
8.3 Materials, Parts and Processes 34
8.3.1 Type of Steel 34
8.3.2 Stress relieving 34
8.3.3 CFRP 34
8.3.4 Fasteners 34
8.3.5 Paints 34
8.3.6 Surface Treatment 34
8.3.7 Thermal Insulation 34
8.3.8 Rodent Protection 34
8.3.9 Name Plates and Product Marking 34
8.3.10 Labels 35
9 Documentation Requirements 36
9.1 Technical Documentation 36
9.2 Software and Software Documentation 36
10 Verification and Quality Assurance 37
11 Key Performance Parameters 40
12 Appendix 41

12.1 Abbreviations and Acronyms 41
12.2 Coordinate System 42
12.2.2 Main Reflector (MR) Coordinate System 42
12.2.3 Secondary Reflector (SR) Coordinate System 43
12.2.4 Focal Plane Coordinate system 43
12.2.5 Azimuth of the Antenna 43
12.2.6 Elevation of the Antenna 44
12.3 Maintenance Definitions 44
12.3.1 Maintenance Approach 44
12.3.2 Periodic Preventive Maintenance 45
12.3.3 Overhaul 45

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.

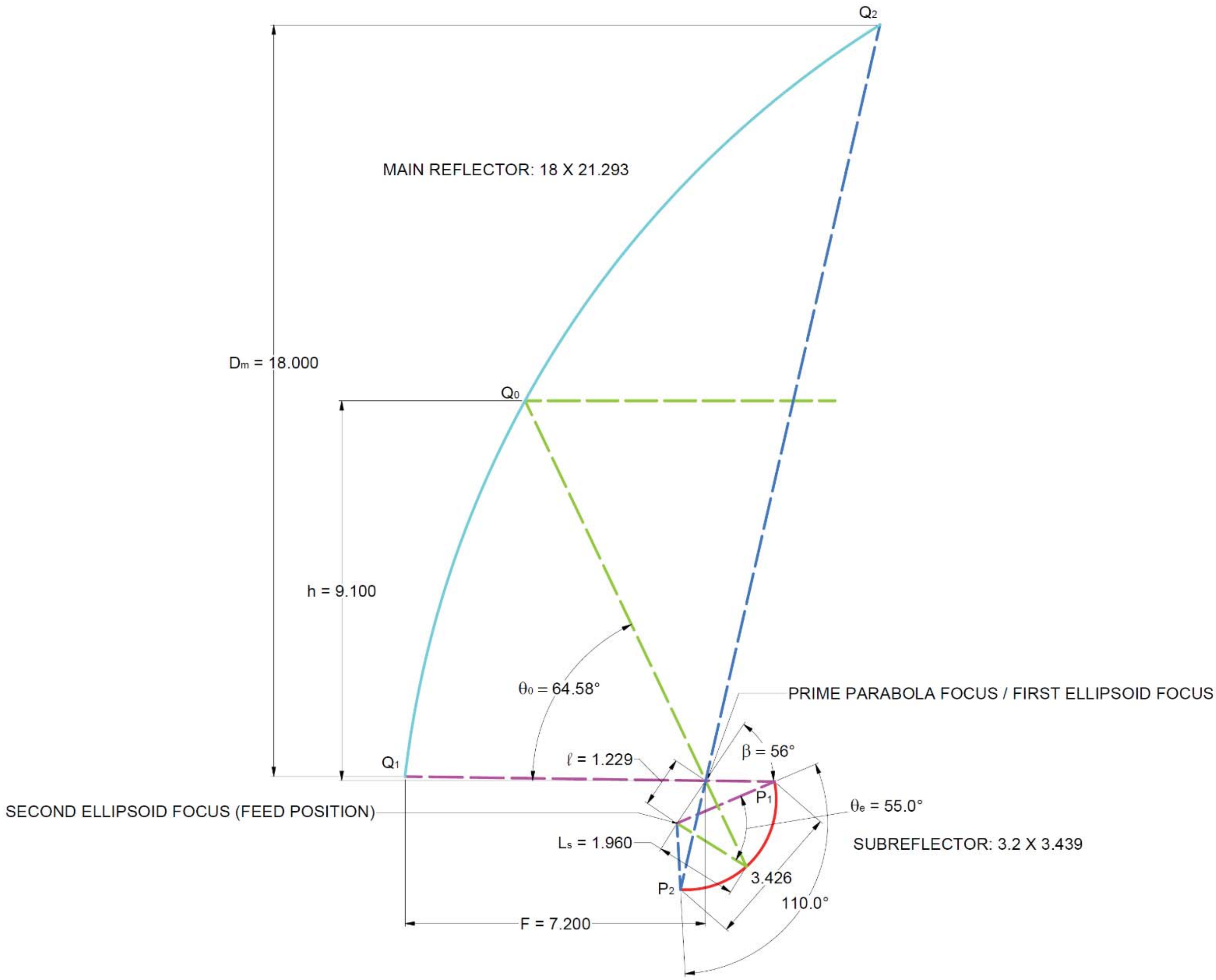


Figure 1 - Cross-section of the optical geometry through the plane of symmetry for unshaped (paraboloid ellipsoid) reflectors. Values may be refined in the design.

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/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 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.

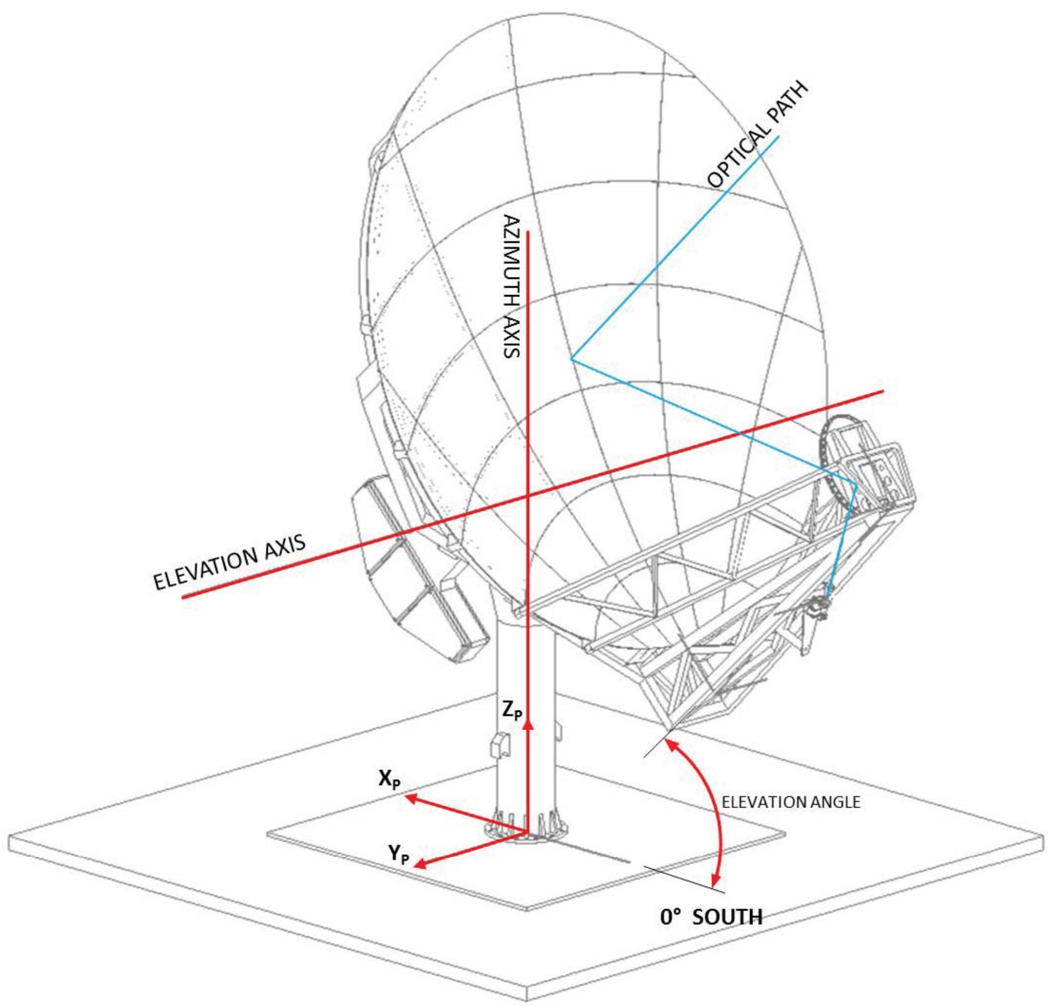


Figure 2 - Cartoon of the antenna pad coordinate system and major axes. Separate Cartesian reference frames define each mirror surface, the focus, and the pad respectively. Antenna design is diagrammatic only.

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).

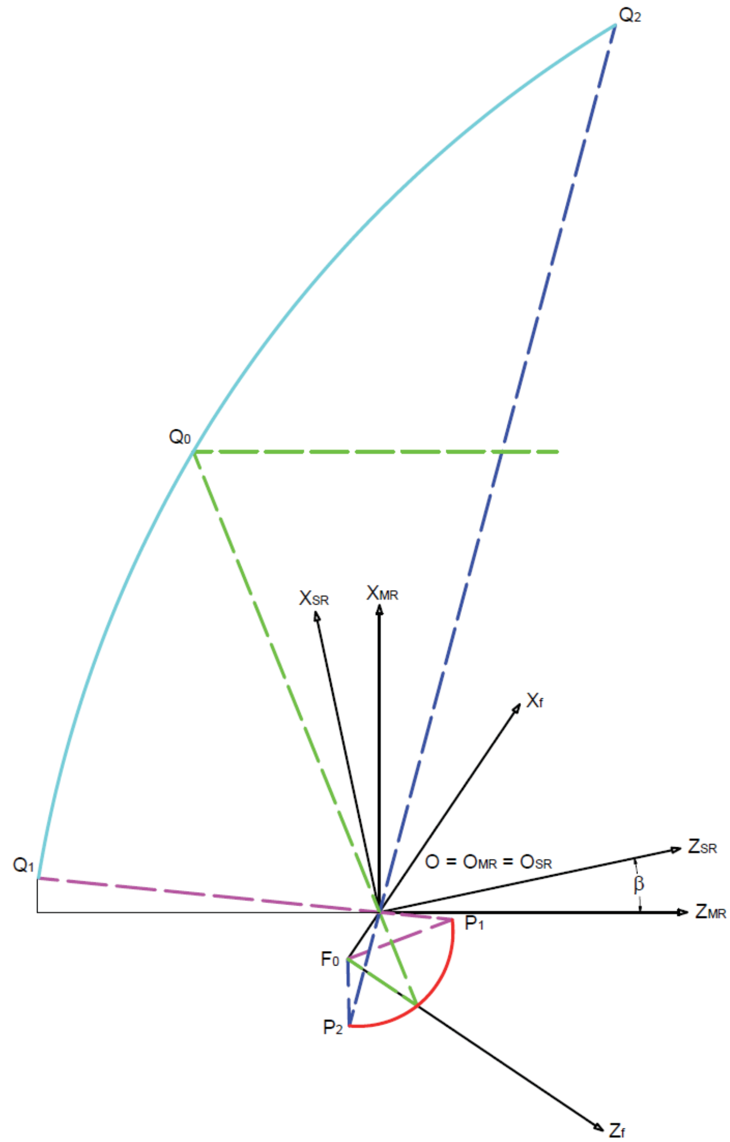


Figure 3 - Antenna optical coordinate system. Separate Cartesian reference frames define each reflector surface and the secondary focus.

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.

ngVLA Optical Reference Design: Analysis of the ngVLA Antenna Optical Design #6 with Ideal and Actual Feed

020.25.01.00.00-0001-REP-A-ANTENNA_OPTICAL_REF_DESIGN_REPORT

Status: **RELEASED**

PREPARED BY	DATE
L. Baker	2018-01-08

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.29 14:32:30 -06'00'	Electronics Div., NRAO	2019-07-29
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.29 14:41:09 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-29

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.29 14:41:27 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-29

Change Record

Version	Date	Author	Reason
1	2018-01-08	L. Baker	First distributed version of the document.
2	2019-06-14	R. Carver	Formatting and applying template.
3	2019-06-19	A. Lear	Copyediting and preparation for approvals.
4	2019-06-23	R. Selina	Minor corrections for release as part of the reference design.
A	2019-07-29	A. Lear	Prepared PDF for signatures and release.

Table of Contents

1 Introduction 4
2 High-Efficiency Mapping Function.. 4
3 Optical Design and Reflector Geometry 6
4 Physical Optics Analysis with an Ideal Feed.. 7
5 Tipping Curve with an Ideal Feed 12
6 Physical Optics Analysis with an Actual Feed.. 14
7 Tipping Curve with an Actual Feed 21
8 Conclusions 22

1 Introduction

This document presents a reference design targeting high-efficiency optics for the ngVLA. A new aperture illumination function and its corresponding mapping function underlies this shaped design. The ngVLA specifications allow for higher than typical near-in sidelobes, which allows for a nearly uniform, high-efficiency aperture illumination. However, a high-efficiency design still must have very low spillover so that noise temperature is minimized. The design presented here achieves both of those goals along with very low intrinsic cross polarization and excellent beam symmetry.

2 High-Efficiency Mapping Function

A new mapping function that provides very high illumination efficiency has been developed and implemented in the dual reflector shaping software. This function gives a uniform aperture illumination over almost all of the aperture, with a sharp roll-off near the edge. The function is a scaled and translated version of a hyperbolic tangent function.

The equation for this function is displayed in Figure 1, where it is plotted for the parameters used in this design. The parameter *t* sets the steepness of the roll-off and x0 is chosen indirectly to give the desired edge taper at scaled radius = 1. Figure 1 is for *t* = 10 and x0 is chosen to give an edge taper of .1, –10 dB. The calculated efficiency of this illumination is .95. It is to be expected that an illumination this uniform will result in higher than typical near-in sidelobes.

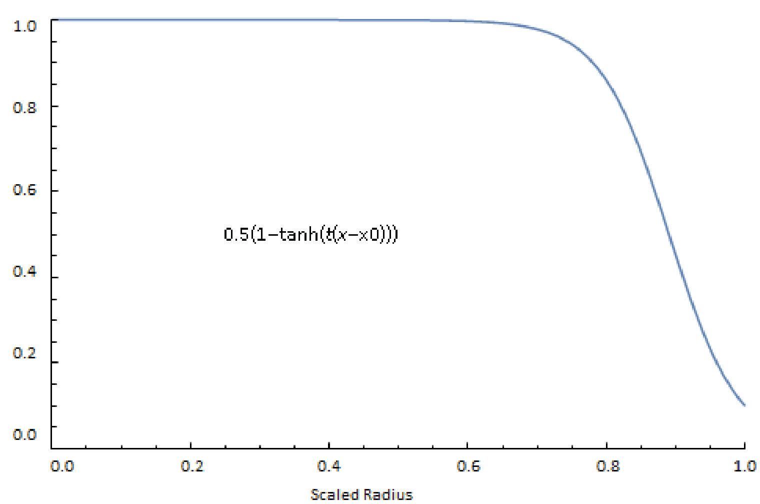


Figure 1 - Aperture illumination relative amplitude.

This function has several useful features besides its general shape of being flat over most of the aperture. It is continuous with continuous derivatives and is composed of a single function over the whole span. It is integrable in closed form on the unit disk (by Mathematica), which facilitates manipulations to obtain the mapping function. It does not go negative for scale radii above one, which allows shaping of the reflectors with extension points beyond the nominal physical edges.

The desired mapping from the feed to the aperture is provided by the transformation given by the shaped optics. The feed pattern function here is taken as a cosine raised to a noninteger power. The power is chosen to give the desired edge taper on the rim of the subreflector. This function also integrates in closed form in spherical coordinates. In this design, the edge angle is 55° and the chosen edge taper is –16 dB.

Transforming this deeply tapered feed pattern to the aperture illumination shown in Figure 1 requires significant redistribution of power, which is described by the mapping function shown in Figure 2. This curve is obtained by equating the integral power inside a given elevation angle at the feed to the same integral power inside the corresponding radius in the aperture. The plot is scaled by the maximum elevation angle and aperture radius so the curve goes from the point 0,0, which is the central ray, out to the point 1,1, which is a ray on the edges of the subreflector and primary. The plot extends beyond the point 1,1 so the reflector shapes can have extension points beyond the physical edges. The dashed straight line passes through the points 0,0 to 1,1 and is close to what a conic section design produces.

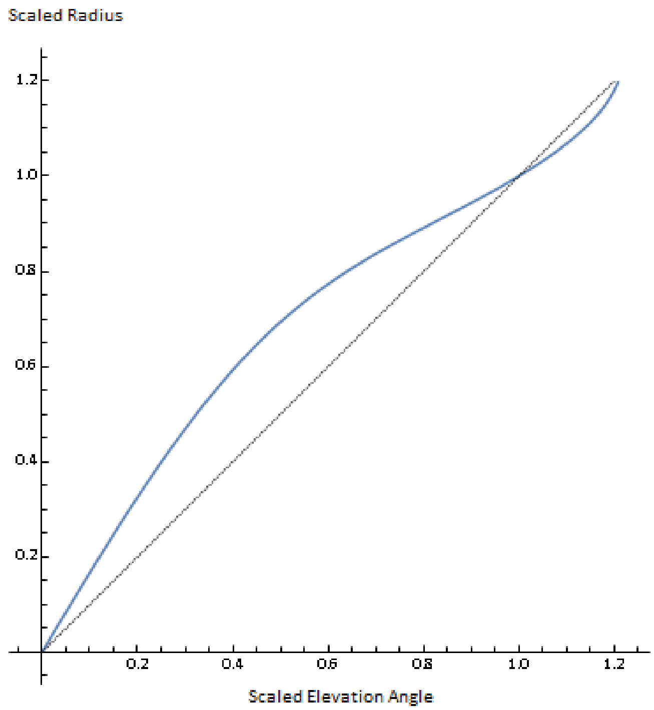


Figure 2 - Scaled mapping function.

The effect of the mapping function can be described as follows. Near the center of the reflectors, the slope of the map is greater than the straight line, which gives a larger increment in radius for a given increment in elevation. This results in the intense central peak of the feed pattern being spread out over a larger area in the aperture plane, reducing its intensity.

Near the middle of the map, the slope is the same as the line and the spreading is moderated. In this area, the feed pattern is lower and less spreading gives an aperture intensity which is the same as near the center. Beyond the middle, the slope of the map is less than the line and this corresponds to the feed intensity being squeezed to raise the intensity in the aperture. The feed pattern is even smaller in this region and the squeezing keeps the aperture intensity uniform. At the very end, the slope starts to increase again, which along with the very low feed intensity provides the sharp roll-off in intensity at the very edge of the aperture. The resultant intensity in the aperture is quite sensitive to small changes in the mapping function because of this derivative behavior. This requires a lot of attention to the calculation and software implementation of any mapping function.

3 Optical Design and Reflector Geometry

Figure 3 shows the cross section of the optical design implementing the mapping function. The geometric parameters are the ngVLA antenna specifications: an 18-meter diameter aperture, a 3.5-meter diameter subreflector, and a 55˚ half opening angle. This design has the subreflector spaced a longer distance from the lower, left edge of the primary. This has the beneficial effect of reducing the tilt angle of the primary and making it somewhat smaller at the expense of a longer feed arm. This choice of the geometry was made in collaboration with the structural design team. The tilt angle of the central ray from the focus is optimized to give low cross polarization, analogous to the Mizugutch condition in conic sections.

The numbers above the secondary and below the primary are the rim-to-rim distance, the area of the surface, and the area of the surface as a fraction of the aperture area.

The behavior described in the mapping section can be seen in the cross section of the optics shown in Figure 3. The rays emanating from the focus are equally spaced in elevation angle. The spacing of the rays in the aperture is larger near the center and get progressively closer together moving outward. The last radial increment at the edge is slightly bigger, which contributes to the deep roll-off in intensity there.

For reference when discussing the physical optics analysis, note the distance from the focus to the surface of the secondary varies by roughly a 2:1 ratio across the span of elevation angles. At lower frequencies, this places the left part of the secondary in the near field of the feed. Another effect is that the area on the secondary inside a quadrilateral formed by four adjacent rays varies by the same 2:1 ratio. These effects combine to blur the illumination of the secondary towards the primary in the vicinity of the ray going to the far right edge of the primary. This gives a progressively larger spillover over the right edge of the primary at lower frequencies.

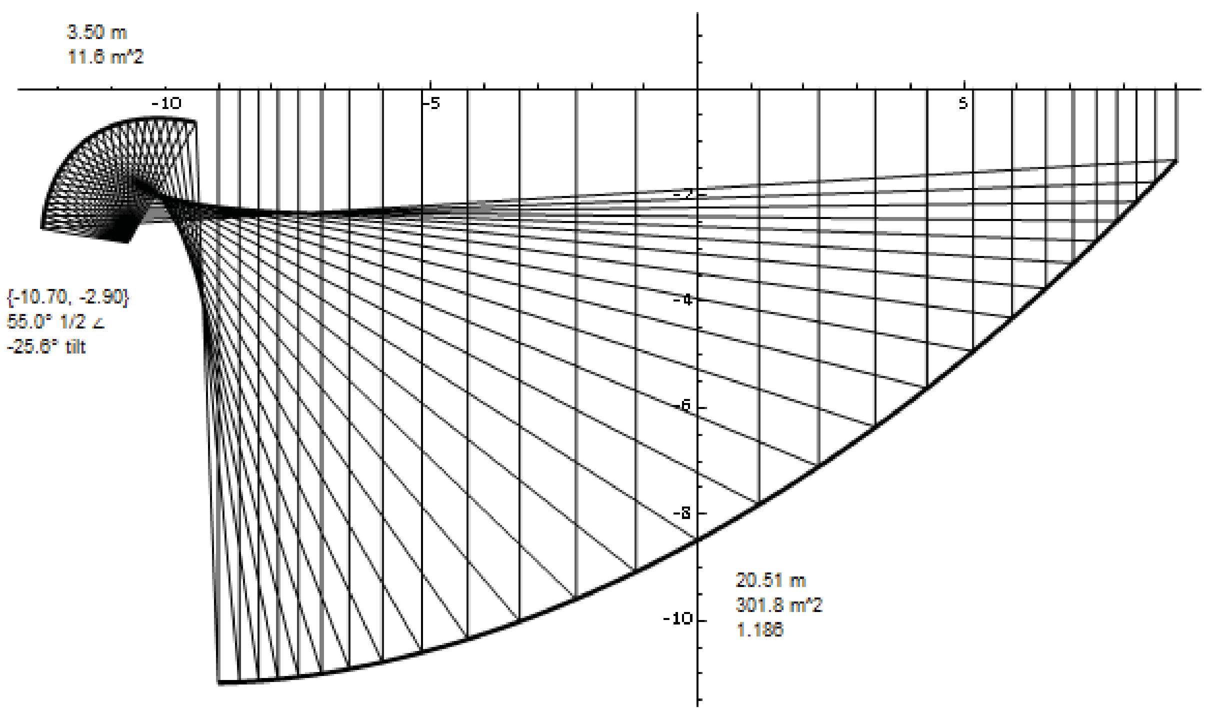


Figure 3 - ngVLA_6 Optics: Cross-section in the symmetry plane.

4 Physical Optics Analysis with an Ideal Feed

The geometry shown in Figure 3 was imported into GRASP for analysis. The first analysis is done with an ideal Gaussian feed pattern having a –16 dB edge taper at 55°. This differs slightly from the cosine function used to develop the mapping function but is the best available choice in GRASP.

This first analysis was performed at 5 GHz, which is a good compromise between fast runs and avoiding most low-frequency diffraction effects. Analyzing the optics with a perfect feed establishes a baseline performance so the effects of a real feed can be seen separate from the optics performance.

The copolar aperture illumination on the plane at z = 0 is shown in Figure 4. The illumination is nearly uniform across the aperture with a steep roll-off at the edge. This confirms that the design mapping function was successfully achieved. Although obscured by the wide logarithmic scale, there is some diffraction ripple across the aperture plane, which is expected since the z = 0 plane is some distance from the primary reflector. The left side of the plot shows the interference effects of the feed spillover interacting with the aperture illumination. This does not affect the main beam performance since the spillover and aperture project to different angles in the far field.

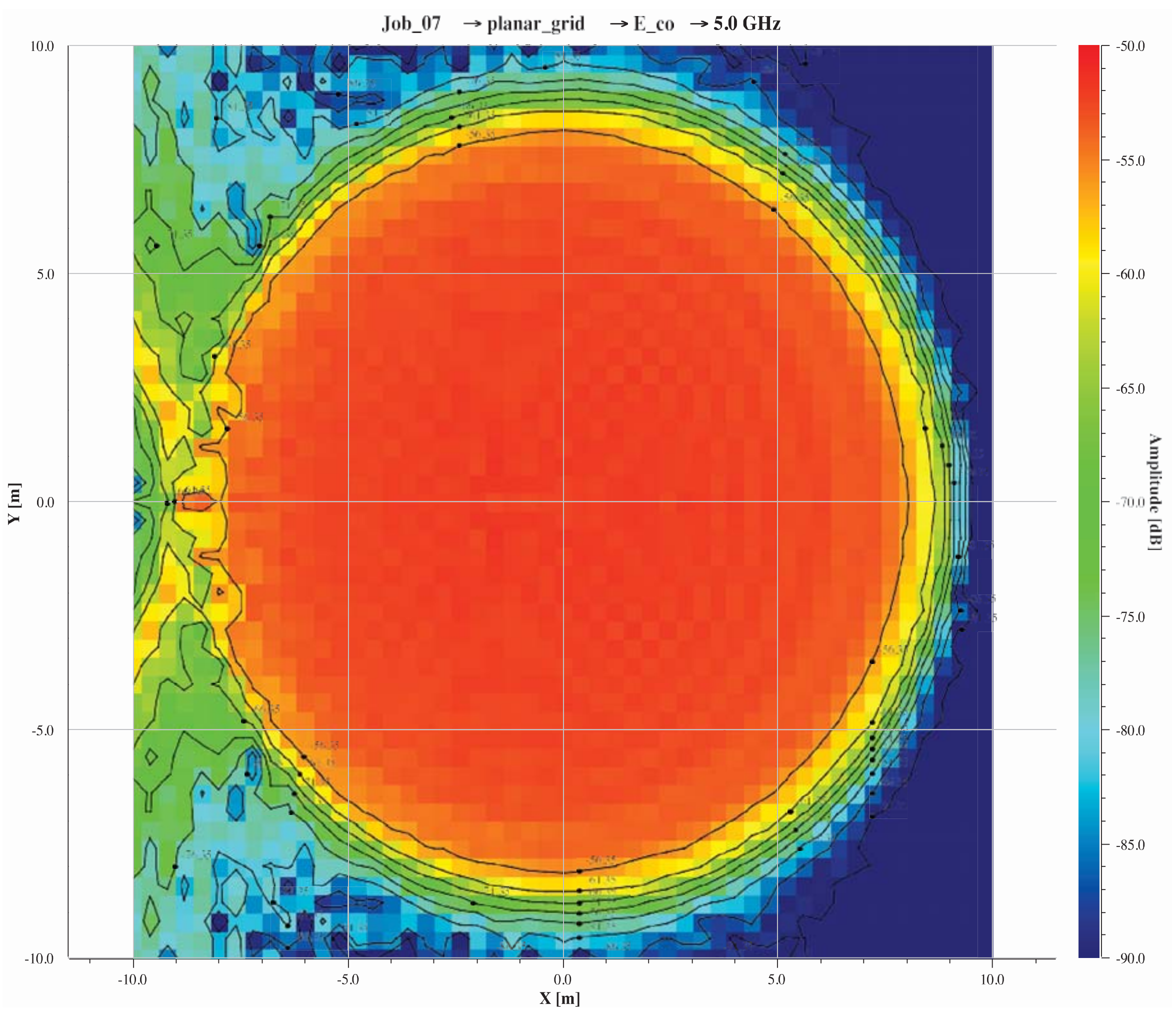


Figure 4 - Copolar aperture illumination on the plane at z = 0.

Figure 5 shows the close-in far-field pattern in three azimuth cuts at 0°, 45°, and 90°. The vertical scale is gain over isotropic in dB. The peak gain is 59.0 dB, which corresponds to an overall efficiency of .89. The illumination efficiency is .95 and the feed spillover past the secondary is a factor of .98.

Other small factors combine to give the final overall efficiency. The first sidelobe level is –19 dB below peak. The second sidelobe level about –27 dB. These values are higher than typical designs with conics and result from the nearly uniform aperture illumination. The maximum cross-polar level is about –45 dB below the main beam peak. The cross polarization is everywhere zero in the symmetry plane and peaks in the plane perpendicular to the symmetry plane. The intrinsic cross polarization of the optics is very small, smaller than the cross polarization introduced by any realistic feed. The rotational symmetry of the main beam is essentially perfect.

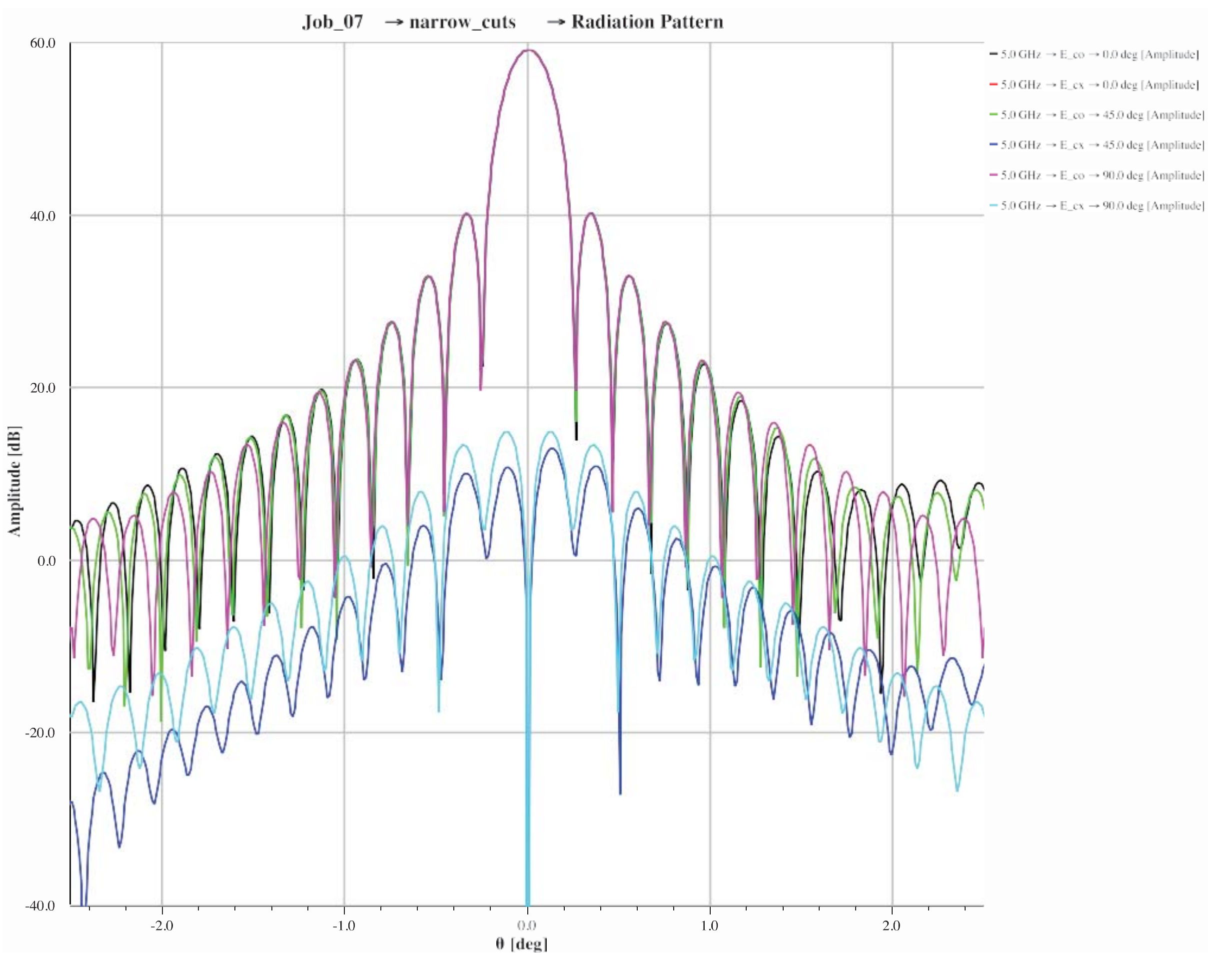


Figure 5 - Close-in far-field pattern using azimuth cuts at 0°, 45°, and 90°.

To better understand the wide-angle pattern and especially the tipping curve, it is useful to visualize the entire far-field sphere to see the general features. Figure 6 and Figure 7 show the far-field sphere in two halves, the north and south hemispheres. Each hemisphere is projected and plotted on a unit disk, which distorts the view slightly but still gives a good sense of the features. The color bar gives the scaling in dBi.

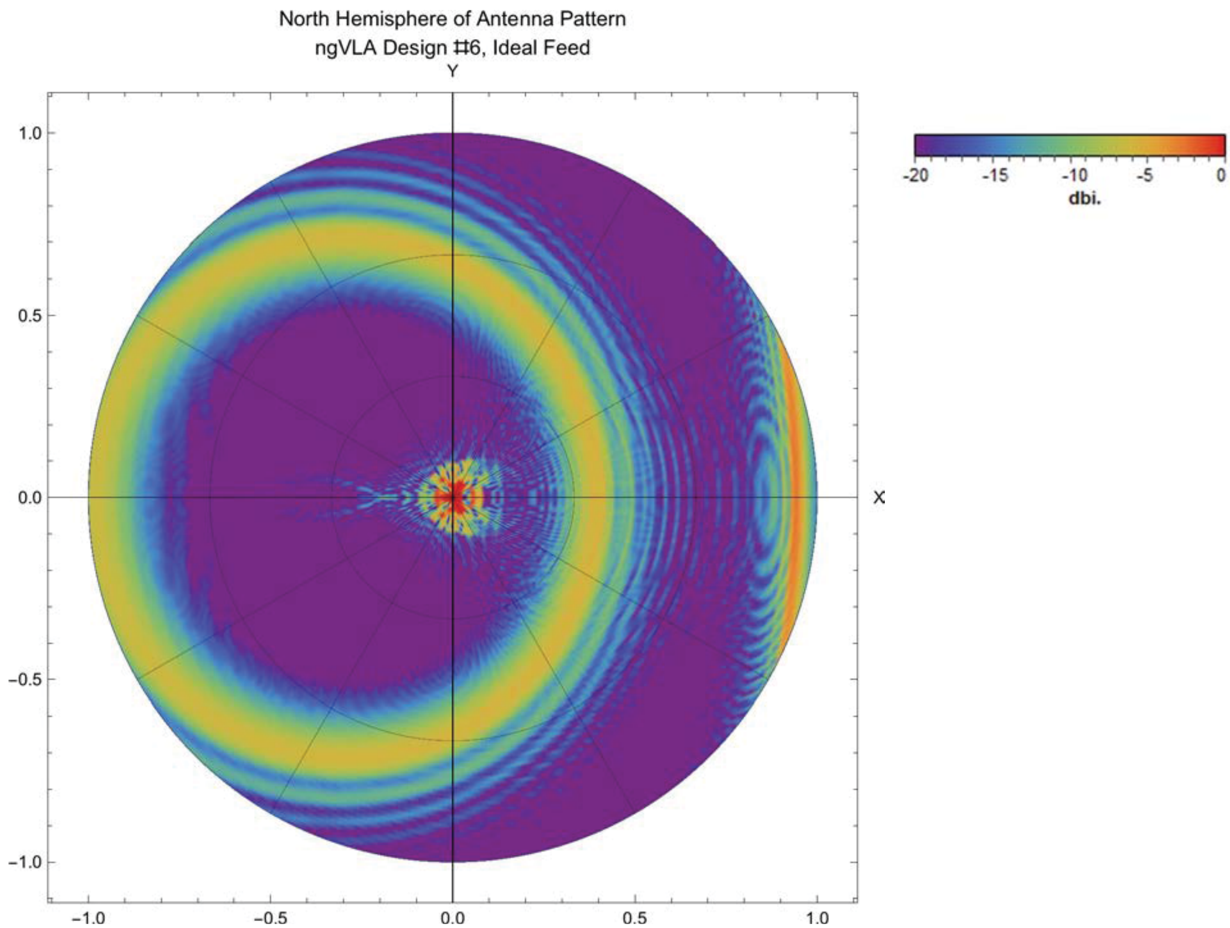


Figure 6 - Unit disk projection of the far-field response, north hemisphere.

There are two main features outside of the main beam at the North Pole. In the north hemisphere, the feed spillover past the secondary is very clear. The feed tilt angle is about –25° with an opening angle of +/–55°. In the symmetry plane, the spillover is just past the geometric edges at –80° and 30°. Perpendicular to the symmetry plane, the spillover is just past +/–55°.

On the right side of the north hemisphere, there is a small part of the secondary spillover past the primary. This area corresponds to the ray that goes from the left edge of the secondary to the right edge of the primary and is slightly above the horizon.

Looking at the arc of the secondary spillover above the horizon shows it is slightly more intense than the rest of the secondary spillover seen in the south hemisphere. As discussed above, this is due to that part of the secondary being closer to the focus. The effect is very minor at 5 GHz and will get smaller at higher frequencies and larger at lower frequencies.

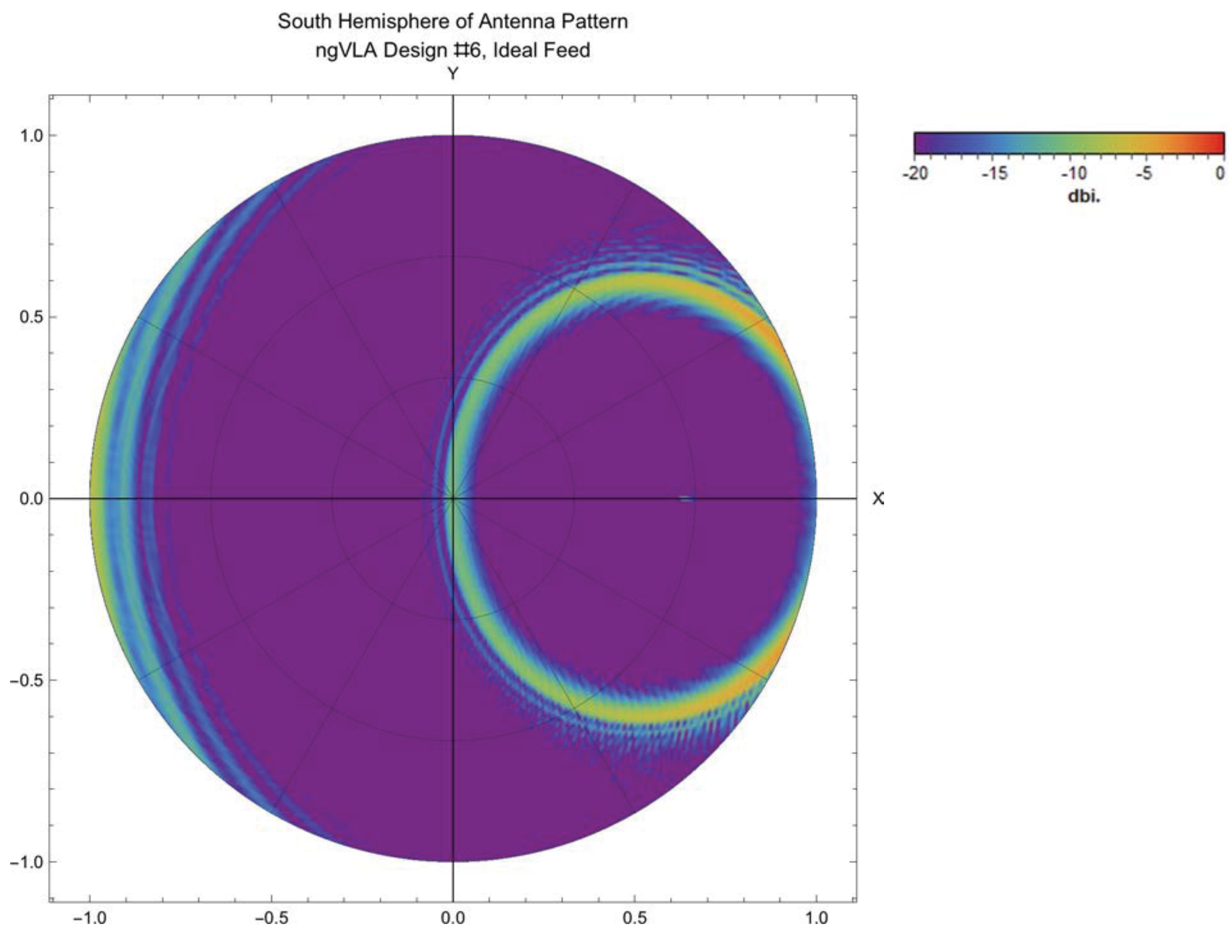


Figure 7 - Unit disk projection of far-field response, south hemisphere.

Figure 8 shows the far-field pattern over the entire range of elevation angles and the same three azimuth cuts. The main features here are the very low wide-angle sidelobes. The peaks of the wide pattern are at least –6 dB below isotropic except the small peak at 85° which is the spillover past the primary discussed above. The other peaks correspond to various parts of the feed spillover as shown above.

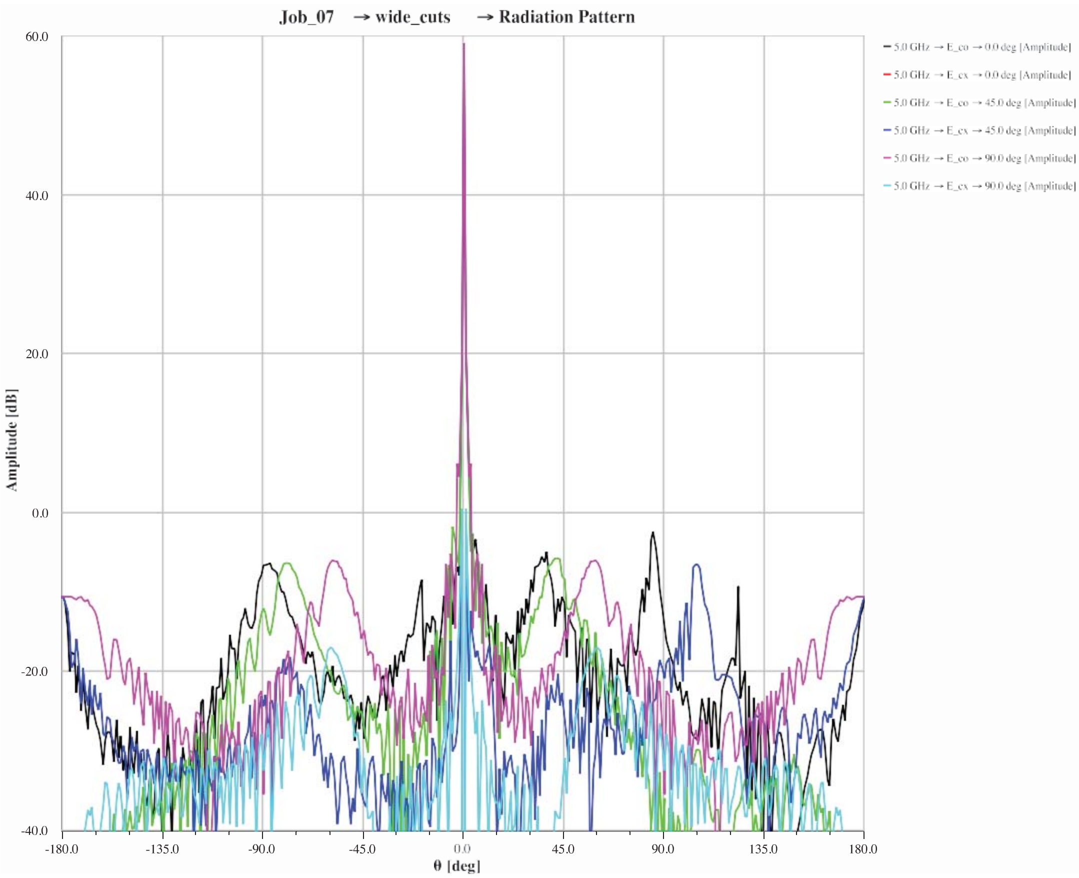


Figure 8 - Plot of far-field pattern over the entire range of elevation angles and azimuth cuts of 0°, 45°, and 90°.

One effect might slightly disturb the far-field main beam: The edge diffraction past the rim of the secondary fans out in a range of angles, some of which are essentially parallel to the main beam. This small contribution to the main beam has a different path length and goes in and out of phase with varying frequency. This produces a small gain ripple versus frequency on boresight. This effect was first documented by the South African MeerKAT/SKA team. In this case, it is mitigated by the very deep edge taper on the secondary. A future calculation could quantify its effect here.

5 Tipping Curve with an Ideal Feed

A key parameter of the antenna design is the contribution to system noise temperature from spillover outside of the main beam area at all pointing angles. To calculate this, a model of the noise environment surrounding the antenna is required. Figure 9 shows the SKA standard noise model at 5 GHz. Comparison with site specific data at the VLA site shows this model to be slightly pessimistic in the upper hemisphere. The contribution of the receiver is not included in these plots.

To compute the tipping curve, the noise model is multiplied by the antenna pattern at various tilt angles and integrated over the sphere. To simplify the calculation the simple noise model is tilted instead of the complicated antenna pattern, but the result is the same.

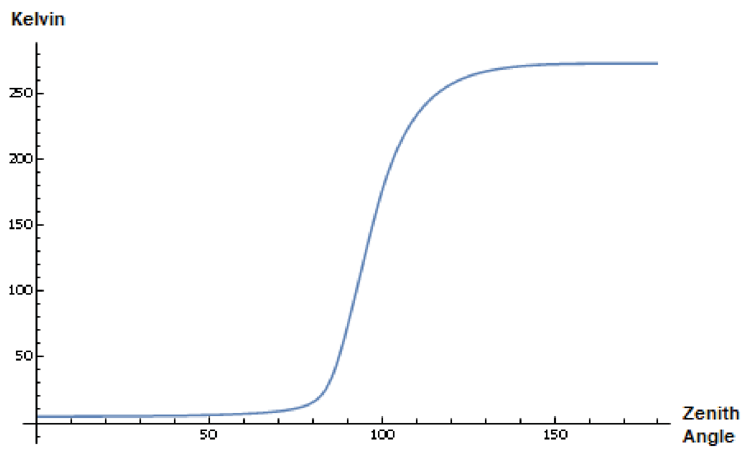


Figure 9 - SKA noise model of brightness temperature at 5 GHz.

The result of the calculation is shown in Figure 10 for both feed arm up and feed arm down pointing. The noise model is also shown so that the effect of spillover can be directly seen. If the antenna pattern was a delta function, then the tipping curve would be the same as the noise model. Any difference is due to the small wide-angle spillover illuminating various parts of the noise model.

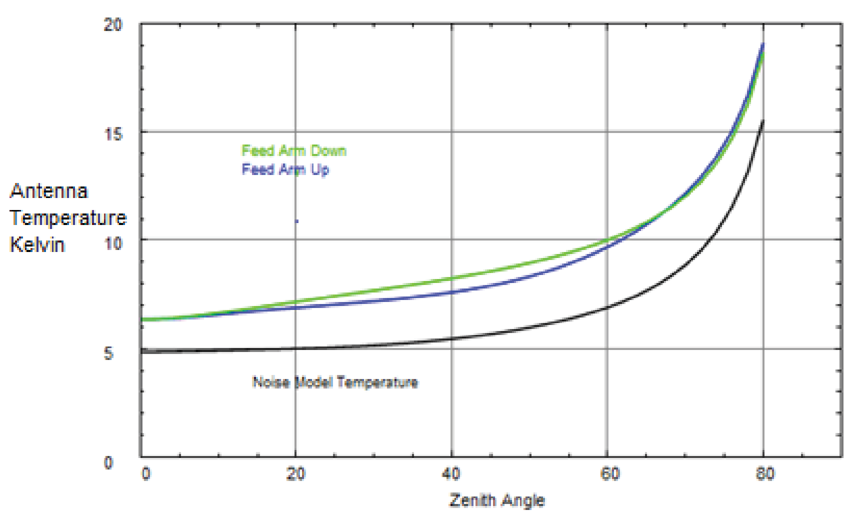


Figure 10 - ngVLA Design #6, tipping curve at 5 GHz with ideal feed and SKA noise model.

There is only a small difference between feed up and feed down pointing. Feed arm down pointing steadily rotates the feed spillover on to the warm ground while the spillover past the primary rotates up on to the cold sky. In this case the feed spillover is a bit larger so the net effect is a slightly larger noise increase. The converse happens for feed up pointing. The feed spillover stays on the sky until at larger zenith angles where the part at +30° crosses the horizon. The smaller spillover past the primary rotates completely on the ground and stays there.

The MeerKAT and SKA antenna designs from the South African design team have an extension on the lower edge of the subreflector, which redirects part of the feed spillover to over the far edge of the primary. For feed arm down pointing, this mitigates the effect of the feed spillover striking the ground and gives a better result. Such an extension could be investigated as an addition to this design.

Another possible way to improve the tipping curve would be increasing the edge taper on the secondary to a level below –16 dB, capturing more of the feed energy in the optics.

Reiterating a point discussed before, the slightly larger spillover due to diffraction effects on the secondary will get larger as the frequency goes lower. In the SKA case, where the operating frequency goes well below 1 GHz, it gets very large and dominates the tipping behavior. Conversely, at frequencies higher than the 5 GHz here, it will get even smaller.

For comparison to other designs and reports, Figure 11 plots the difference between the noise model and tipping curves in Figure 10. Leaving the details aside, the spillover noise contribution is very small overall. At the higher-frequency bands of the ngVLA, the sky and receiver temperatures will dominate over this small contribution.

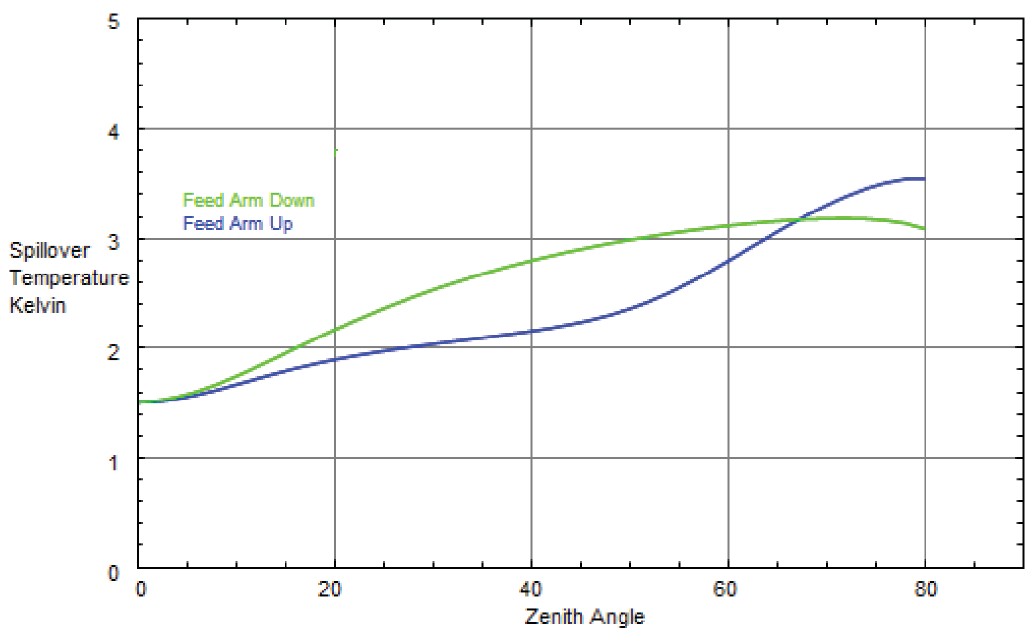


Figure 11 - ngVLA Design#6, spillover curve at 5 GHz with ideal feed and SKA noise model.

6 Physical Optics Analysis with an Actual Feed

The optics are next analyzed with the corrugated horn feed shown in Figure 12, with the pattern plot in Figure 13. This axial ring design was developed for the DVA1 project at L-band. It has excellent performance over an octave bandwidth and is compact, an important trait at L-band. The original L-band design was scaled to the frequency range of 4 to 8 GHz, which places the 5 GHz analysis frequency in the lower part of the frequency coverage.

The performance with this feed is very close to the performance with a perfect feed. The commentary in the previous sections applies, with small changes, so only the differences in the two cases will be discussed.

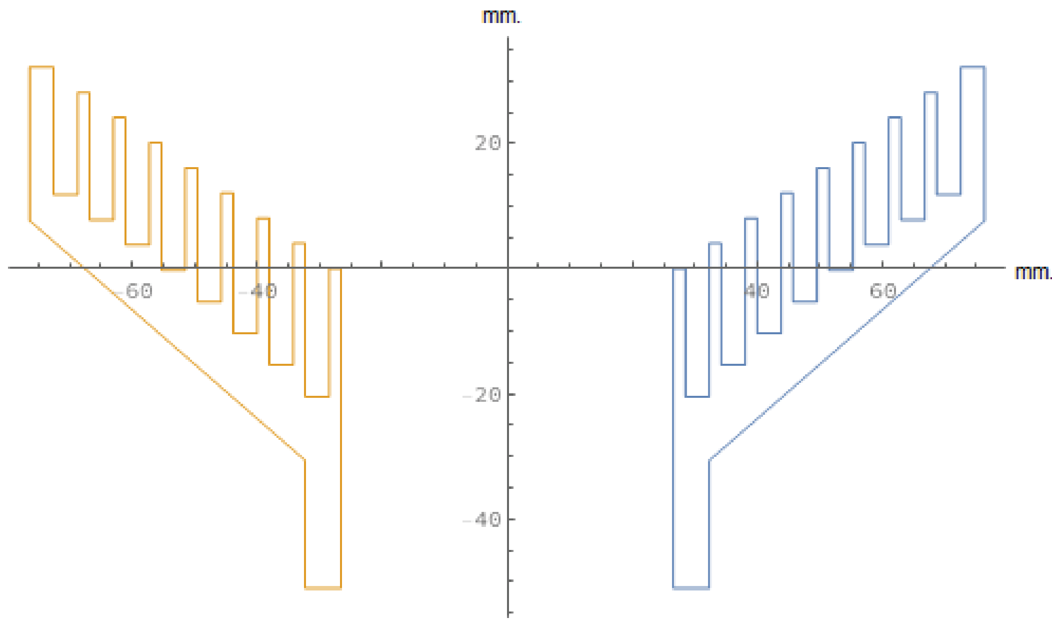


Figure 12 - Cross-section of corrugated feed horn used for analyzing the ngVLA_6 optics performance.

The feed pattern in Figure 13 has an edge taper slightly deeper than –16 dB. However, when placed in the optics, it has a slightly larger spillover than the perfect Gaussian feed. This may be due to a difference in overall shape and possibly small phase errors in outer edges of the feed illumination.

Otherwise, the pattern is almost perfectly rotationally symmetric and has small cross polarization, which is zero in the principle planes and peaks in the diagonal planes.

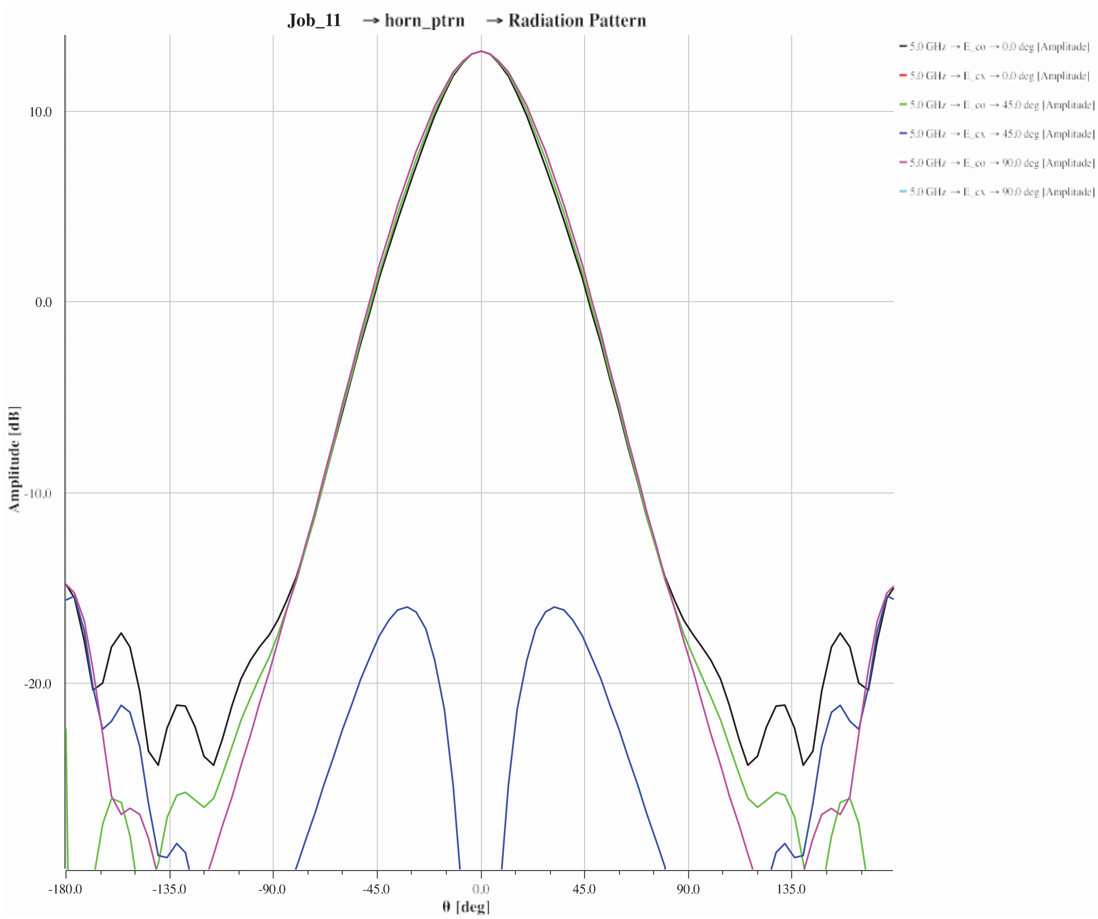


Figure 13 - ngVLA_6 feed pattern plot, using the corrugated horn feed shown in Figure 12.

The illumination in the z = 0 aperture plane (Figure 14) is very similar to before. The diffraction ripple is a little more evident, which may be due to this plot being generated with quadruple the number of data points. The deep cutoff at the edge is still the same. The interference effect on the left side is a little more extensive, evidence that the spillover from this horn feed is slightly larger than the perfect feed.

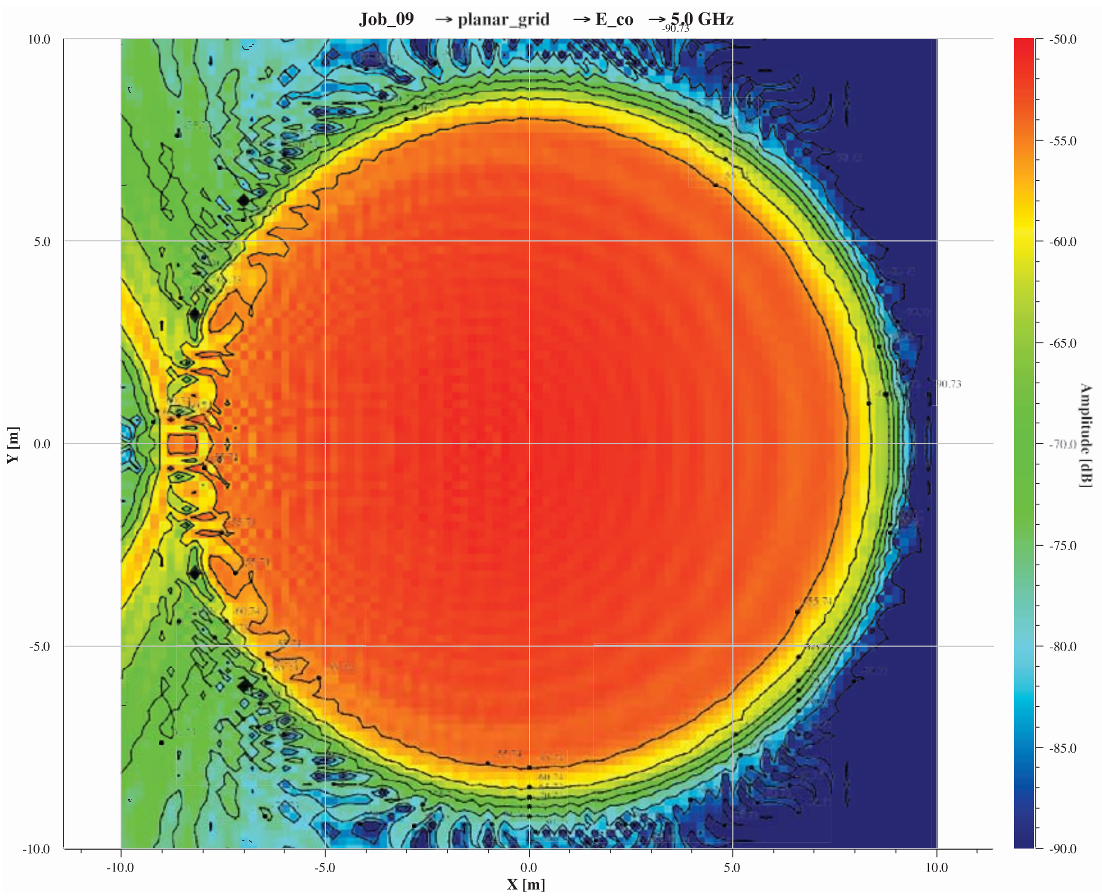


Figure 14 - Illumination pattern of ngVLA_6 in z = 0 aperture plane using the corrugated feed horn.

The close-in beam pattern is shown is Figure 15. The peak gain is 58.9 dBi, which is slightly lower and corresponds to an overall efficiency of 0.87. The small drop in efficiency is partly caused by small phase errors in the real feed. Any realistic feed will have some phase errors in the low level parts of the pattern. Another difference is the increased cross polar level in the diagonal plane. Corrugated horns have a "four leaf clover" cross polar pattern, and this is what causes the increased cross polar level. It is still quite small at about –32 dB below peak and the peak is outside the –3 dB level on the main beam. There is also a tiny asymmetry in the sidelobes.

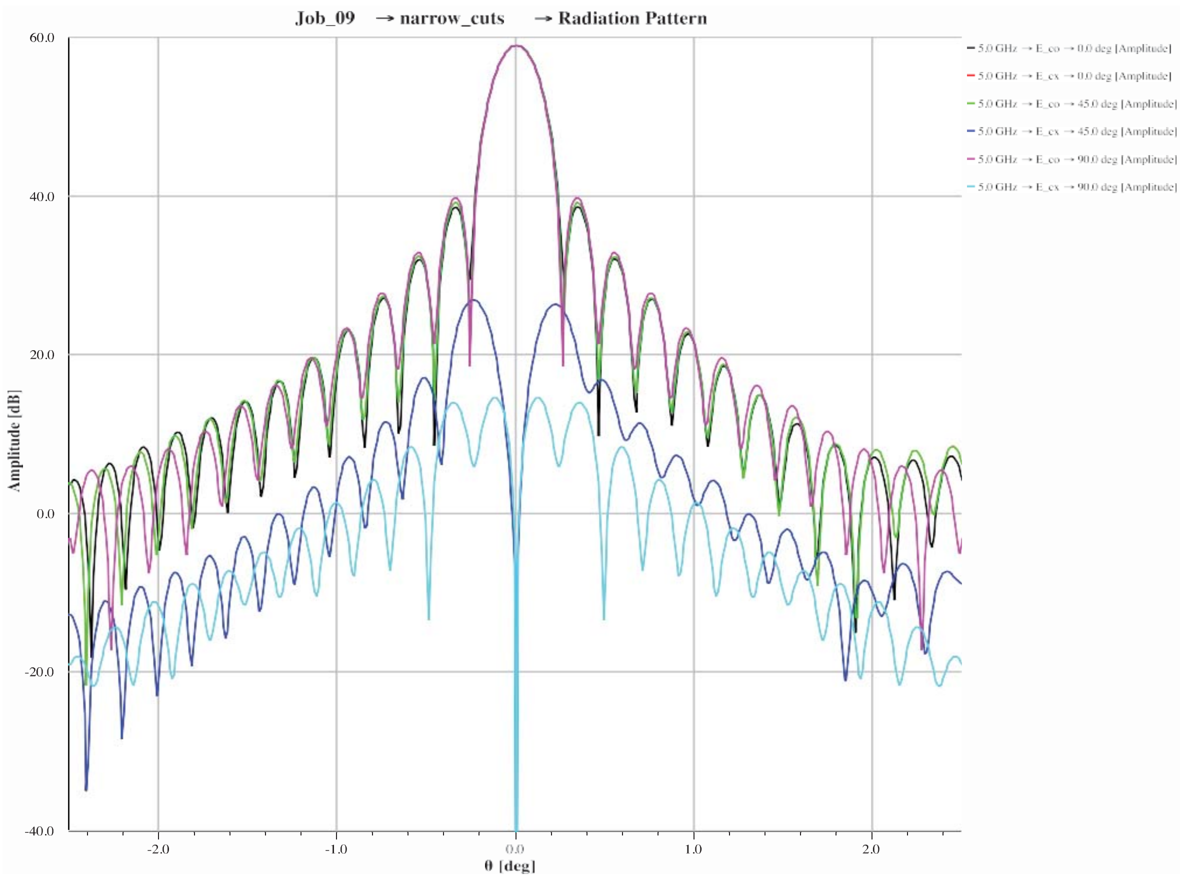


Figure 15 - Plot of close-in beam pattern for ngVLA_6 using the corrugated feed horn.

Figure 16 and Figure 17 show the pattern on the far-field sphere. The slightly larger spillover of the feed past the secondary is evident. This will have a small effect on the tipping curve, especially feed down. Otherwise, all of the previous commentary holds.

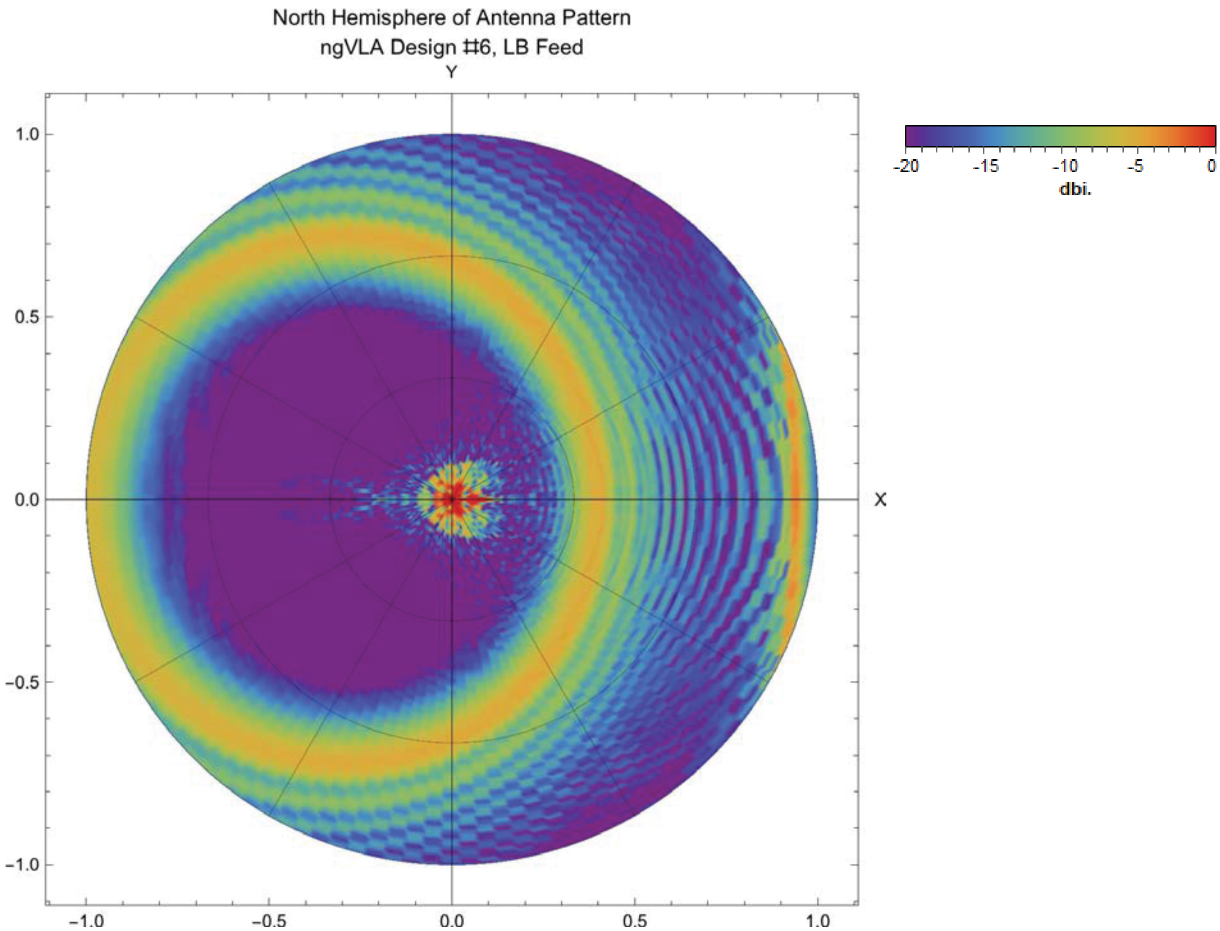


Figure 16 - Unit disk projection of far-field illumination pattern using corrugated feed horn, north hemisphere.

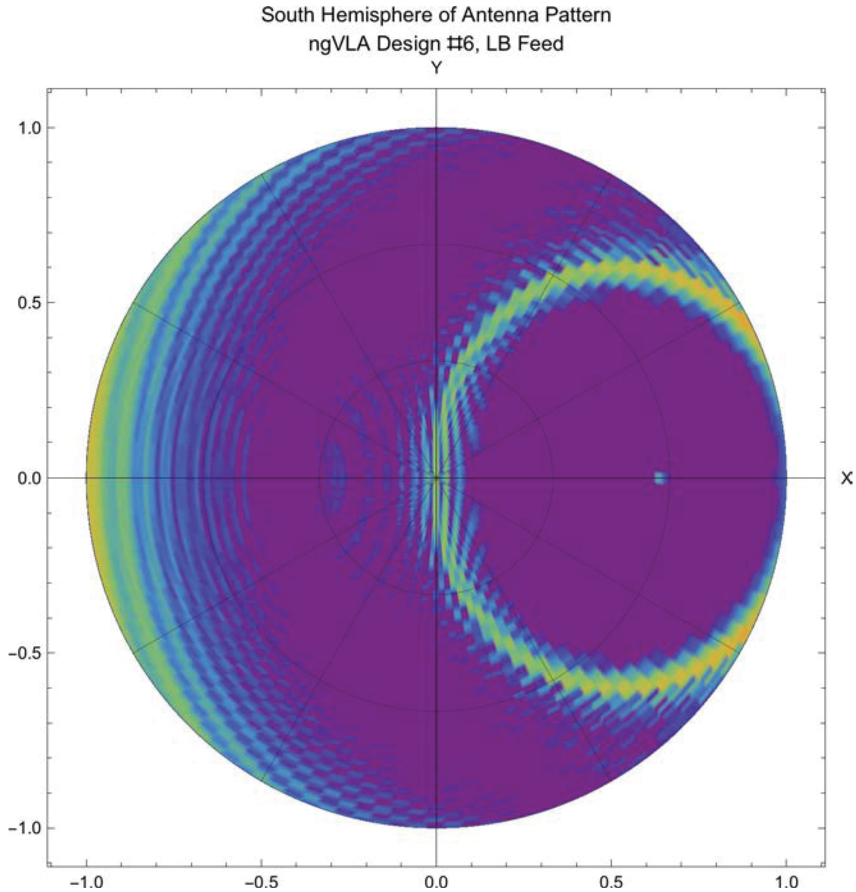


Figure 17 - Unit disk projection of far-field illumination pattern using corrugated feed horn, north hemisphere.

Figure 18 shows the wide-angle far-field pattern. All of the general features are the same with the peaks of the feed spillover being approximately 1 dB larger.

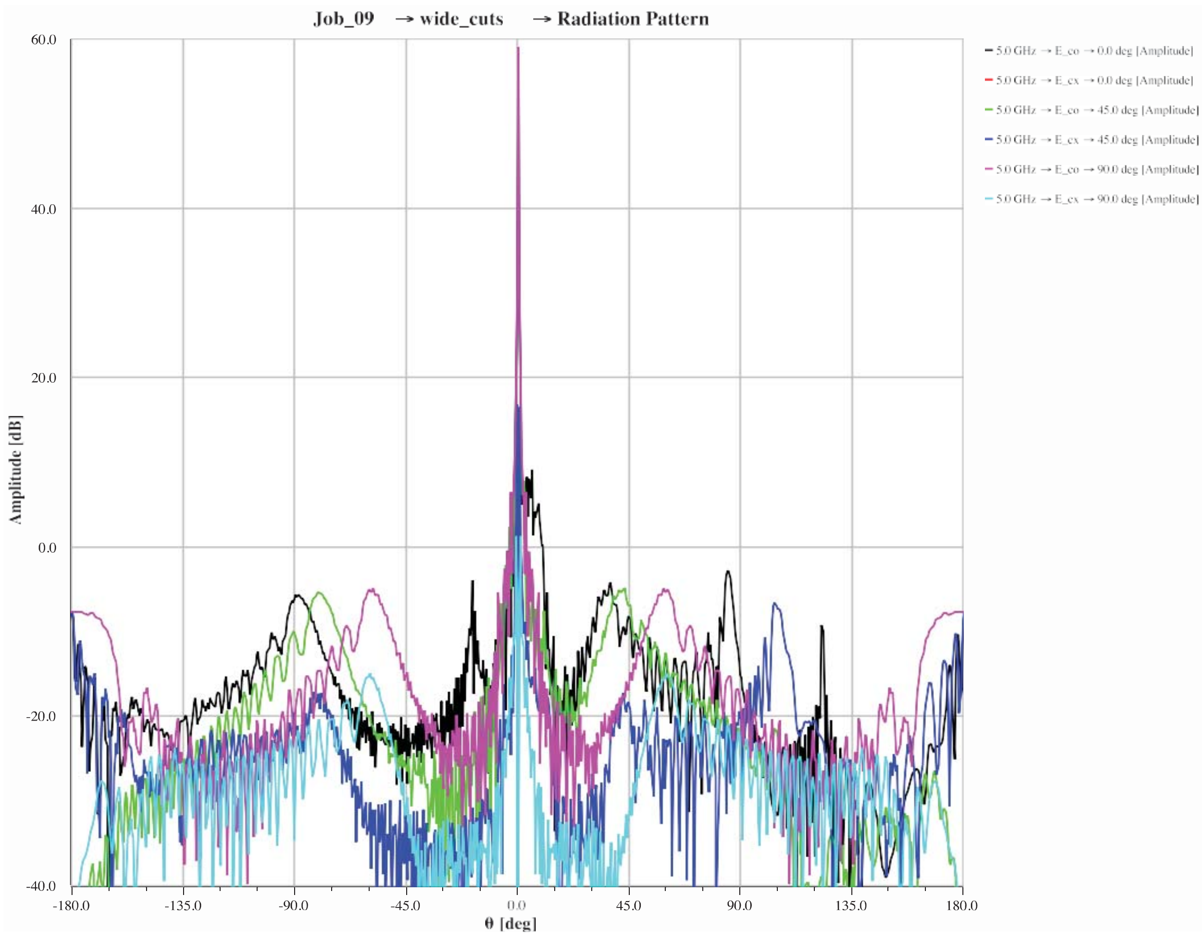


Figure 18 - Plot of wide-angle far-field illumination pattern using corrugated feed horn.

7 Tipping Curve with an Actual Feed

Figure 19 shows the tipping curve, which is mostly similar to before with an extra .5 Kelvin at zenith and the feed down curve being somewhat worse. Again, for feed down, a subreflector extension would likely improve the performance.

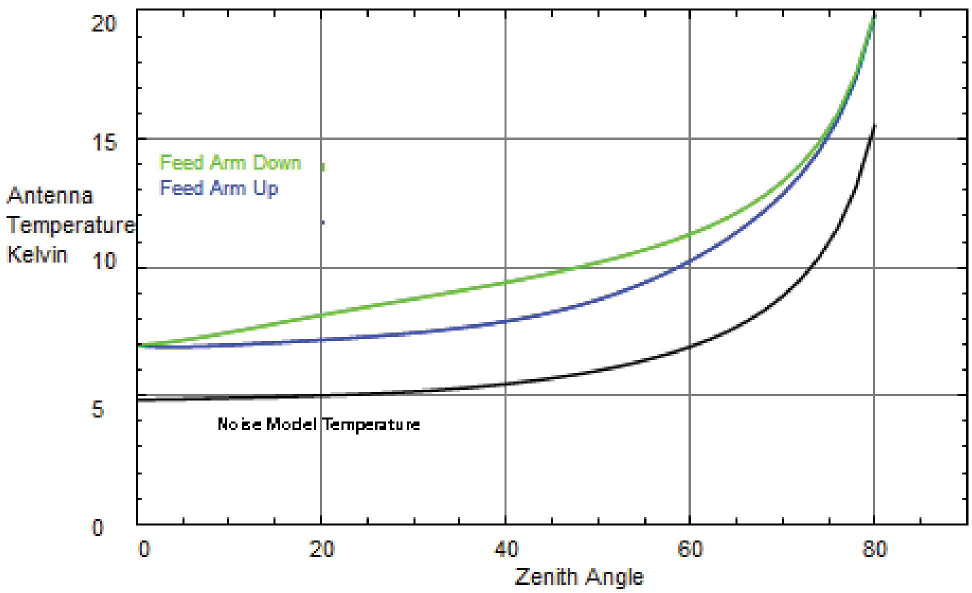


Figure 19 - ngVLA_6 tipping curve at 5 GHz with corrugated feed horn and SKA noise model.

Figure 20 shows spillover performance. The spillover temperature differs notably between feed arm up and feed arm down.

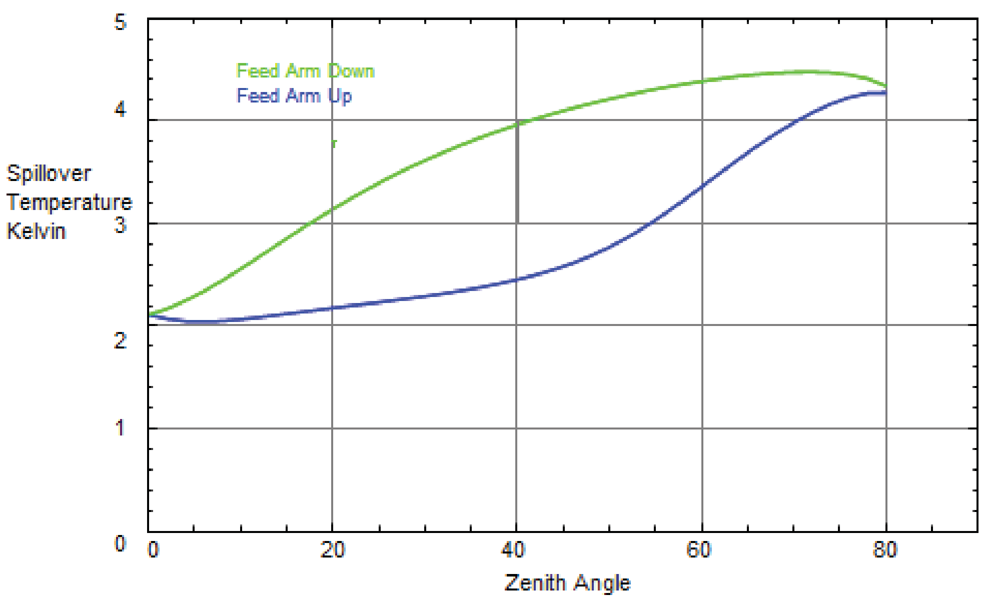


Figure 20 - ngVLA_6 spillover curve at 5 GHz with corrugated feed horn and SKA noise model.

8 Conclusions

This first design for the ngVLA antenna optics is very successful, achieving both high efficiency and very low antenna temperature. The performance with a realistic feed horn is very close to the performance with a mathematically perfect feed at 5 GHz.

It should be emphasized that the performance is dominated by the choice of feed. Other possible feeds should be analyzed in the optics to compare performance results. This first design could be modified with an extension on the subreflector or a modification to the optics to improve the feed-down tipping. Review of the overall geometry from a structural perspective might also suggest changes.

ngVLA 18m Antenna Preliminary Design Document

Document Number 101-0000-001-PDD-001

Revision: 1

Author .... Dean Chalmers

Date 2019-07-25

Status .... Released

Classification.. Unrestricted

Prepared By	Name	Dean Chalmers	Signature	
	Organisation	NRC		
Reviewed By	Name	Gordon Lacy	Signature	Gordon Lacy Gordon Lacy (Jul 29, 2019)
	Organisation	NRC		
	Name		Signature	
	Organisation			
	Name		Signature	
	Organisation			
Approved By	Name	Scott Roberts	Signature	Scott Roberts Scott Roberts (Jul 30, 2019)
	Organisation	NRC		
Issued By	Name	Donna Morgan	Signature	
	Organisation	NRC		

[This document describes preliminary design for the ngVLA 18m Antenna Design project.]

DOCUMENT HISTORY

Revision	Date	Change Request	Change Description
A	17Sep2018		Initial draft for comment
B	24Jan2019		Post PDR Update
1	25July2019		Approved for release

DOCUMENT SOFTWARE

Application		Version	Filename
Wordprocessing	MSWord		101-0000-001-PDD-001_PreDesignDoc_1_2019-07-25

ORGANISATION DETAILS

Designation	Name	Organisation
Primary Author and Responsible Organisation	Dean Chalmers	NRC
Contributors	G. Lacy	NRC
	M. Islam	NRC
	M. Fleming	Minex
	M. Wessel	SED Systems
	R. Osterried	SED Systems
	R. Hellyer	NRC
	J. Fitzsimmons	NRC
	L. Baker	Consultant
	B. Veidt	NRC

TABLE OF CONTENT

1 INTRODUCTION 10

1.1 Purpose of Document 10

1.2 Scope of Document 10

1.3 Intended Audience 10

1.4 Project WBS 11

2 APPLICABLE AND REFERENCE DOCUMENTS 12

2.1 Applicable Documents 12

2.2 Reference Documents 12

3 OPERATIONAL CONTEXT 14

3.1 Operational Environment 14

4 ASSUMPTIONS AND RISKS 17

4.1 Assumptions 17

4.1.1 SRC Transportation to Antenna Locations 17

4.2 Risks 17

5 PRELIMINARY DESIGN 21

5.1 Design Background 22

5.2 Design Overview 25

5.2.1 Elevation Rotating Assembly 25

5.2.2 Mount 39

6 PERFORMANCE 54

6.1 System Noise Contribution 54

6.2 Integrated Model Finite Element and Electromagnetic Analysis 55

6.3 Aperture Efficiency 56

6.3.1 Simulated Efficiencies 57

6.3.2 Calculated Efficiencies 82

6.3.3 Total Efficiency 85

6.4 Pointing 87

6.5 Survivability 92

6.6 Potential Areas of Improvement 92

7 MAINTENANCE, RELIABILITY AND LIFETIME 95

7.1 Maintenance and Reliability 95

7.2 Design Life 96

8 FUTURE WORK 97

8.1 Design and Analysis 97

8.1.1 Drive System Trade Study 97

8.1.2 iBUS to oBUS Connection 97

8.1.3 Surface Adjusters 97

8.1.4 Feed/Secondary Support Structure 97

8.1.5 Feed Indexer 97

8.1.6 Complete Integrated FEA Model 97

8.1.7 Yoke Structure Optimization 98

8.1.8 Multi-piece Primary Reflector Concept 98

8.2 Logistics 98

8.3 Prototyping and Testing 98

8.3.1 Surface Adjusters 98

8.3.2 Process Induced Distortion Study 98

8.3.3 Multi-piece Concepts 98

8.4 Materials Analysis and Testing 98

LIST OF TABLES

Table 1 Applicable Documents........ 12
Table 2 Reference Documents........ 12
Table 3 Precision Operating Conditions........ 14
Table 4 Normal Operating Conditions........ 15
Table 5 Limit to Operating Conditions........ 15
Table 6 Survival Conditions........ 16
Table 7 Project Risks........ 18
Table 8 Product Risks........ 19
Table 9 Elevation Drive Loads (based on average wind speeds)........ 41
Table 10 Elevation Drive Performance Matrix........ 43
Table 11 Azimuth Rotating Structure Components........ 46
Table 12 Azimuth Drive Loads (based on average wind speeds)........ 48
Table 13 Direct Drive Azimuth Motor Performance Matrix........ 50
Table 14 Azimuth Direct Pinion Drive Performance Matrix........ 52
Table 15 System Noise Contributions Requirement........ 54
Table 16 Aperture Efficiency Related Requirements........ 56
Table 17 Proposed Antenna Efficiency Specification........ 57
Table 18 Gain for Undistorted Surfaces........ 61
Table 19 Gain and Efficiency, Gravity Load Cases........ 67
Table 20 Gain and Efficiency, Wind Load Cases........ 74
Table 21 Primary Reflector Component CTEs........ 75
Table 22 Gain and Efficiency, Thermal Load Cases........ 81
Table 23 Precision Operating Target Surface Accuracy Error Budget........ 82
Table 24 Normal Operating Target Surface Accuracy Error Budget........ 82
Table 25 Secondary Surface Accuracy Precision........ 83
Table 26 Secondary Surface Accuracy Normal........ 83
Table 27 Secondary Reflector Efficiency Precision........ 84
Table 28 Secondary Reflector Efficiency Normal........ 84
Table 29 Primary Surface Accuracy Precision........ 84

Table 30 Primary Surface Accuracy, Normal........ 85
Table 31 Primary Reflector Efficiency Precision........ 85
Table 32 Primary Reflector Efficiency Normal........ 85
Table 33 Efficiency Calculation Cases........ 86
Table 34 Aperture Efficiency, Precision Operating Condition........ 86
Table 35 Aperture Efficiency, Normal Operating Condition........ 87
Table 36 Estimated Efficiency for All Frequency Bands, Precision........ 87
Table 37 Estimated Efficiency for All Frequency Bands, Normal........ 87
Table 38 Precision Pointing Requirements........ 88
Table 39 Normal Pointing Requirements........ 88
Table 40 Reference Pointing Model Compensation........ 89
Table 41 Pointing Errors; Precision, Uncompensated (except SPEM)........ 90
Table 42 Pointing Errors; Normal, Uncompensated (except SPEM)........ 91
Table 43 Maintenance Requirements........ 95
Table 44 Design Life Requirements........ 96

LIST OF FIGURES

Figure 1 NRC ngVLA 18m Antenna Design Concept........ 21
Figure 2 NRC Mk1 Dish........ 22
Figure 3 NRC Mk2 Dish........ 23
Figure 4 Allen Telescope Array 6m Antenna........ 23
Figure 5 DVA1 Antenna........ 24
Figure 6 NRC 15m Antenna Study........ 25
Figure 7 Primary surface edge adjuster tab concept........ 26
Figure 8 Primary surface edge adjuster with oBUS........ 27
Figure 9 Surface Reinforcement Patches........ 27
Figure 10 Assembled oBUS structure........ 28
Figure 11 oBUS assembly details........ 29
Figure 12 Cross Section of Antenna at Low (12º) Elevation Angle........ 30
Figure 13 iBUS with its 11 Discrete Connection Points to the oBUS........ 30

Figure 14 iBUS structure 31
Figure 15 Secondary Support Structure. 32
Figure 16 Stiffening Ribs on Primary Reflector to Support Secondary Support Structure 33
Figure 17 Secondary and Feed Support Structure. 33
Figure 18 Primary Surface cut Panel Dimensions [ft] 34
Figure 19 Proposed multi-piece primary surface connection detail 35
Figure 20 Cross section through one of the primary surface joining bolts showing the inserts 35
Figure 21 Lifting points added to one of the 4 primary surface panels 36
Figure 22 Assembly jig for the primary surface parts 37
Figure 23 One of the four primary surface parts on its transport jig and flat deck trailer 37
Figure 24 Nesting multiple instances of primary surface pieces for transport to remote sites 38
Figure 25 Four primary surface parts being added to the assembly jig 38
Figure 26 Elevation Drive Stator Pylon Structure 40
Figure 27 Elevation Drive Load Path and Drive Components 41
Figure 28 Elevation Drive Configuration 42
Figure 29 Azimuth Rotating Structure 45
Figure 30 Yoke and Elevation Drive Structure 45
Figure 31 Azimuth Bearing Detail 46
Figure 32 Azimuth Pinion/Gear Drive 47
Figure 33 Azimuth Drive Options 48
Figure 34 Inside Cylindrical Rotor Direct Drive 49
Figure 35 Direct Drive Azimuth Motor X-section 49
Figure 36 Direct Pinion/Gear Drive 51
Figure 37 Reflector Surface Noise Measurement Results 54
Figure 38 (a) Integrated FE model (15° elevation angle), (b) example FEA results 55
Figure 39 Undistorted Surfaces Beam Pattern 10 GHz 58
Figure 40 Undistorted Surfaces Beam Pattern 30 GHz 59
Figure 41 Undistorted Surfaces Beam Pattern 50 GHz 60
Figure 42 15° Elevation Angle Gravity Loading Case Beam Pattern 10 GHz 62
Figure 43 15° Elevation Angle Gravity Loading Case Beam Pattern 30 GHz 63
Figure 44 15° Elevation Angle Gravity Loading Case Beam Pattern 50 GHz 64

Figure 45 90° Elevation Angle Gravity Load Case Beam Pattern 10 GHz 65
Figure 46 90° Elevation Angle Gravity Load Case Beam Pattern 30 GHz 66
Figure 47 90° Elevation Angle Gravity Load Case Beam Pattern 50 GHz 67
Figure 48 Wind load cases: (a) & (c) are pressure coefficient contour plots at Az: 0° El: 16° and Az: 90° El: 66° 68
Figure 49 Wind Load Case 1 Beam Pattern 10 GHz 69
Figure 50 Wind Load Case 1 Beam Pattern 30 GHz 70
Figure 51 Wind Load Case 1 Beam Pattern 50 GHz 71
Figure 52 Wind Load Case 2 Beam Pattern 10 GHz 72
Figure 53 Wind Load Case 2 Beam Pattern 30 GHz 73
Figure 54 Wind Load Case 2 Beam Pattern 50 GHz 74
Figure 55 Beam Pattern, Thermal Bath 10 GHZ 76
Figure 56 Beam Pattern, Thermal Bath 30 GHZ 77
Figure 57 Beam Pattern, Thermal Bath 50 GHZ 78
Figure 58 Beam Pattern, Thermal Gradient, 10 GHz 79
Figure 59 Beam Pattern, Thermal Gradient, 30 GHz 80
Figure 60 Beam Pattern, Thermal Gradient, 50 GHz 81
Figure 61 Deforms at the secondary support locations 94

LIST OF ACRONYMS AND ABBREVIATIONS

ALMA	Atacama Large Millimeter Array
ATA	Allen Telescope Array
BUS	BackUp Structure
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Polymer
COTS	Commercial-off-the-shelf
CTE	Coefficient of Thermal Expansion
DVA	Dish Verification Antenna
EM	ElectroMagnetic
ERA	Elevation Rotating Assembly
FEA	Finite Element Analysis
iBUS	Inner Backup Structure
MRC	Multi-piece Rim-supported Composite
ngVLA	next generation Very Large Array
NRAO	National Radio Astronomy Observatory (USA)
NRC	National Research Council (Canada)
oBUS	Outer Backup Structure
PDR	Preliminary Design Review
PE	Pointing Error
PID	Process Induced Distortions
RMS	Root Mean Square
RTM	Resin Transfer Moulding
SPEM	Systematic Pointing Error correction Model
SRC	Single-piece Rim-supported Composite
TDP	Technology Development Program
VLA	Very Large Array
VLT	Very Large Telescope
WBS	Work Breakdown Structure

1 INTRODUCTION

1.1 Purpose of Document

The purpose of this document is to describe the Preliminary Design of the National Research Council of Canada (NRC) Next Generation Very Large Array (ngVLA) 18m Antenna Design as called out in Statement of Work NRC ngVLA 18m Antenna Study, AD03.

1.2 Scope of Document

This document describes the operational context of the design and the operating conditions as defined in the ngVLA Antenna: Preliminary Technical Specifications, AD01.

The project assumptions and risks are presented with their status and mitigation plans.

A descriptive overview of the NRC antenna design is provided.

Error budgets are presented along with methods of deriving allocations and current status of the analysis results for key performance requirements are presented.

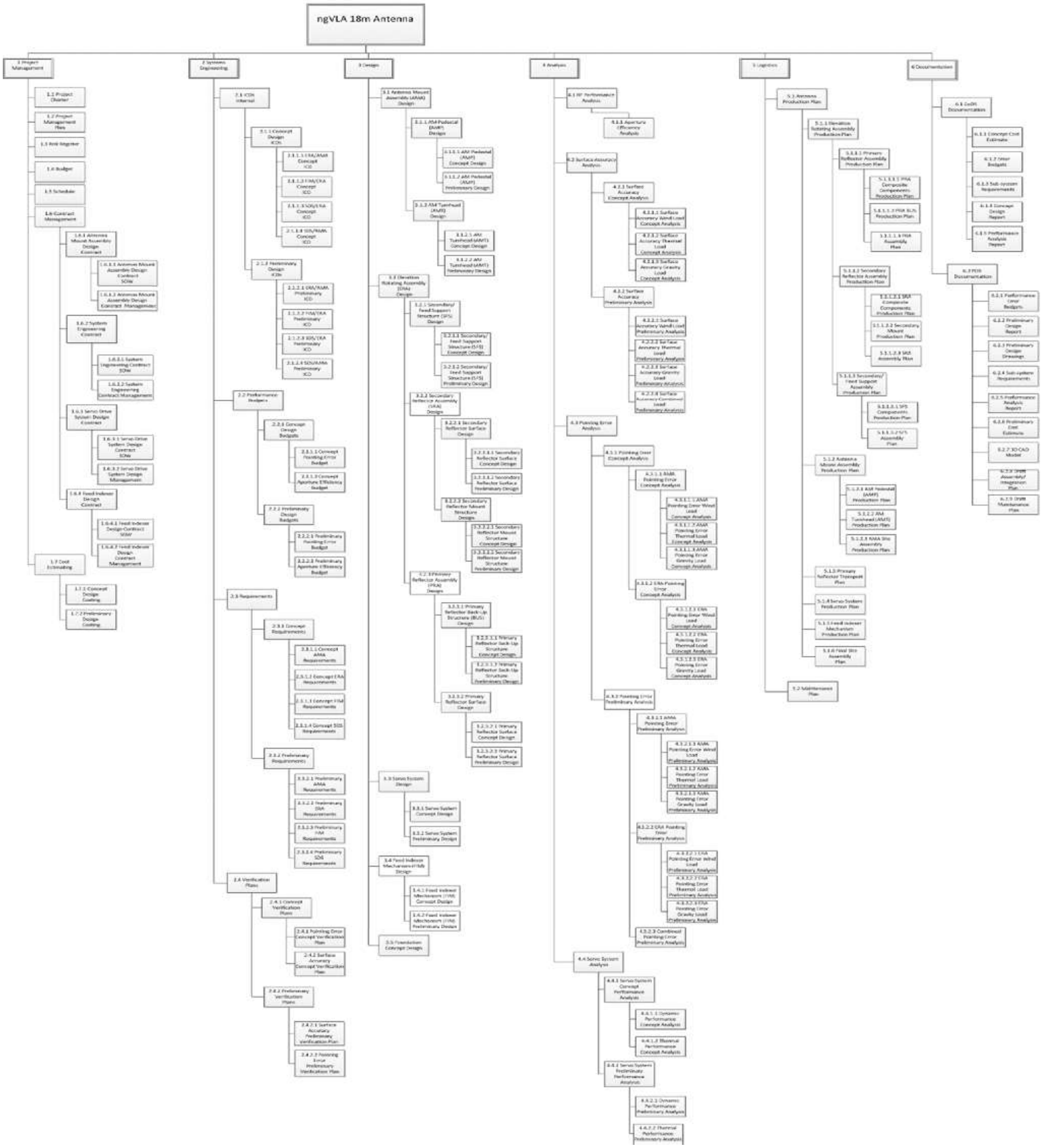
Finally, a summary of the key future tasks is provided.

1.3 Intended Audience

This document is expected to be used by the NRC ngVLA Antenna Design Team, National Radio Astronomy Observatory (NRAO) Antenna Integrated Product Team and Management Teams, and the ngVLA System Engineering and Management Team. This document is expected to be read by review panel members of the Preliminary Design Review (PDR).

The project Work Breakdown Structure (WBS) follows in the next section.

1.4 Project WBS



2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The following documents at their indicated revision form part of this document to the extent specified herein.

Table 1 Applicable Documents

Ref No	Document/Drawing Number	Document Title	Revision
AD01	020.25.00.00.00-0001-SPE	ngVLA Antenna: Preliminary Technical Specifications	B
AD02	ngVLA Memo # 17	ngVLA Reference Design Development & Performance Estimates	
AD03	020.05.40.05.01-0002-SOW	Statement of Work, NRC ngVLA 18m Antenna Study	
AD04	101-0000-004-PLN	ngVLA 18m Antenna Preliminary Production Plan	A

2.2 Reference Documents

The following documents provide useful reference information associated with this document. These documents are to be used for information only. Changes to the date and/or revision number do not make this document out of date.

Table 2 Reference Documents

Ref No	Document/Drawing Number	Document Title	Revision
RD01		"Fabry-Perot Resonator Design for the Measurement of Surface Reflectivity," D. Henke et al. in 9th Global Symp. on Millimeter-Waves., Espoo, Finland, Jun. 6–8, 2016.	
RD02		"Measurements of Composite Reflectors across Q-Band (33–50 GHz) and W-Band (75–115 GHz)," D. Henke et al. [*accepted*] in *18th Int. Symp. Antenna Technol. Appl. Electromagn. (ANTEM)*, Aug. 19–22, 2018.	
RD03	ngVLA Memo # 26	ngVLA Technical Study Offset Gregorian Antenna	
RD04	ngVLA Memo # 27	Various Suitable Mounts for 18m Antenna	
RD05	101-0000-001-REG-001	ngVLA 18m Antenna Risk Register	A

RD06	101-0200-001-RPT-001	ngVLA 18m Antenna Elevation Rotating Assembly Analysis Report	B
RD07	101-0100-000-RPT-001	ngVLA 18m Antenna Antenna Mount Analysis Report	B
RD08	9P033REP01	ngVLA Report, Main Drive Axes, Phase USA	
RD09	TBD	ngVLA AIV Timeline	01
RD10		Spring-back Analysis of Telescope Dish: Final Report	
RD11		DVA-1 Optics Design and Analysis	5
RD12		DVA-1 Dish Mechanical and Thermal Design	1
RD13		Long-term properties of fibre reinforced epoxy resins(composites)	
RD13	LTR-AL-2010-0017 Final Report	Wind Tunnel Investigations of Symmetric- and Offset-Reflector Radio-Telescope Antennas for the Square Kilometre Array (SKA): Mean Winds Loads and Surface Pressures	
RD14	101-0000-001-RPT	ngVLA 18m Antenna Servo System Analysis Report	

3 OPERATIONAL CONTEXT

The ngVLA array will consist of 244 x 18m antennas and 19 x 6m antennas. The 18m antennas will be deployed on and off of the Plains of San Agustin in New Mexico with baselines up to 1000 km, AD02. The array will be centred at the current Very Large Array (VLA) site, approximately 170 of the antennas will be located on the plains with the remainder being located in single antenna stations around New Mexico, Texas and Mexico. All antennas will be fixed position, the array will not be reconfigurable.

The project has defined four functional regimes:

1. Precision Operating: low wind speed, at night, low temperature rate of change, no precipitation.
2. Normal Operating: moderate wind speed, day/night, moderate temperature rate of change,no precipitation.
3. Limit to Operations: higher wind speed, low and high temperature limits and precipitation resulting in ice build-up.
4. Survival Conditions: high winds, extreme temperatures, snow and/or ice accumulation and hail.

Additionally, requirements are identified for seismic and lightning strike events.

3.1 Operational Environment

The antennas will be located primarily in desert and semi-desert locations at altitudes up to 2500 m. Many antennas will be located at remote sites and all will be operated remotely. The defined operating conditions are shown in Table 3, Table 4, Table 5 and Table 6.

Table 3 Precision Operating Conditions

Parameter	Req. #	Value	Traceability
Solar Thermal Load	ANT1411	Night time only; no solar thermal load within last 2 hours.	SYS2411
Wind Speed	ANT1412	$0 \leq W \leq 5$ m/s average over 10 min time. 7 m/s peak gusts.	SYS2412
Temperature	ANT1413	-15 C $\leq T \leq 25$ C	SYS2413
Temperature Rate of Change	ANT1414	1.8 °C/Hr.	SYS2414
Precipitation	ANT1415	No precipitation.	SYS2415

Table 4 Normal Operating Conditions

Parameter	Req. #	Value	Traceability
Solar Thermal Load	ANT1421	Exposed to full sun.	SYS2421
Wind Speed	ANT1422	W ≤ 7 m/s average over 10 min time. 10 m/s peak gusts.	SYS2422
Temperature	ANT1423	-15 C ≤ T ≤ 35 C	SYS2423
Temperature Rate of Change	ANT1424	3.6°C/Hr.	SYS2424
Precipitation	ANT1425	No precipitation.	SYS2425

Table 5 Limit to Operating Conditions

Parameter	Req. #	Value	Traceability
Wind	ANT1431	W ≤ 15 m/s average over 10 min. W ≤ 20 m/s gust.	SYS2432
Temperature	ANT1432	-20 C ≤ T ≤ 45 C	SYS2433
Precipitation	ANT1433	Any precipitation rate that does not result in accumulation of ice on the antenna structure.	SYS2434

Table 6 Survival Conditions

Parameter	Req. #	Value	Traceability
Wind	ANT1441	0 m/s ≤ W ≤ 50 m/s average.	SYS2441
Temperature	ANT1442	-30 C ≤ T ≤ 50 C	SYS2442
Radial Ice	ANT1443	2.5 cm	SYS2443
Snow Load	ANT1444	25 cm	SYS2444
Hail Stones	ANT1445	2.0 cm	SYS2445
Antenna Orientation	ANT1446	Stow-survival, as defined by designer	

4 ASSUMPTIONS AND RISKS

4.1 Assumptions

4.1.1 SRC Transportation to Antenna Locations

It was initially assumed that it would be possible to transport 18m Single-piece Rim-supported Composite (SRC) reflector assemblies from a central production facility to all 244 antenna locations (see Risk 101-R5). A site survey with a qualified contractor (Precision Heavy Haul who moved the Atacama Large Millimeter Array (ALMA) prototype antenna from the Very Large Array (VLA) to Kitt Peak) was conducted and it was confirmed that this will be possible only for the 175 antennas located on the Plains of San Agustin. For the remaining antennas an alternate solution is proposed.

NRC has carried out development under the following assumptions:

- The SRC design will be used for the on-plains antennas.
- A multi-piece version of the SRC primary reflector, Multi-piece Rim-supported Composite (MRC) will be used for the remaining antennas.
- Development of the MRC will continue in parallel with the SRC.

4.2 Risks

Risks have been categorized into either Project or Product risks. Project risks are those that might impact the completion of the design work within the defined budget and schedule, while product risks are those that might impact the ability of the design to meet the requirements. Both project and product risks are further categorized as to the nature of their impact; Budget, Schedule, Logistical or Technical. All identified risks are tracked in the project risk register, RD05.

Table 7 Project Risks

101-R7	Design contract costs are underestimated	Retired	Project	Budget	Obtain quotes and request NRAO funding for drive contract	2018-01-03: Initial/retired
101-R8	Work delay due to unexpected loss of resources	Retired	Project	Schedule		2018-01-03: Initial 2018-09-24: Retired
101-R9	Procurement delays related to contracts	Retired	Project	Schedule		2018-01-03: Initial 2018-09-24: Retired
101-R10	Loss of personnel due to retirement and employees seeking employment elsewhere	Retired	Project	Schedule		2018-01-03: Initial 2018-09-24: Retired

Table 8 Product Risks

Risk#	Description	Status	Type	Category	Mitigation Plan	Probability	Impact
101-R1	Production cost exceeds ngVLA expectations	Open	Product	Budget	Initiate cost evaluation early in project and update often to track cost.	20%	2
101-R2	Reflectivity of surface is not high enough.	Retired	Product	Technical	Testing of latest material is underway. 2018-04-25: Material tests show system temperature on par with reference aluminum	20%	2
101-R3	Bond between reflective material and surface structure is not strong enough	Open	Product	Technical	Send material structure samples for lifecycle testing.	30%	2
101-R4	Repeatability of single piece reflector surface accuracy during production cannot be proven.	Open	Product	Technical	Provide quality assurance protocols for production. 2018-09-24:Surface adjustment incorporated in design.	50%	3
101-R5	Transport of 18m single piece reflectors is not feasible/cost effective.	Realized	Product	Logistical	2018-01-16: Initial contact with vendor indicates that transport of 1 pc reflectors by trucking is likely feasible for antennas on the plain but not for antennas located off of the plain. Currently investigating feasibility and cost of transporting reflectors off-plain by helicopter. 2018-04-23: Transport by helicopter not feasible due to weight and altitude. Two piece reflector design concpet to be developed for off-plain antennas. 2018-09-24: Transport of ~170 antennas possible. Multi-piece design concpet being developed for other antennas.	50%	2
101-R6	Long term surface accuracy stability cannot be **proven**.	Open	Product	Technical	Review and re-issue of report done produced for SKA project. Conduct further accelerated life testing.	75%	2
101-R11	Surface accuracy requirement cannot be met.	Open	Product	Technical	Minimize deformation due to environmental effects to allow maximum allocation to as-manufactured errors. 2018-09-24: Contract Convergent Technologies to perfrom analysis of process induced distortions of 18m with new design and materials.	50%	3

101-R12	Tangential surface adjusters cannot reduce distortions to meet surface requirement.	Open	Product	Technical	Model and prototpye at an early stage.	50%	2
101-R13	Strength, stiffness and long-term endurance of surface adjusters are unproven.	Open	Product	Technical	Model, prototpye and test adjusters at an early stage.	50%	2
101-R14	Mould accuracy/stability cannot be achieved.	Open	Product	Technical	Work closely with industrial mould manufacturer to ensure requirements are well understood and ability to meet them is demonstrated.	25%	3
101-R15	Durability of surface reflective material is compromised by moisture ingess.	Open	Product	Technical	Provide quality control measures for production and repair procedures for operations.	20%	1

5 PRELIMINARY DESIGN

The preliminary design for the ngVLA 18m antennas is a Single-piece Rim-supported Composite (SRC) Reflector on a steel yoke and pedestal mount, Figure 1.

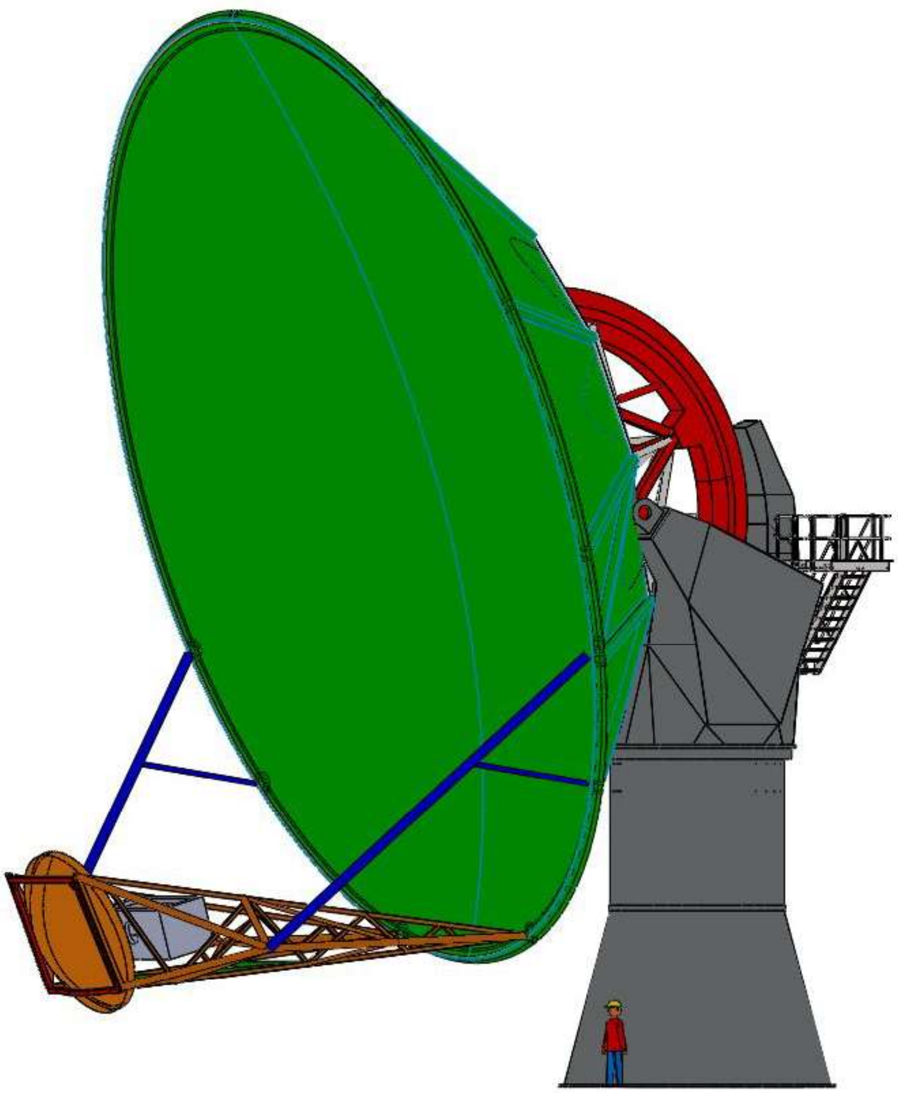


Figure 1 NRC ngVLA 18m Antenna Design Concept

5.1 Design Background

The proposed design is an evolution of work that has been carried out at NRC and Minex Engineering over the past 12 years. The concept of a single-piece composite reflector was first explored at NRC in 2006 with the fabrication of the Mark 1 (Mk1) reflector, Figure 2.

Figure 2 NRC Mk1 Dish

Based on the results of the Mk1 design, changes were incorporated in order to improve the surface accuracy and manufacturability and were implemented in the Mk2 in 2008, Figure 3.

Figure 3 NRC Mk2 Dish

The single-piece rim-supported reflector concept was used by Minex Engineering in construction of the Allen Telescope Array (ATA) 6m antennas, Figure 4, using a hydro-formed aluminium reflector surface.

Figure 4 Allen Telescope Array 6m Antenna

Figure 5 DVA1 Antenna

The collaboration of the NRC's Square Kilometre Array (SKA) effort and the US Technology Development Program (TDP) SKA program brought the two concepts together and resulted in the Dish Verification Antenna 1 (DVA1), Figure 5. The composite reflector surface allowed a larger, more thermally stable surface to be manufactured and the rim-support concept provided uniform support to the surface without any hard points on the reflecting surface. Despite a catastrophic transport incident the repaired DVA1 met the design requirements of high efficiency performance at frequencies up to 10 GHz. It has since been used to make record breaking antenna noise measurements and is currently being used for a polarization survey.

With the increased interest in higher frequency observing in radio astronomy and the desire to upgrade the VLA, the DVA2 project was undertaken to push the SRC technology to higher frequencies. The DVA1 mould had limitations in terms of stability and so an interim frequency of 50GHz was selected as the target for the DVA2. The mould was reworked to achieve a higher surface accuracy, a new reflecting material was developed and modifications were made to the BackUp Structure (BUS) design to increase the stiffness. Additional improvements were made to the secondary reflector structure and mount to improve the overall performance. At this time the DVA2 primary reflector has been fabricated, installed on the BUS, and measured to confirm that it meets the requirements to achieve high efficiency at 50 GHz.

In 2017 NRC conducted a Community Design Study for an ngVLA capable antenna based on the DVA1/2 reflector design, Figure 6. The feed-low reflector configuration and tight pointing requirements drove the team to consider a wheel & track design. Details of this design can be found in RD03 and RD04.

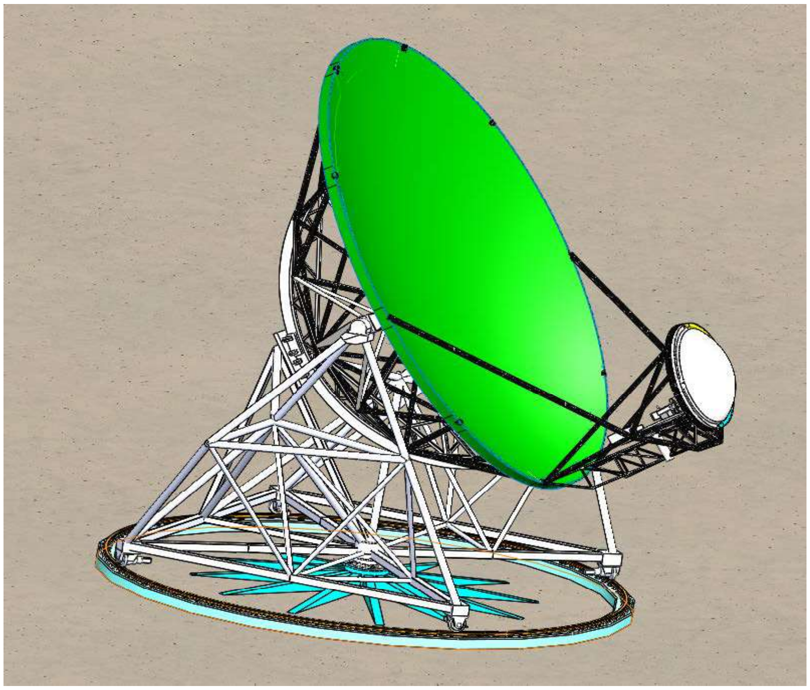


Figure 6 NRC 15m Antenna Study

5.2 Design Overview

5.2.1 Elevation Rotating Assembly

The Elevation Rotating Assembly (ERA) design features a SRC primary reflector surface supported by a composite shell outer BackUp Structure (oBUS) which attaches to a fabricated steel inner BUS (iBUS). Incorporated into the iBUS is the elevation axis tube and elevation drive arc. A composite space frame secondary support structure attaches to the oBUS at the rim of the primary reflector and supports the feed package and secondary reflector.

5.2.1.1 Primary Reflector Surface

The primary reflector surface manufacturing technique is based on the vacuum infused carbon fibre/epoxy resin layup process used in the fabrication of the DVA antennas. The surface is ~5mm thick and consists of 5 layers of quasi-isotropic carbon fibre fabric, a copper reflective layer and protective layers of thin fibreglass veil. The primary surface infusion is of uniform thickness and does not include a rim or other features that may result in process induced distortions. The exception is the surface adjuster tabs which will be infused with the surface. These will be designed to result in minimal distortions and are located around the perimeter in a small band of the surface outside of the optical surface. Figure 7 shows a concept sketch for the adjuster tabs. The metal spool would be added at the edge of the layup, then overwrapped around its perimeter with a pre-cured carbon-fibre ‘fan’ as illustrated in the figure. The green zone in the figure represents the 100mm wide extension to the primary surface which is outside of the aperture. The carbon fibre ‘fan’ would be incorporated into the centre of the layup (through-thickness) during the primary layup and in this way would form an integral part of the structure.

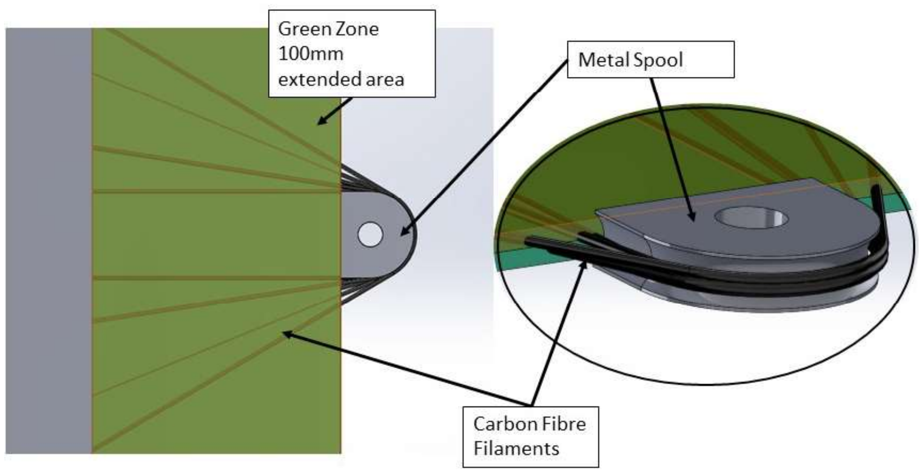


Figure 7 Primary surface edge adjuster tab concept

Figure 8 shows the primary surface edge adjuster concept in context with the oBUS edge structure. The primary surface (left hand panel) is suspended from the oBUS by the primary surface edge adjuster tabs shown in Figure 7 together with a clevis and stud arrangement. Nuts and washers located on each side of the oBUS flange on the studs will allow for the adjustment of the perimeter tension loads on the surface and, in turn, the shape of the surface.

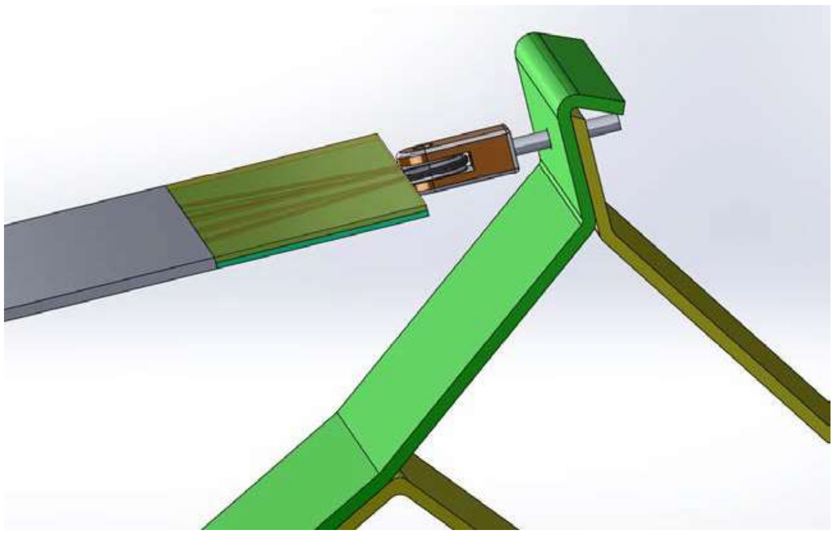


Figure 8 Primary surface edge adjuster with oBUS

Two surface reinforcement patches are added adjacent to where the forward feed legs attach to the oBUS to further reduce distortions in the primary surface. To avoid process induced distortions due to changes in the laminate thickness these will be fabricated separately and bonded on after the primary infusion, Figure 9.

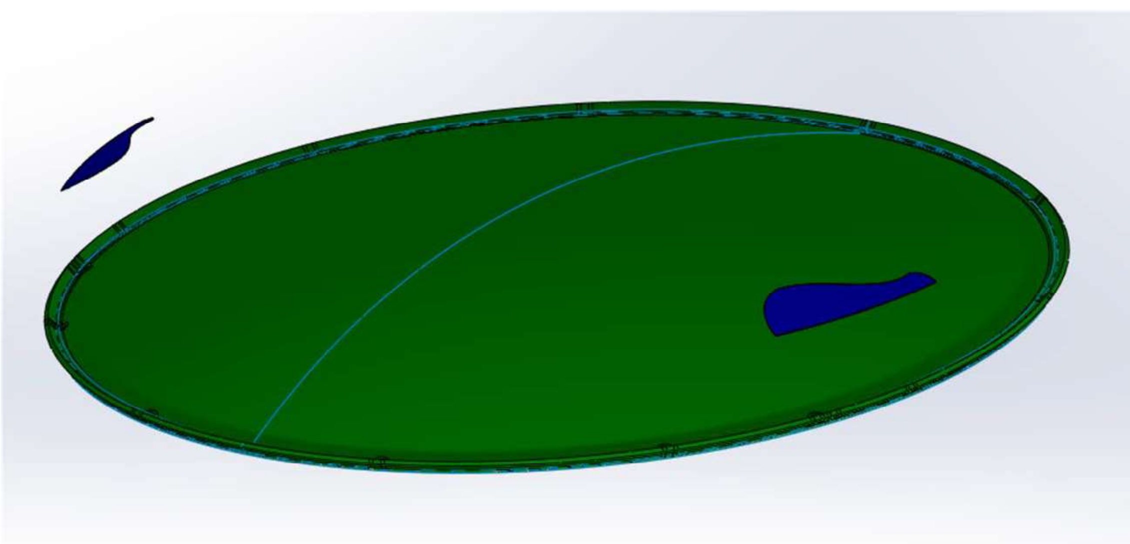


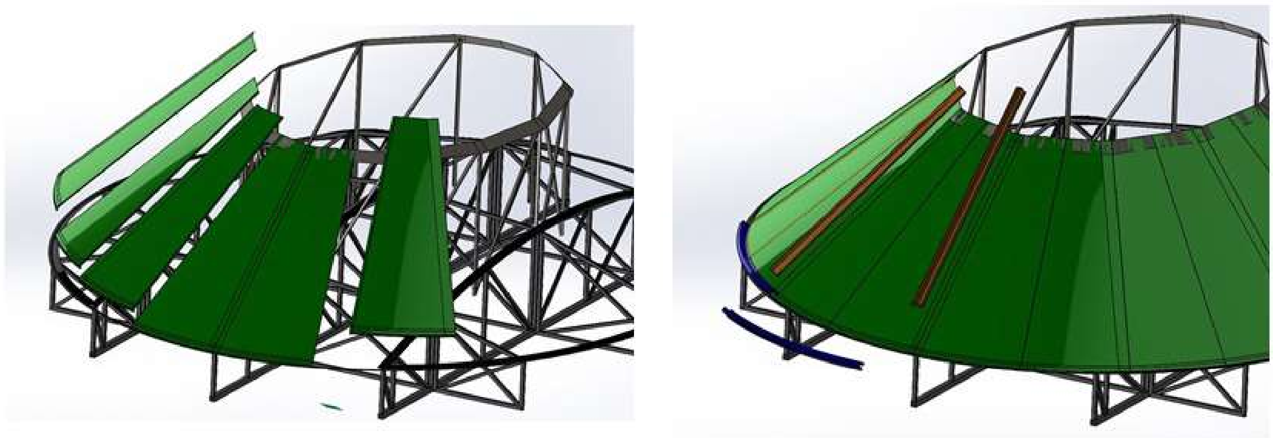
Figure 9 Surface Reinforcement Patches

5.2.1.2 Outer Backup Structure

The oBUS is comprised of 22 panels, 15 ribs and 11 rim beam sections. The complete oBUS structure is depicted in Figure 10.

Figure 10 Assembled oBUS structure

The component dimensions are designed to enable standard transport to site. The panels and ribs are carbon fibre/epoxy composite layup similar to that used in the surface (without the reflective layer). The ribs provide stiffening at the panel joints and load paths from the feed/secondary support structure connections to the iBUS. The structure is stiffened by the circumferential rim beam. Figure 11 depicts a partially assembled oBUS and illustrates some of the components that make up the structure. The 22 surface panels will be added to the oBUS assembly jig and bonded along their long edges via a bond lap joint. Once this is accomplished the 11 segments of the rim beam will be bonded on (see Figure 11, the blue beams). Finally the 11 radial beams and the extra four angled beams that directly support the secondary structure will be bonded on. Finally, there will be a steel frame added to the lower elliptical edge of the oBUS that will provide stiffness to this open end of the oBUS during shipping and handling, and ultimately comprise the connection between the oBUS and the iBUS.



The panels are assembled on the assembly jig. Connecting edges are bonded lap joints.

Then the rim beam (shown in blue) and the radial beams (in brown exploded view) are added.

Figure 11 oBUS assembly details

The resulting structure is very stiff in shear between the reflector surface and iBUS. This is of particular importance for the feed-down configuration because the reflector will spend most of its time oriented in a vertical or near vertical orientation where the shear stiffness of the oBUS will provide the larger portion of necessary support for the primary surface (imagine the reflector surface being dragged downward by gravity) in Figure 12.

The oBUS is connected to the iBUS through bolted connections between the metal ring defining the bottom edge termination of the oBUS and the metal ring defining the same location on the iBUS. The connection points will be at 11 discrete points directly over the 11 corners defining the 11 sided connecting polygon. When the iBUS and oBUS are combined, they will provide the stiffness required to achieve the pointing and surface accuracy.

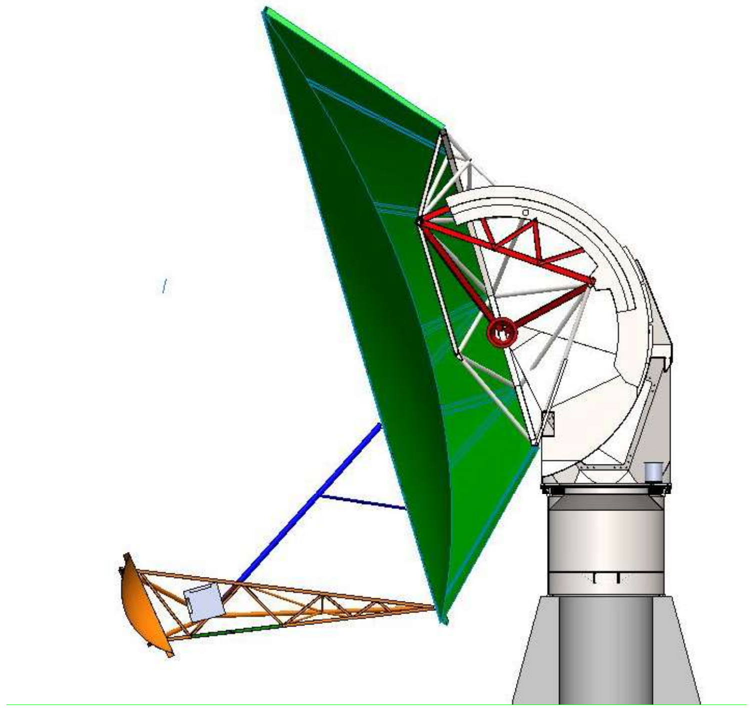


Figure 12 Cross Section of Antenna at Low (12°) Elevation Angle

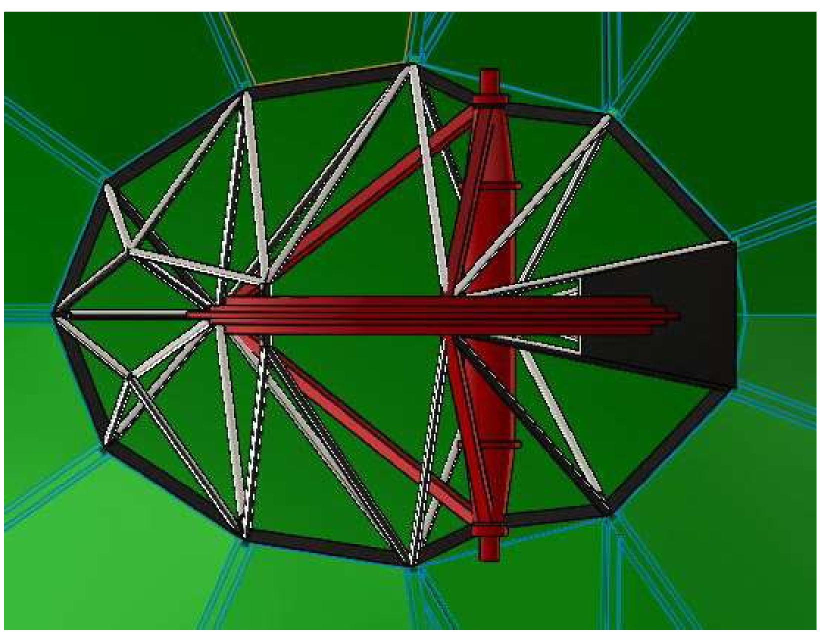


Figure 13 iBUS with its 11 Discrete Connection Points to the oBUS

5.2.1.3 Inner Backup Structure

The iBUS provides the interface and transfers drive loads between the reflector assembly and the yoke. It is an assembly of machined and fabricated steel components. The iBUS connects to the oBUS through the metal frame that defines the lower edge of the opening near the centre of the oBUS.

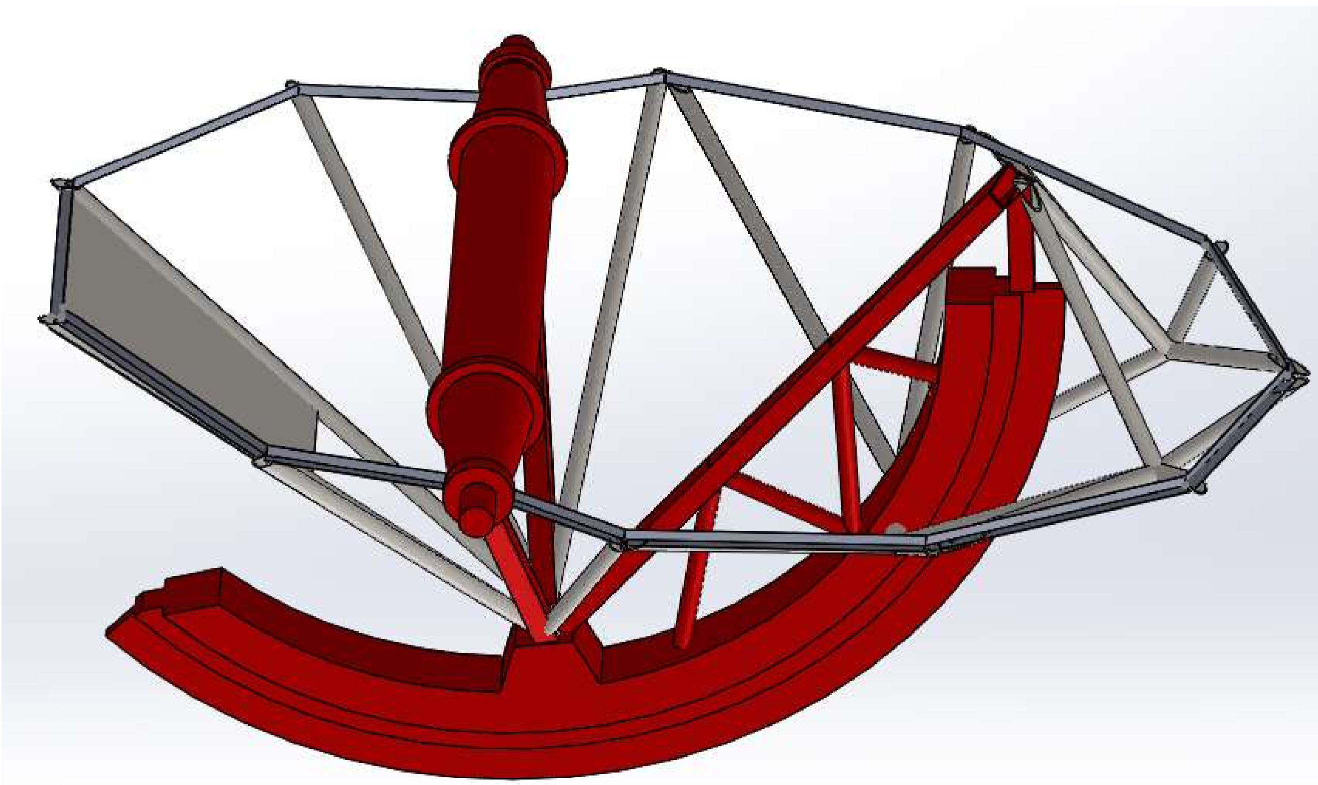


Figure 14 iBUS structure

In Figure 14 the red part of the iBUS, together with the two members the oBUS form a stiff tetrahedral structure between the elevation axle and the top rail of the truss attached to the elevation drive arc. The white steel members represents a second level of structure in the iBUS which carries the loads for the eleven discrete attachment points that connect the iBUS to the oBUS around the perimeter of the ellipse which defines the interface between the two. The iBUS will be assembled on-site from large, but shippable sub-assemblies. Once assembled, the iBUS will be lifted into position onto the yoke-tower assembly. The primary reflector assembly will be lifted by crane and the connection between the oBUS and iBUS made once in position.

5.2.1.4 Secondary Support

The secondary support structure is a carbon fibre truss to minimize weight and coefficient of thermal expansion (CTE), and maximize stiffness. Figure 15 shows the general arrangement.

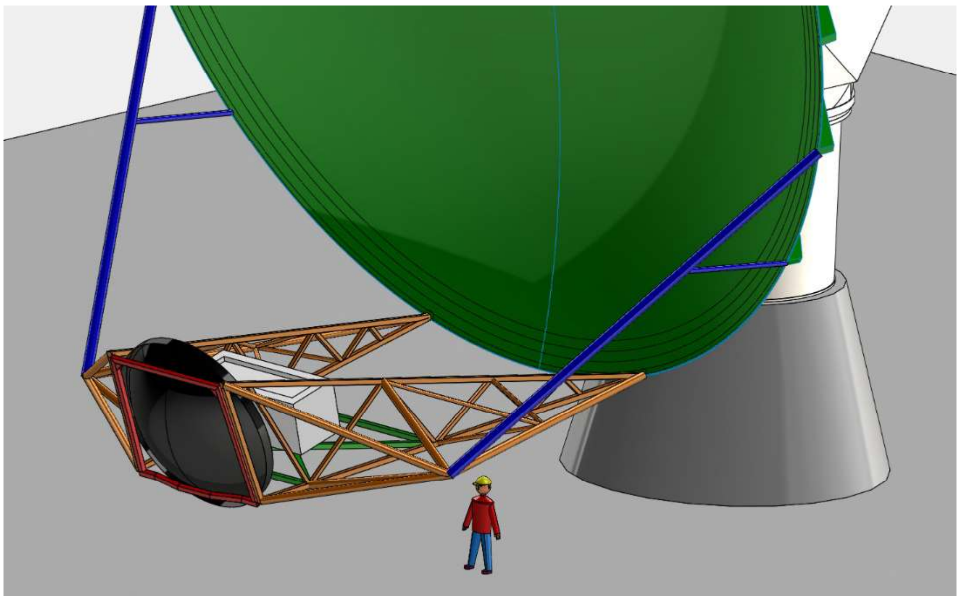


Figure 15 Secondary Support Structure.

The primary truss structures (orange) support the secondary reflector (black) and attach to the rim of the primary reflector at two points. A carbon tube on each side (blue in Figure 15) connects to the rim of the primary reflector as far around the rim as practical while still staying out of the optical path and keeping the tube length down to practical limits. An additional small brace added to each of these carbon tubes increases their buckling strength and natural frequency thus minimizing the dynamic coupling with the vibration caused by vortex shedding. The feed package and indexer (white box) is supported by an intermediate truss structure (green).

Stiffening ribs integrated into the oBUS transfer the loads from the secondary legs to the iBUS, Figure 16.

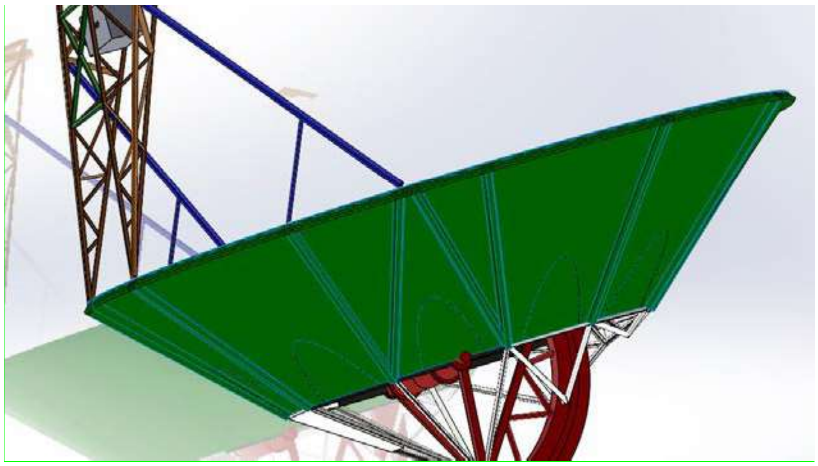


Figure 16 Stiffening Ribs on Primary Reflector to Support Secondary Support Structure

Figure 17 shows a close-up view of the feed and secondary support structure. The different colours indicate separate shippable parts. On-site assembly would occur, with a combination of glue-bonded and bolted connections.

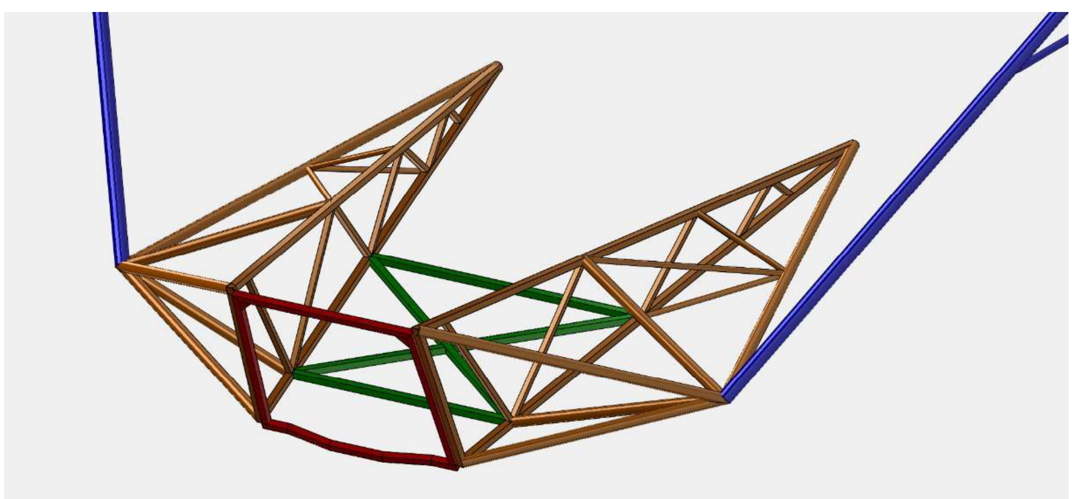


Figure 17 Secondary and Feed Support Structure.

5.2.1.5 Multi-piece Reflector for Remote Site Antennas

For those reflectors that will be transported off the plain that surrounds the Socorro VLA site a multi-piece reflector concept has been developed. The underlying structural principles are the same: a rim supported monocoque primary surface with a carbon-cone outer back structure supported by a steel inner back structure. The principle difference is that the primary surface will be cut into 4 sections for transport after it is fabricated. Figure 18 shows the surface panel cut line concept. In consulting with a trucking firm about width, length, and height restrictions on US roads it was determined that parts over 18 feet wide were quite expensive to move, splitting the reflector into 4 pieces will keep the width to ~16 feet. While 68 feet is quite a long load, it shouldn't exceed the 90 foot overall truck and trailer length which represents another (albeit softer) dimensional boundary. For height, 10 feet off the deck of the flat deck trailer is the number given, the 4 pieces will easily remain below that.

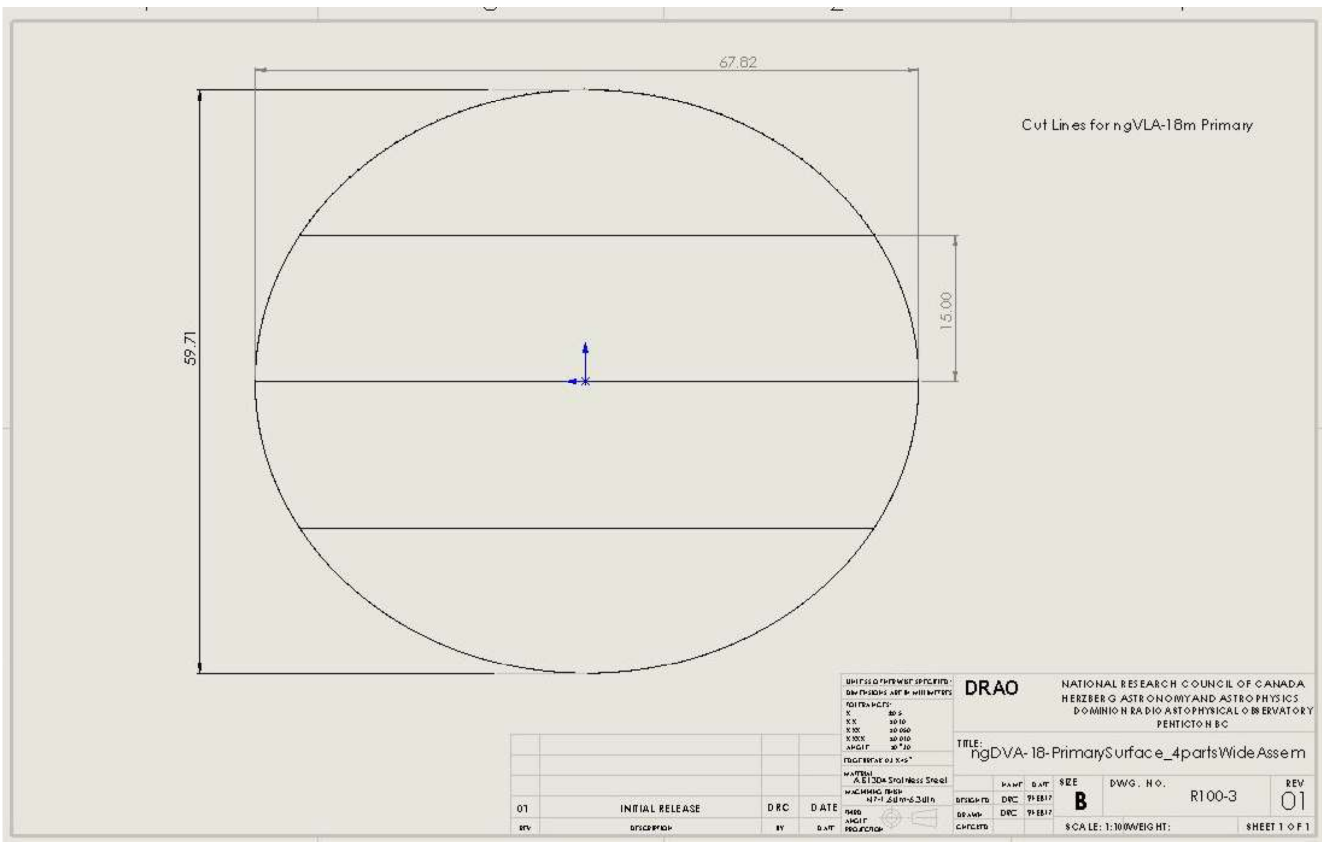


Figure 18 Primary Surface cut Panel Dimensions [ft]

The concept is to fabricate the reflector in one piece on the mould using the identical process as would be used for the ~170 one-piece reflectors. Once the reflector has been fabricated (vacuum infused), and while it is still on the mould, the connectors will be bonded on. Figure 19 shows the connector concept.

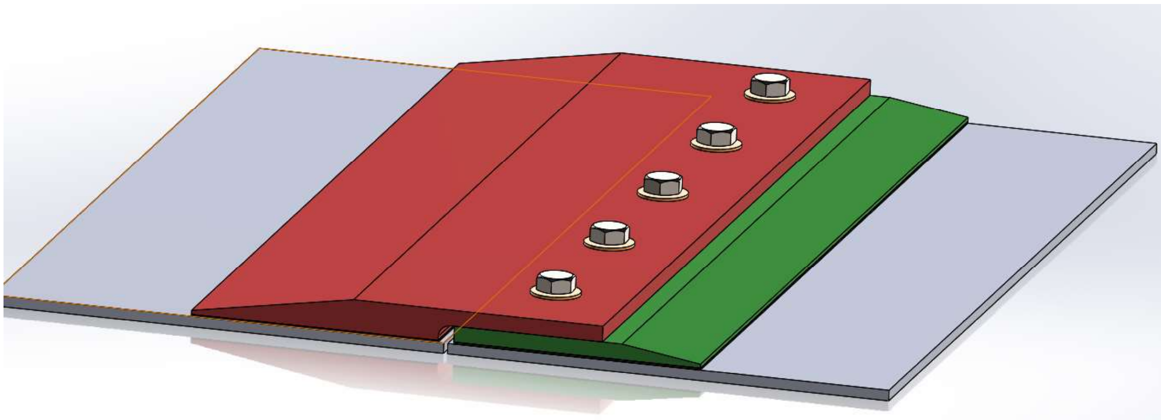


Figure 19 Proposed multi-piece primary surface connection detail

The upper (red) piece would be vacuum infused in carbon fibre, and would require a separate mould for each of the three joints required. The lower (green) piece would also be moulded separately, but would benefit from being built using the RTM (Resin Transfer Moulding) process which allows both the top and bottom surfaces to be moulded. Since the three joints are all close to 70 feet long, it would be more practical to fabricate the upper piece in at least two pieces (which could be joined with a separate overlapping piece), and the lower piece most likely should be built in 4 pieces (but needn't be joined).

The upper and lower pieces would be assembled on a jig and match drilled for the bolts and inserts. Figure 20 shows a cross section through one of the bolts.

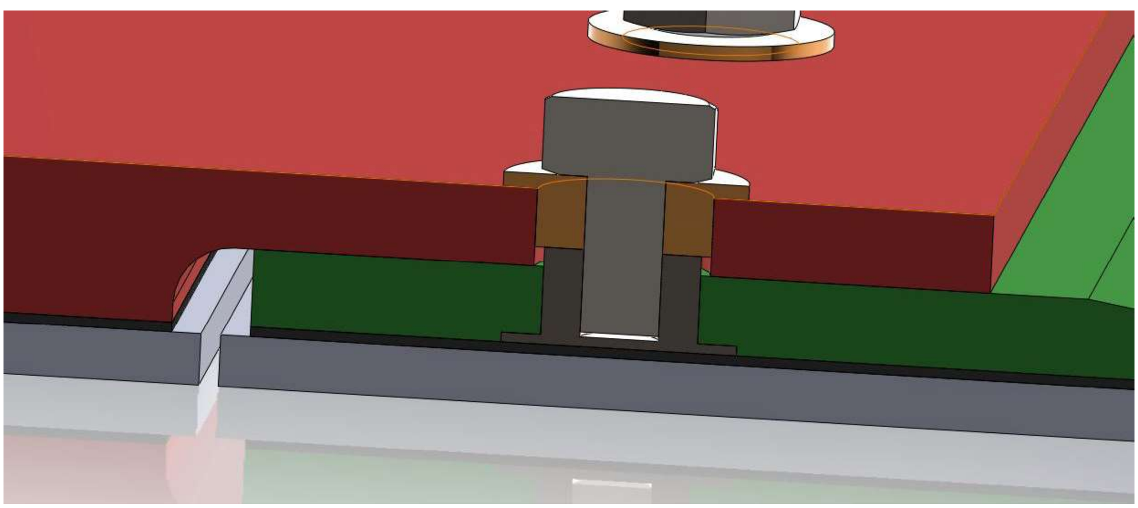


Figure 20 Cross section through one of the primary surface joining bolts showing the inserts

Once assembled on the jig a special drill would be used to drill and counter bore the required holes. Once drilled the parts are again removed from the jig and the metal inserts are pressed in, and finally the upper and lower parts are again placed on the jig and the connecting bolts added. In this way the upper and lower parts of the joint connector are pre-aligned before being added to the primary surface.

The pre-assembled primary surface connector units are positioned on the back of the primary reflector surface, aligned using alignment jigs attached to the edges of the mould and laser projected lines, and bonded on.

Next, lifting tabs (also built from carbon fibre) would be bonded onto the back of each of the 4 primary surface parts. Figure 21 shows the arrangement typical for one of the pieces. These lifting points are made from carbon fibre to insure a matched CTE with the surface material, and would be placed such that each panel could be safely lifted (with appropriate spreader bars). Initially the whole primary surface would be lifted in one piece using some of the lifting points situated on each panel, and using different spreader bars designed for the purpose.

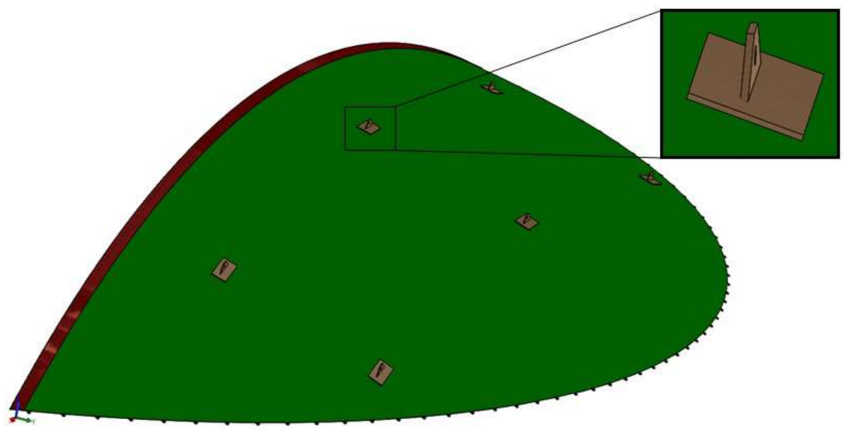


Figure 21 Lifting points added to one of the 4 primary surface panels

This first lift would be to move the (currently one piece) primary surface from the mould onto a cutting jig, Figure 22. The one piece primary surface would be aligned to the cutting jig using pre-defined alignment tabs built into the ends of the joint connectors. A circular saw equipped with a diamond blade would be pulled through a guide situated under each of the three desired cut lines, and in this way the cuts would be accomplished at the correct locations. Once all the cuts were completed, the bolts between each part would be removed and the parts lifted off the cutting jig in a specific order from one side to the other in the direction that the overlapping joint flanges overlapped.

Note that lifting points have only been detailed on the right hand primary surface part in Figure 22, but similar lifting points would be bonded to the other 3 primary surface parts as well.

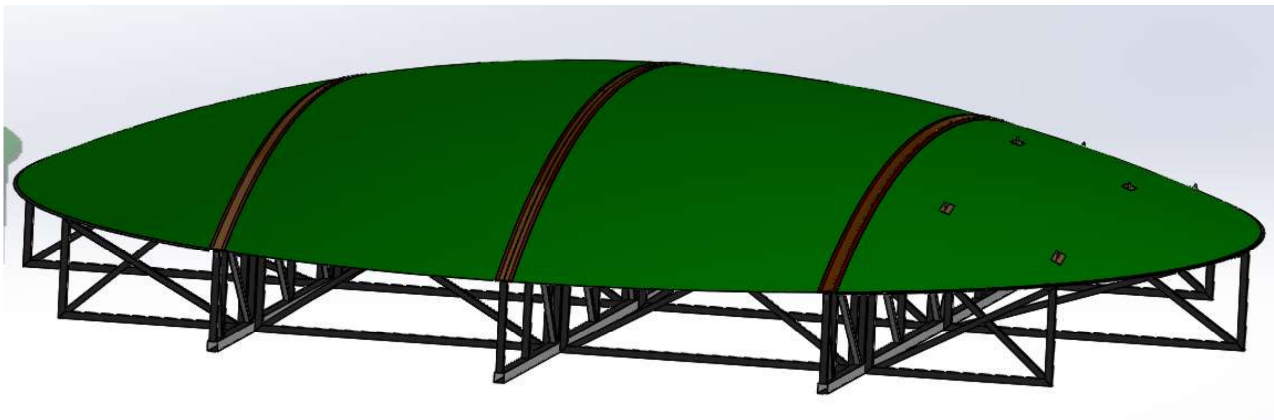


Figure 22 Assembly jig for the primary surface parts

Each of the 4 primary surface parts must be supported for transport once they are removed from the cutting jig. Figure 23 shows a typical arrangement. The transport trailer shown is 70 feet long to accommodate the middle two pieces, the side pieces being a bit shorter. The transport jig is notional.

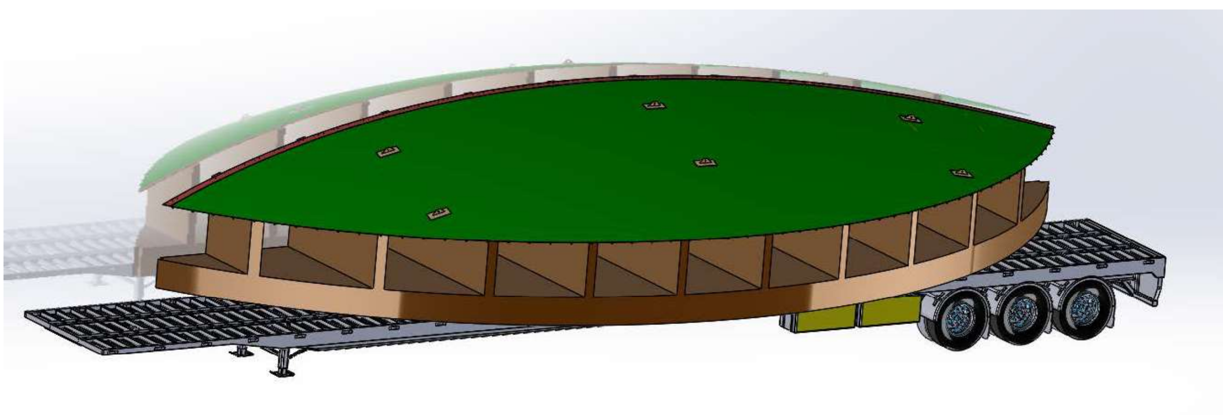


Figure 23 One of the four primary surface parts on its transport jig and flat deck trailer

For remote sites where more than one antenna will be located or where multiple antenna stations lie along a given route, it is possible to nest like pieces for transport, Figure 24,

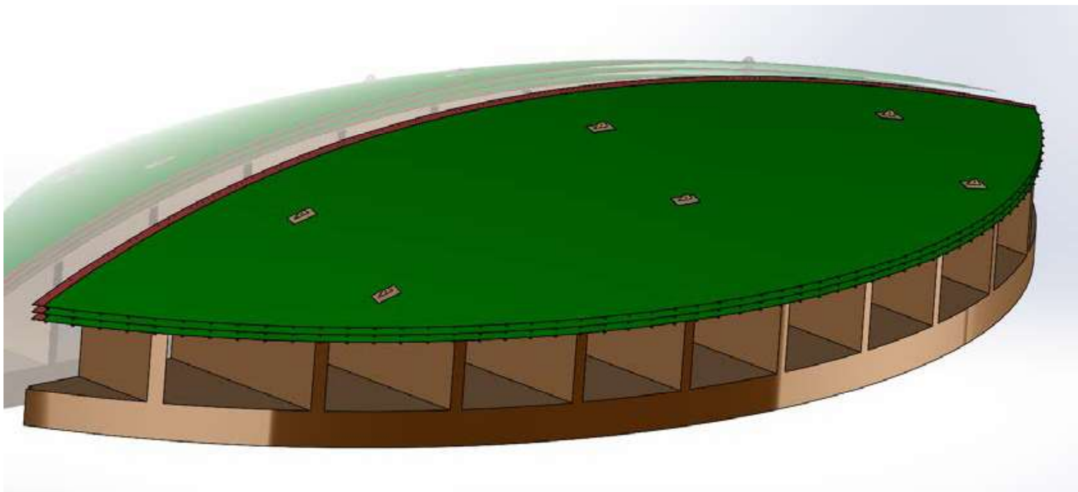


Figure 24 Nesting multiple instances of primary surface pieces for transport to remote sites

Once at the antenna station the four primary surface parts would be assembled to the assembly jig Figure 23. The assembly jig would be key to predetermined alignment tabs located along the edge of each of the primary surface parts. As each piece of the primary surface was added, the bolts connecting the parts together would also be added.

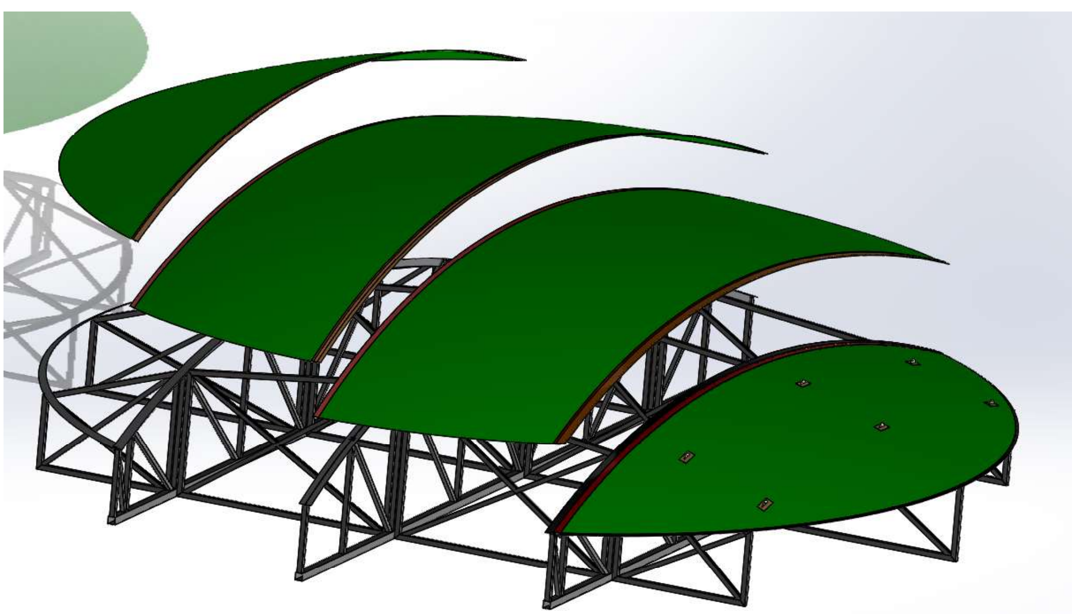


Figure 25 Four primary surface parts being added to the assembly jig

Once the primary surface has been bolted together, the same assembly jig would be used to assembly the oBUS to the primary surface. The oBUS would first be preassembled on a jig at the antenna station using the same methodology as for the single piece reflectors. Once assembled the oBUS would be lifted onto the primary surface assembly jig and connected. This step would require some more structure around the rim of the primary surface jig, a structure that is not shown in Figure 25.

The primary assembly jig would break down into flat transportable pieces. Each of these pieces would be made up as weldments, but would require some precision machined surfaces and would be connected using taper pins and bolts. Pre-alignment between parts would be insured by the taper pins, but a stable foundation would be required at the building site, and a final check using a laser tracker would be required on some predefined targets because such a large structure would need to be supported at multiple points where adjustable feet would be supplied for the final alignment. This jig would need to be made by a company such as Janicki Industries that understands the complexities of aligning large metal structures and has the capability to machine large complex (non-planer) surfaces (even though the complex surfaces in this case need only be narrow support strips where the jig touches the surface of the part).

5.2.2 Mount

As mentioned for the 15m design study a wheel and track style of mount was chosen driven by the feed-low configuration and tight pointing requirement. The wheel and track mount has been applied to many radio telescopes in the past but there also have been some issues associated with it in terms of maintenance and reliability. A pedestal mount with the feed-low offset reflector requires an offset between the elevation and azimuth axes which compromises the structural stiffness. However the reliability and low maintenance requirements make it an attractive option especially for an array of many antennas. With a potential wheel and track mount design concept already in hand it was decided to explore the potential of the pedestal mount for this study. The challenge will be in achieving the required stiffness at a reasonable cost.

5.2.2.1 Elevation Drive Configuration

The elevation drive configuration was tied to the yoke vs. turnhead decision; once the decision was made to go with the yoke, the task that remained was to determine a location for the drive arc and drive stator sectors. A large drive arc radius is clearly desirable because it will reduce the physical size and power requirement for the drive motors. Conversely, a large drive arc radius means long yoke arms which then reduce the stiffness of the yoke structure which negatively impacts the pointing. A compromise that was arrived at was to move the drive arc to a high position. This enabled the yoke arms to be shorter and stiffer while maintaining a larger drive sector radius. Additionally the lower end of the drive arc must penetrate through a hole in the yoke central structure just above the azimuth bearing. Also this required the drive stator sectors to be mounted on a structure mounted high up on top of the yoke, Figure 26. Because of the drive stator sector position (and lack of lateral stiffness), elevation axial loads from the reflector must be taken at the elevation bearings and not on the drive sector; however, it is thought that this is a workable solution.

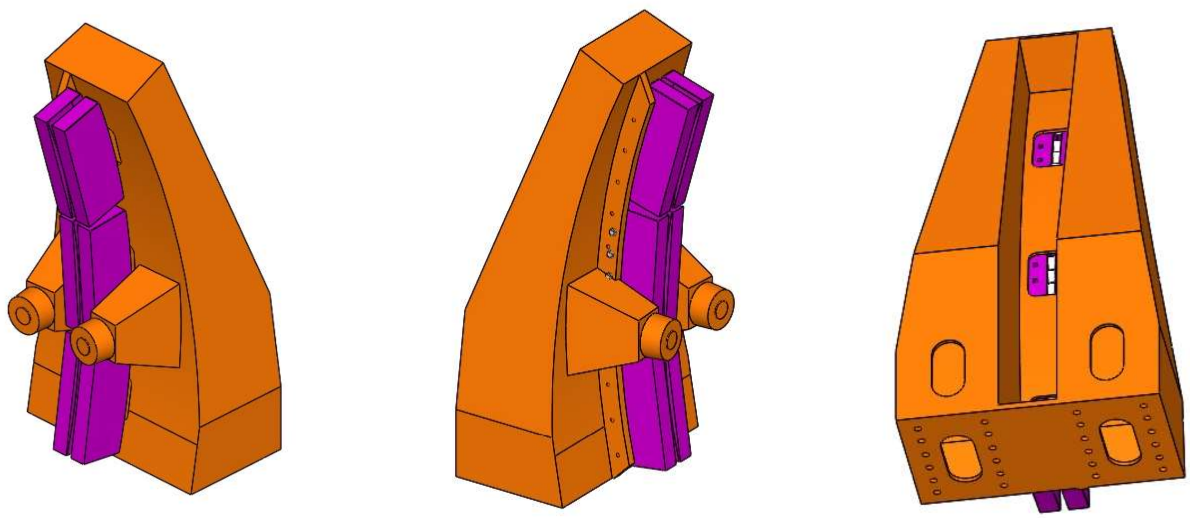


Figure 26 Elevation Drive Stator Pylon Structure

5.2.2.2 Elevation Drive

For the elevation drive, the direct drive appears attractive because of the large radius available. If one examines the loading path between two opposed gear drives as shown in Figure 27, it is clear that changes in gear tooth pressure will result in inconsistent deflections across the large structure. No inconsistent deflections occur with the direct drive. The sector gear itself is expensive and could be considered analogous to the armature magnet plates. Good alignment or gap control is required for both systems. Drive carriages that track the sector can reduce the alignment requirement but it generally results in more deflection parts and maintenance parts. Lubrication of a sector gear and pinion set is a maintenance issue and difficult to keep clean. The direct drive armature magnets may have magnetic dirt issues. The cost of gear and direct drive are more comparable.

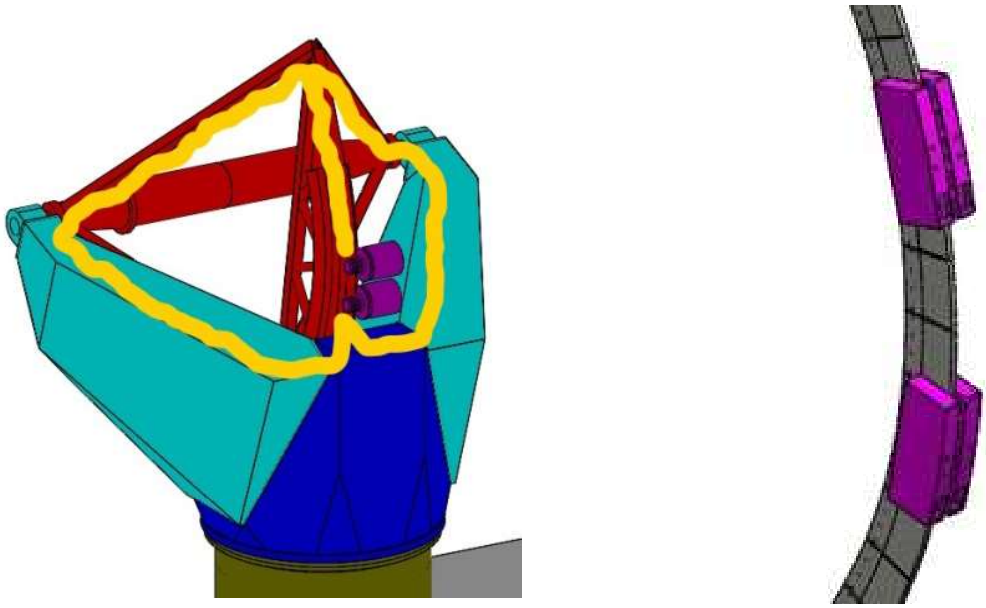


Figure 27 Elevation Drive Load Path and Drive Components

A preliminary elevation drive design has been performed by Phase USA [RD08] based on the mechanical configuration and loading scenarios provided by NRC. Drive loads, based on the NRC wind tunnel data scaled for the reflector size and average wind speeds of the ngVLA, are shown in Table 9.

Table 9 Elevation Drive Loads (based on average wind speeds)

Max Elevation Drive Loads [kNm]			
Precision	Normal	Limit	Survival
35	71	284	1774

The initial drive sizing is performed based on the Limit condition (with a 20% oversizing margin) under which the antenna must be driven to the stow position where brakes and/or stow pins are deployed. The drive configuration is shown in Figure 28.

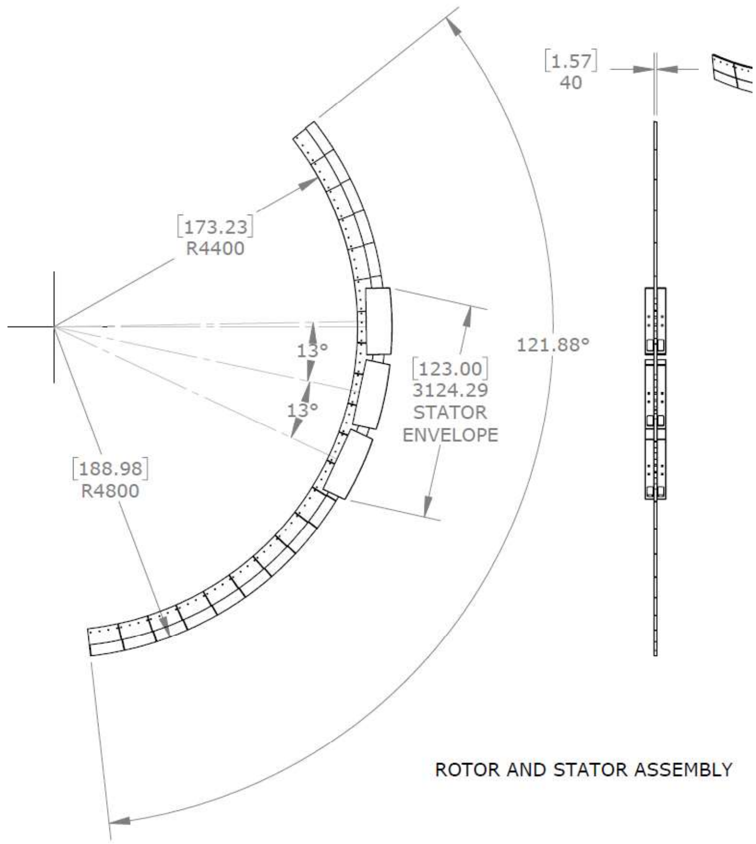


Figure 28 Elevation Drive Configuration

Table 10 Elevation Drive Performance Matrix

perf =

"Tracking , 10m/s"	"Tracking, 18 m/s"	" Survival, peak"	"Pointing, acc."	" WORKING POINT"
79000	167272	305800	254810	" Motor Torque (Nm)"
0.06	0.06	2	1	"Shaft Speed (deg/sec)"
4.86	4.86	166.67	83.33	" Speed Nominal % "
0.08	0.17	10.67	4.45	"Shaft Power (kW)"
16.6	34.86	63.52	52.97	"Tot. Motor Current (Arms)"
57.52	117.68	424.01	254.32	"Motor Voltage (Vrms)"
0	0	0	0	"Id Current (Arms)"
16.6	34.86	63.52	52.97	"Iq Current (Arms)"
1	1	0.72	0.88	"Motor Power Factor"
0	0	0.15	0.05	"Core Loss HiFreq (kW)"
1.25	1.25	43.04	21.44	"Core Loss fund.(W)"
1.25	1.25	43.19	21.49	"Tot stator core loss (W)"
0	0	0.08	0.04	"Rotor Loss HiFreq (W)"
1570.47	6927.57	23002.39	15996.04	"Copper loss (W)"
0	0	0	0	"Mechanical loss (W)"
1571.72	6928.82	23045.66	16017.57	"Overall Motor Loss (W)"
0.05	0.02	0.32	0.22	"Motor efficiency"
44.91	129.82	385.26	273.87	"Copper Temp (°C)"
44.65	128.68	381.47	271.24	"Core Temp (°C)"

The elevation drive performance matrix is shown in Table 10. Tracking the power required is 1.6 kW for Precision and 6.9 kW for Normal wind conditions. Power required to move from slew to stow is about 23 kW.

5.2.2.3 Azimuth Rotating Structure

In the 15m design study performed by NRC in 2017 a wheel and track mount was selected in order to achieve the pointing requirement. In scaling the design to 18m it was found that it was not possible to meet the surface accuracy requirements with the steel tube BUS with discrete attachment points to the reflector surface. Instead a composite cone outer BUS (oBUS) with continuous attachment to the surface was selected, see section 5.2.1. With the cone BUS the necessary structure to attach the elevation axis at the rim, as had been proposed in the 15m concept, no longer existed. The placement of the elevation axis was moved to the back of the oBUS where it connected to a steel fabrication inner BUS (iBUS). This also reduced the width of the elevation axis structure and so a wheel and track mount no longer was applicable and so a pedestal structure design was selected for the design study.

Both the ATA and DVA antennas have used a turnhead type of azimuth rotating structure where the structure is contiguous between the elevation bearings and is located inside the primary reflector BUS. This allowed a compact, stiff structure to be used. In both cases the elevation drive was by a ball bearing jackscrew which could be mounted on the back of the turnhead.

For the ngVLA due to the tight pointing requirement and the desire for low maintenance it was attractive to investigate the use of a direct drive system similar to that used on the European and Japanese ALMA antennas. This requires a large drive arc sector to be mounted on the BUS; use of a turnhead would have necessitated mounting of the drive off to one side, creating offset loads or having two drive arcs one on each side of the turnhead. This would have incurred greater cost and complexity.

A yoke type azimuth rotating structure, Figure 29, allows the drive arc to be mounted centred on the BUS between the yoke arms. In addition the interface to the BUS at the elevation axis can be wider potentially providing more stiffness. A challenge for the yoke will be in achieving the pointing requirement (stiffness of yoke arms). The desired direct drive system requires a large radius to be practical. In general this forces long yoke arms, near 5.9m, causing serious stiffness problems. Additionally it is important to have solid support above and below the azimuth bearing for a distance of at least half the bearing diameter or about 2m. These requirements combine to force the azimuth bearing lower down the pedestal, reducing stiffness. An offset design offers the opportunity to shift the drive sector onto the high side of the BUS. By cantilevering the lower portion of the drive sector it can project through the front face of the yoke centre, Figure 30. This is extremely useful, because it allows a short beam across the front part of the yoke arms shortening the cantilever by about 35%. The short beam also stiffens an important area of the yoke centre above the Azimuth bearing. Now the drive arc can pass just above the Azimuth bearing.

With this type of mount, the yoke arms are often responsible for nearly 50% of the bending deflection. With the encoders mounted on the ends of the yoke arms this is the largest amount of non-repeatable pointing error for the entire mount. It is quite difficult to stiffen these structures and it may be necessary to consider internal reference structures similar to what has been done with ALMA and other high performance antennas.

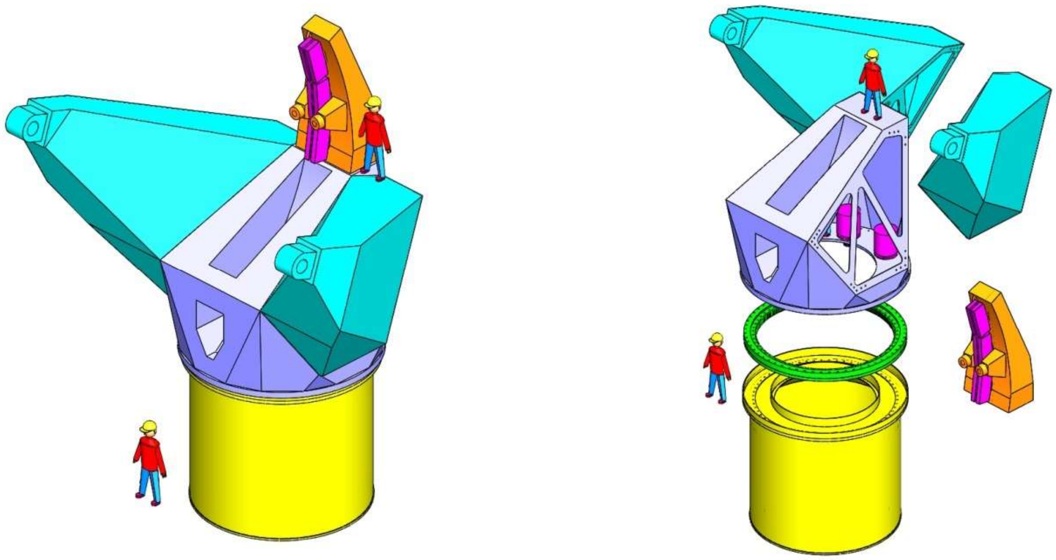


Figure 29 Azimuth Rotating Structure

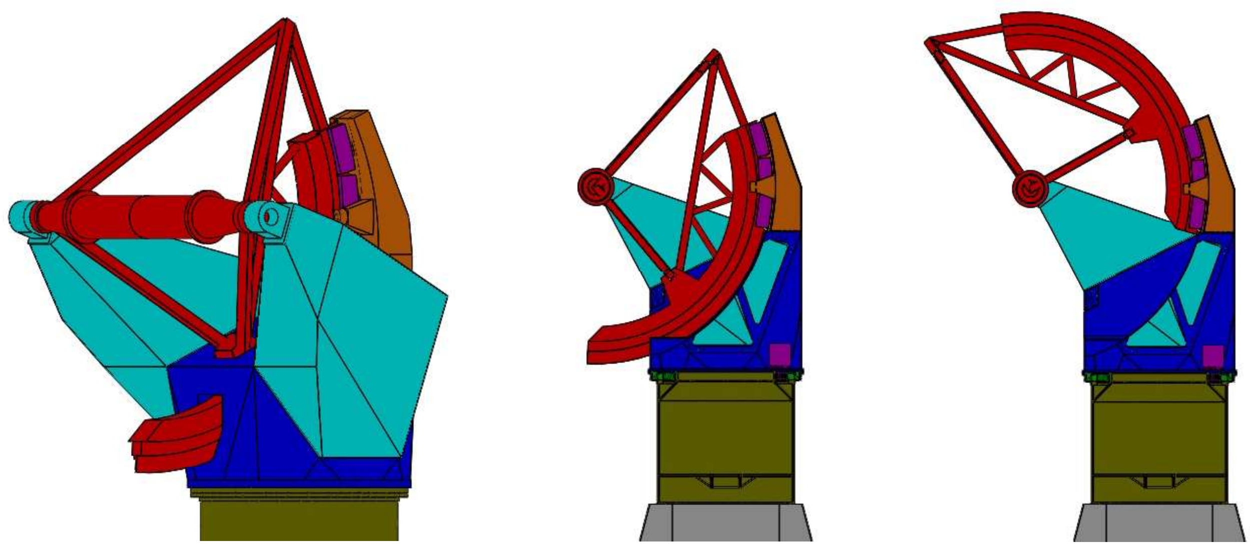


Figure 30 Yoke and Elevation Drive Structure

Table 11 Azimuth Rotating Structure Components

Support Section	26770 lbs = 12140 kg	Plate 1" = 25mm at 150" =3.81m
Yoke Centre Section	24410 lbs = 11070 kg	Plate 5/8 = 16mm
Yoke Arm	16650 lbs = 7550 kg	Plate 5/8 = 16mm
Drive Column	6070 lbs = 2750 kg	Plate 5/8 = 16mm
Azimuth Bearing	11070 lbs = 5020 kg	3.80m, 4130 x 3500 x 235mm
Support & Centre Transport	62350 lbs = 28280 kg no motors	4.32 max dia. x 7.40m long

The azimuth bearing will most likely be a 3 row roller type design, Figure 31. It has good stiffness and the best chance of precision manufacturing at a nominal 3.8 m diameter.

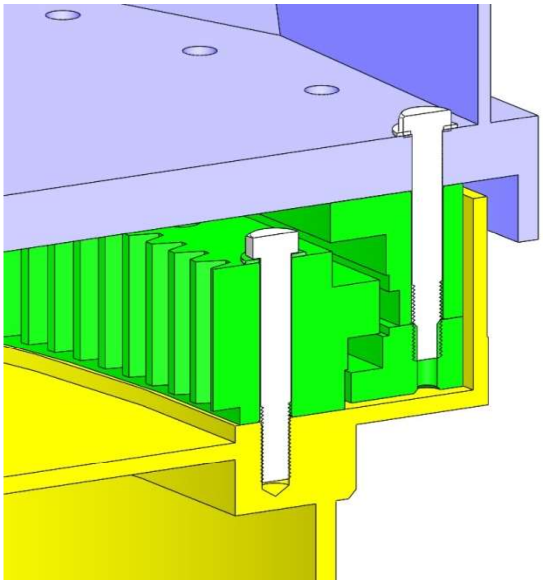


Figure 31 Azimuth Bearing Detail

5.2.2.4 Azimuth Drive

For the azimuth drive system, a direct or geared system could be added either outboard of the azimuth bearing or inboard. Inboard has the advantage of not adding to the transport size of the assembly and an opportunity to do factory assembly and a clean environment for operation and maintenance. It has the disadvantage of acting at a small radius of 1.6m requiring many stators at significant cost and cooling may be a problem. Outboard mounting increases the acting radius to about 2.00m or about 26% more than internal mounting. Cost would be reduced, cooling will be less of a problem but the advantages of interior mounting will be lost. For azimuth using a ring gear and pinion set may have a far less penalty than the elevation case. The loading path between two opposed gear drives as shown in Figure 32 is quite short. The cost for a quality gear material is reasonable, because the high quality bearing steel is already present. The inboard and outboard question is less extreme, with only an 18% difference, allowing us to favour the inboard application. Lubrication is needed, but it can be shared with the azimuth bearing requirement. Applying the direct drive concept to pinions would allow between 14:1 to 18:1 reduction and could be the most economical solution while still avoiding many of the troubles associated with further gear reduction.

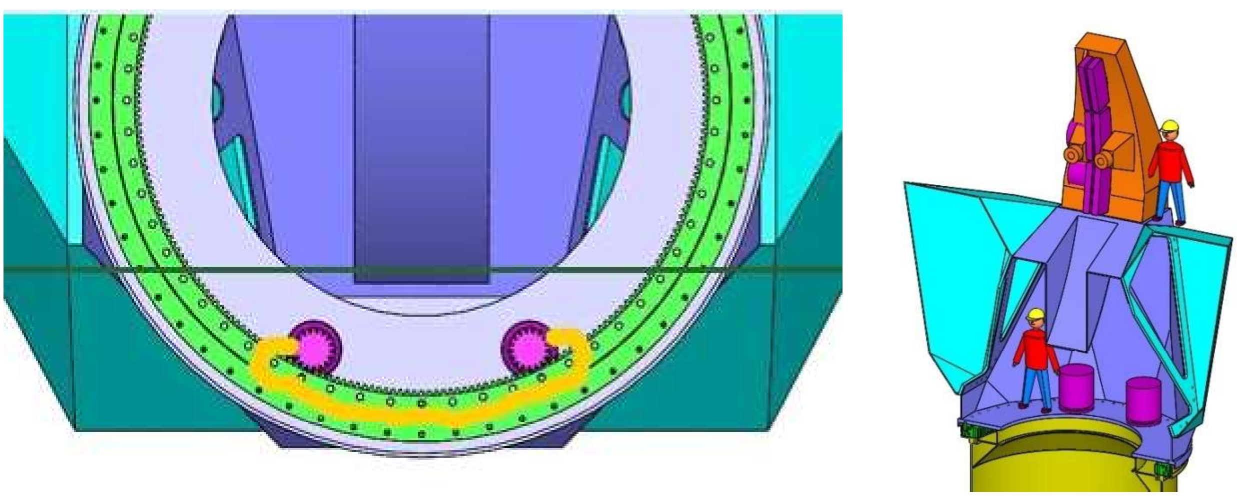


Figure 32 Azimuth Pinion/Gear Drive

Two preliminary azimuth drive designs has been performed by Phase USA [RD08] based on the mechanical configuration and loading scenarios provided by NRC. Drive loads, based on the NRC wind tunnel data scaled for the reflector size and average wind speeds of the ngVLA, are shown in Table 12.

Table 12 Azimuth Drive Loads (based on average wind speeds)

Max Azimuth Drive Loads [kNm]			
Precision	Normal	Limit	Survival
33	67	266	1665

The two drive concepts under consideration are shown in Figure 33; direct drive (left) and direct pinion and gear drive (right).

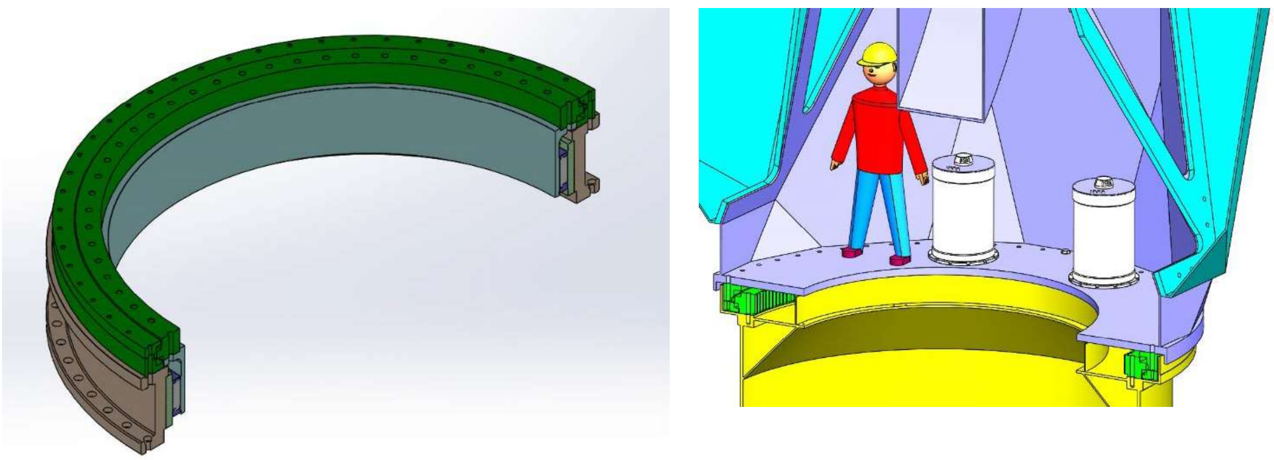


Figure 33 Azimuth Drive Options

5.2.2.4.1.1 Azimuth Direct Drive

The direct drive, similar to that used in the European ALMA antennas, consists of a rotor of magnets and several drive segments as used for the elevation drive.

Azimuth motor is composed of 12 stator sections, Figure 34 distributed within a 3.75m diameter having an active stack length of 210mm and 4mm air gap. Each section can be individually assembled and is suitable for volume production which is ideal when considering the quantity of antennas in the ngVLA. The location of the sectors is as close to the main Azimuth bearing as possible.

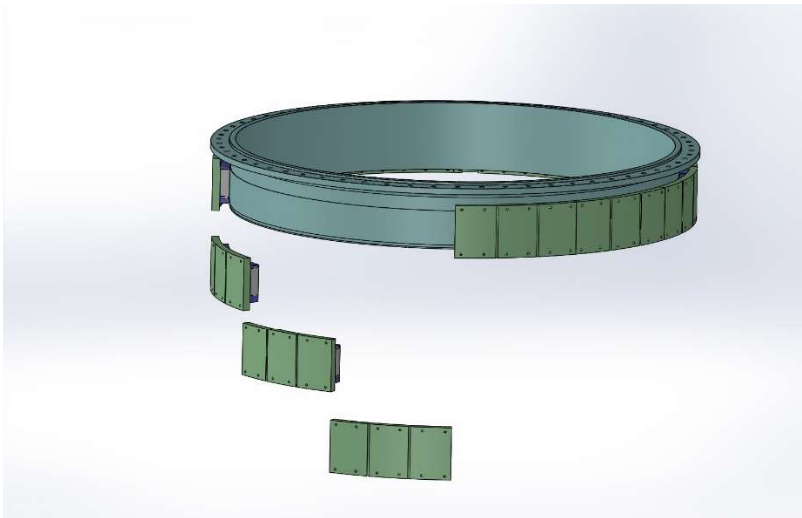


Figure 34 Inside Cylindrical Rotor Direct Drive

The rotor can be comprised of magnetic sectors or a continuous ring, whichever is deemed most feasible during final design. Each magnet is protected with an individual stainless steel protection cover sealed and retained with four stainless steel side screws.

Each motor section is equipped with dedicated holes on the top mounting plane to be used to fix an extraction tool which can be used to pull out radially the section against the magnetic attraction for maintenance purpose. In the same way it is possible to slowly let the section slide in the magnetic plates during the assembly procedure. Additionally, the design is conceived to have a motor sub-assembly which integrates the main Azimuth bearing and stator housing, Figure 35, allowing the unit to be pre-assembled and tested during manufacturing. The total unit can then be transported by standard truck and further integrated into the main structure.

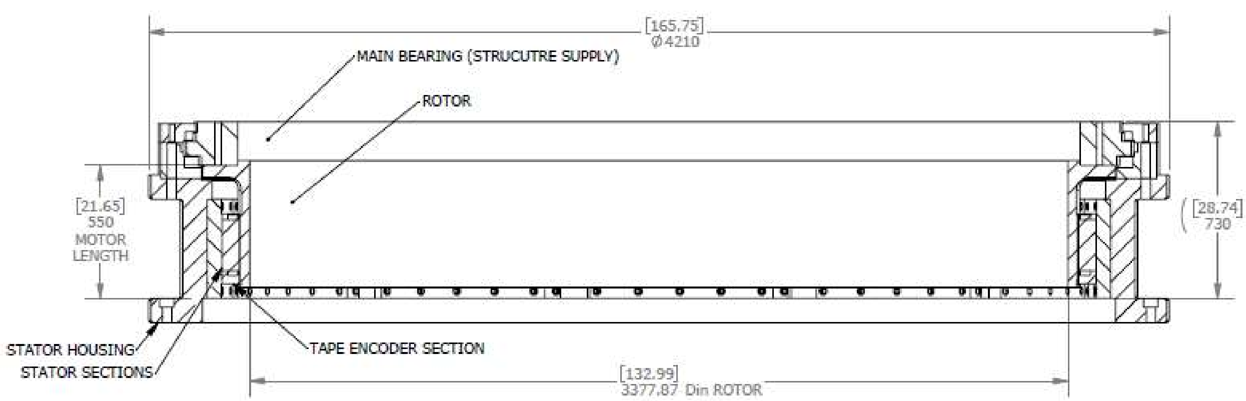


Figure 35 Direct Drive Azimuth Motor X-section

Care is to be taken during maintenance or assembly procedures, as each segment has a magnetic attraction force close to 45,000 N. This force is balanced once the full ring is assembled.

Each stator unit, or forcer, is equipped with an embedded power drive which is fed through a 600 Vdc bus line.

The interface with the control system is through an Ethernet bus with EtherCat Protocol.

For simplicity, from the torque capability point of view, in the following data the Azimuth motor is considered as a single unit even if in practice the total torque is generated by the sum of each single drive section.

Table 13 Direct Drive Azimuth Motor Performance Matrix

perf =

"Tracking, 10 m/s."	"Track, 18 m/s"	" Survival slewing"	"Pointing, accel "	" WORKING POINT"
81400	173993	321400	340988	" Motor Torque (Nm)"
0.06	0.06	0.83	1	"Shaft Speed (deg/sec)"
1.67	1.67	23.81	28.57	" Speed Nominal % "
0.08	0.18	4.67	5.95	"Shaft Power (kW)"
17.43	37.08	68.36	72.52	"Tot. Motor Current (Arms)"
84.96	177.59	368.6	399.5	"Motor Voltage (Vrms)"
0	0	0	0	"Id Current (Arms)"
17.43	37.08	68.36	72.52	"Iq Current (Arms)"
1	1	0.98	0.97	"Motor Power Factor"
0	0	0.01	0.02	"Core Loss HiFreq (kW)"
0.77	0.77	11.07	13.29	"Core Loss fund.(W)"
0.77	0.77	11.08	13.3	"Tot stator core loss (W)"
0	0	0	0	"Rotor Loss HiFreq (W)"
2481.69	11227.21	38156.43	42937.51	"Copper loss (W)"
0	0	0	0	"Mechanical loss (W)"
2482.47	11227.99	38167.52	42950.81	"Overall Motor Loss (W)"
0.03	0.02	0.11	0.12	"Motor efficiency"
35.67	90.89	260.98	291.17	"Copper Temp (°C)"
34	83.34	235.32	262.3	"Core Temp (°C)"

The direct drive azimuth performance matrix is shown in Table 13. Tracking the power required is 2.5 kW for Precision and 11.2 kW for Normal wind conditions. Power required the slew to stow is about 38 kW.

5.2.2.4.1.2 Azimuth Direct Drive Pinion

More traditional solutions for Azimuth drives consider a rack and pinion mechanical transmission, Figure 36. This solution considers Phase Motion Control's standard TK series of frameless, brushless motors in a packaged configuration containing a pinion output shaft. This arrangement transfers the torque generated by the rotor magnets to the pinion gear and plays a role in the overall stiffness of the antenna structure. In this gear train, the bending of the gear teeth, attachment flanges, and torsion of the shaft influence the stiffness. From a thermal sizing perspective, the motors are typically designed to minimize the temperature rise. This causes motor sizing to lend preference to oversizing of the units to satisfy operation. When compared to Direct Drive solutions the additional cost the costs of the rack, pinion and lubrication system must be considered.

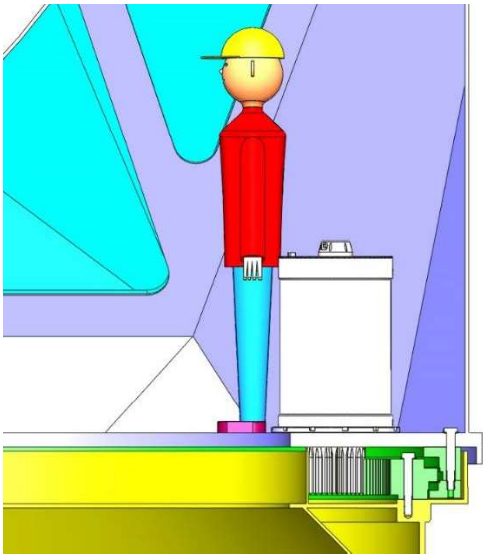


Figure 36 Direct Pinion/Gear Drive

Table 14 Azimuth Direct Pinion Drive Performance Matrix

perf =

"Tracking 10 m/s"	"Tracking 18 m/s"	"Survival slewing"	"Pointing Acc"	" WORKING POINT"
2260	4833	8927	9471	" Motor Torque (Nm)"
1.2	1.2	16.6	20	"Shaft Speed (deg/s)"
1	1	13.83	16.67	" Speed Nominal % "
0.05	0.1	2.57	3.29	"Shaft Power (kW)"
13.88	29.75	55.91	59.62	"Tot. Motor Current (Arms)"
60.23	126.81	261.63	282.69	"Motor Voltage (Vrms)"
0	0	0	0	"Id Current (Arms)"
13.88	29.75	55.91	59.62	"Iq Current (Arms)"
1	1	1	1	"Motor Power Factor"
0	0	0.12	0.17	"Core Loss HiFreq (W)"
0.86	0.86	11.91	14.35	"Core Loss fund.(W)"
0.86	0.86	12.03	14.52	"Tot stator core loss (W)"
0.31	0.31	4.06	4.84	"Rotor Loss HiFreq (W)"
1112.94	6301.19	35852.03	43737.12	"Copper loss (W)"
0	0	0	0	"Mechanical loss (W)"
1114.11	6302.36	35868.11	43756.49	"Overall Motor Loss (W)"
0.04	0.02	0.07	0.07	"Motor efficiency"
48.04	112.78	"N.A."	"N.A."	"Copper Temp (°C)"
47.2	108.03	"N.A."	"N.A."	"Core Temp (°C)"

The direct pinion azimuth performance matrix is shown in Table 13 (note values are per motor). Tracking the power required is 2.2 kW for Precision and 12.6 kW for Normal wind conditions. Power required the slew to stow is about 72 kW.

5.2.2.4.1.3 Azimuth Drive Comparison

As antennas become larger, the need and challenge to control their movement becomes ever more significant. A critical point includes not altering the antenna or antenna performance achieved through optimal mechanical and thermal design allowing fast switching drive systems operating in harsh conditions. This introduces very high torque requirements in acceleration (pointing) due to the very large mass of the structure. Additionally, radio antennas must reach survival torque conditions in storms and can easily reach million Nm. Overall a servo system is realized with high resolution and wide control bandwidth.

To achieve the desired performance, many factors must be considered. Both Direct Drive and Direct Pinion Drive solutions are considered. These large structures are heavy, so friction is also important. The use of geared motor drives, including rack and pinion introduces:

- A resonance between motor inertia and structure distributed inertia, limiting the achievable control bandwidth.
- A high spatial frequency error due to gear inaccuracies, which may fall outside the control loop bandwidth and thus affect the antenna motion.
- A nonlinearity due to stick-slip friction or gear backlash; in either case this would generate an instability at low speed, typically seen in the Elevation axis at meridian crossing.
- Potentially, lower up-front cost with additional cost of ownership.
- Maintenance Requirements, Lubrication, Additional power requirements, Wear components, etc.

Utilizing direct drives, the control system comprises a number of electromagnetic thrusters, or forcers, integrated within the structure and can apply the required force to obtain motion directly to the stiffest parts, or nodes, of the actuated structure. These thrusters do not add inertia to the system and can brace the system. The force is generated electromagnetically and can be integrated into the structure.

In further comparison, switching and tracking motions require high pulse power to accelerate and brake the large antenna inertia. This requires a high control bandwidth and clean linear response, which tend to very long settling times in gear solutions. The resulting effect is not meeting specification or introducing pointing errors, whereas direct drives settle in a fraction of a second. Additionally, the geared solutions add the motors inertia multiplied by the square of the transmission ratio to the antenna inertia. Direct drives do not add inertia relative to the structure. The motion energy can also be stored in pre-charged capacitors to minimize the power requirement from the grid to be minimal.

From a performance standpoint the direct drives are very attractive. Future work will include a full lifecycle trade study in order to make a final selection.

6 PERFORMANCE

6.1 System Noise Contribution

Table 15 System Noise Contributions Requirement

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.	

NRC has conducted tests of its reflecting materials to determine the system noise contributions. The test method is detailed in RD01 and the latest results are detailed in RD02 and presented in Figure 37. Samples A1/2 are the materials developed for DVA1, B1/2 material developed for DVA2 and the most recent material developed for the ngVLA project is C1/2. Gains were made between DVA1 and 2 by switching from aluminium to copper and further gains to the most recent material were due to material configuration changes.

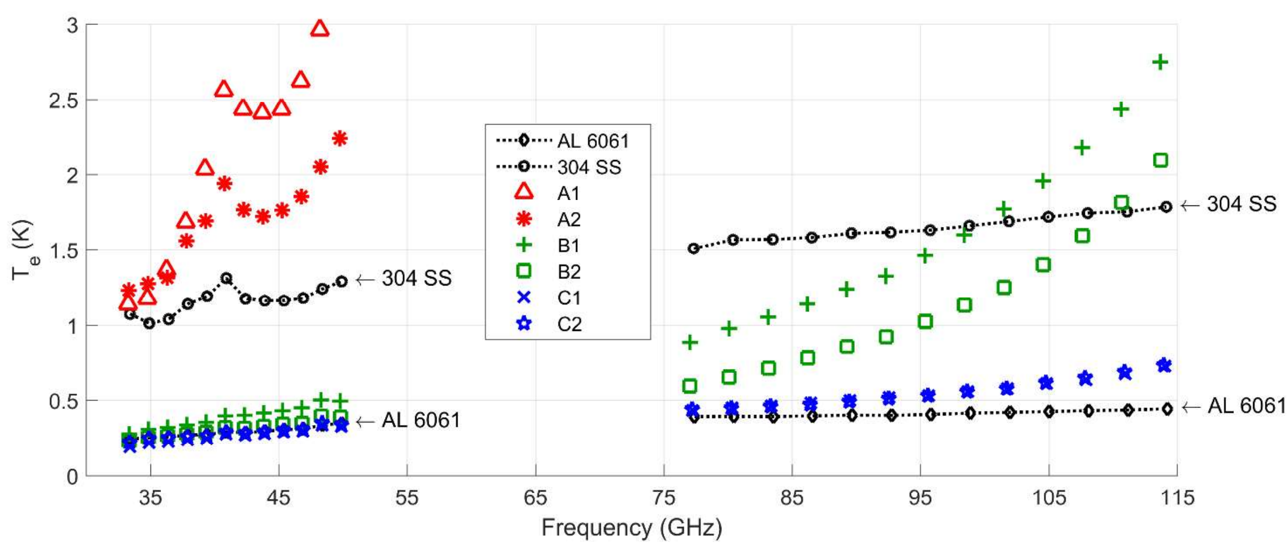


Figure 37 Reflector Surface Noise Measurement Results

The worst case noise temperature contribution from the surface for the C materials is ~0.75 K @ 115 GHz. The resistive loss is calculated as follows;

$$\%loss = \left[1 - \frac{1}{\left(\frac{Tn}{290} + 1\right)}\right] * 100\% = \left[1 - \frac{1}{\left(\frac{0.75}{290} + 1\right)}\right] * 100\% = 0.3\%$$

6.2 Integrated Model Finite Element and Electromagnetic Analysis

Post PDR an integrated finite element analysis (FEA) model of the entire antenna assembly was created, Figure 38. Analysis results presented here are from that integrated model. See [RD06] for more details.

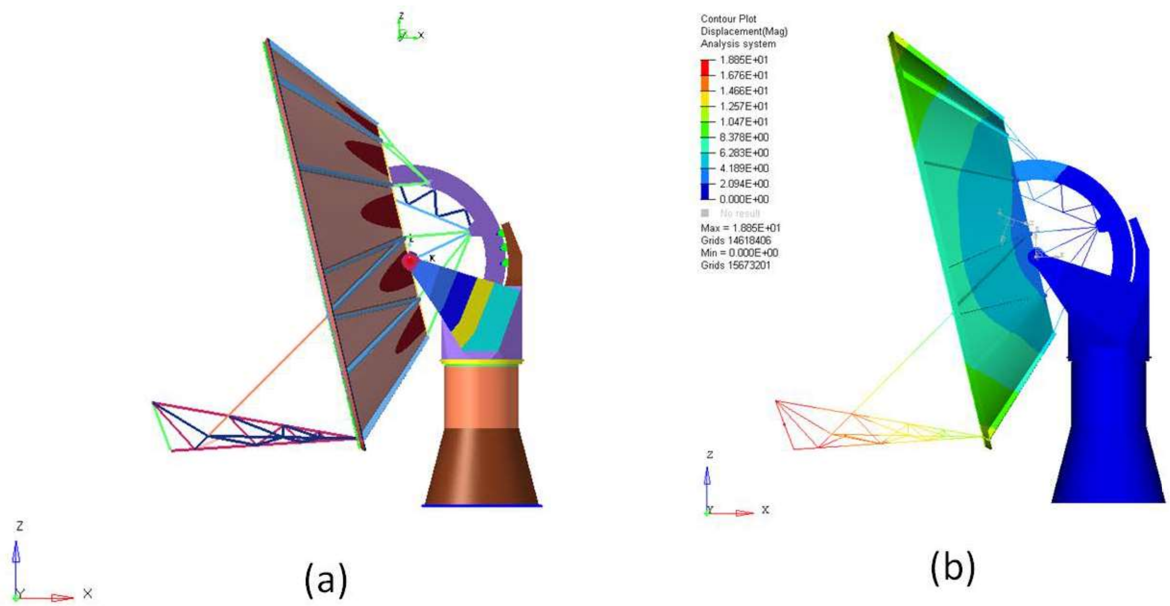


Figure 38 (a) Integrated FE model (15° elevation angle), (b) example FEA results

The following procedure is used:

1. A particular load case is applied to the integrated FEA model.
2. Primary surface distortions, and secondary reflector and focal point solid body motions (translations and rotations) are calculated.
3. Node data of the distorted primary surface is exported, re-gridded to a regular grid and imported into GRASP.
4. Secondary reflector and feed position solid body motions are applied to the GRASP model (at this time secondary surface distortions are not modelled).
5. The GRASP simulation is run to calculate the antenna gain and pointing error.

6. The aperture efficiency is calculated by comparing the distorted model gain to the un-distorted model gain.

6.3 Aperture Efficiency

The key requirements for aperture efficiency relate to surface accuracy and reflector surface continuity, Table 16. Operating conditions requirements are reproduced in Table 3 and Table 4.

Table 16 Aperture Efficiency Related Requirements

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.	

Strictly speaking the NRC SRC does not meet the requirement for Reflector Construction (ANT0503) as the surface reflecting material does have perforations, however as demonstrated by the low system temperature contributions in the previous section this will not prevent the reflectors from achieving the required aperture efficiency.

The results of the analysis method outlined in 6.2 are antenna efficiency but the ngVLA antenna specification [AD01] specifies surface accuracy in microns root mean square (RMS). NRC has suggested a change to the way the efficiency is specified and NRAO has proposed the method shown in Table 17. The values listed in the “**Structure**” column are the applicable to the analysis results presented here.

Table 17 Proposed Antenna Efficiency Specification

	Antenna Efficiencies								
Freq.	Taper	Spill.	Block.	Pol.	**Illumination**	Focus	Surface	**Structure**	**Total**
GHz	η_T	η_S	η_B	η_X	$\eta_T\eta_S\eta_B\eta_X$	η_F	η_{RUZE}	$\eta_P\eta_{RUZE}$	η_A
2.0	0.95	0.83	1	1	**0.79**	1	1	**1**	**0.79**
6.0	0.95	0.83	1	1	**0.79**	1	1	**1**	**0.79**
10.0	0.95	0.92	1	1	**0.87**	1	1	**1**	**0.87**
30.0	0.95	0.92	1	1	**0.87**	0.99	0.96	**0.95**	**0.83**
50.0	0.95	0.92	1	1	**0.87**	0.99	0.89	**0.88**	**0.77**
80.0	0.95	0.92	1	1	**0.87**	0.97	0.75	**0.73**	**0.64**
100.0	0.95	0.92	1	1	**0.87**	0.96	0.64	**0.61**	**0.54**
120.0	0.95	0.92	1	1	**0.87**	0.94	0.52	**0.49**	**0.43**

For an SRC reflector the following factors contribute to the surface error; mould accuracy, process induced distortions (PID), aging, wind, gravity and thermal loads. The efficiency loss due to the last three of these are estimated by simulation while losses for the first three have been estimated from experience and engineering judgement.

6.3.1 Simulated Efficiencies

In order to calculate the efficiency under loading the undistorted surfaces must first be modelled in GRASP to determine the ideal gain. The beam patterns for the undistorted surfaces are shown in Figure 39 (10 GHz), Figure 40 (30 GHz), Figure 41 (50 GHz).

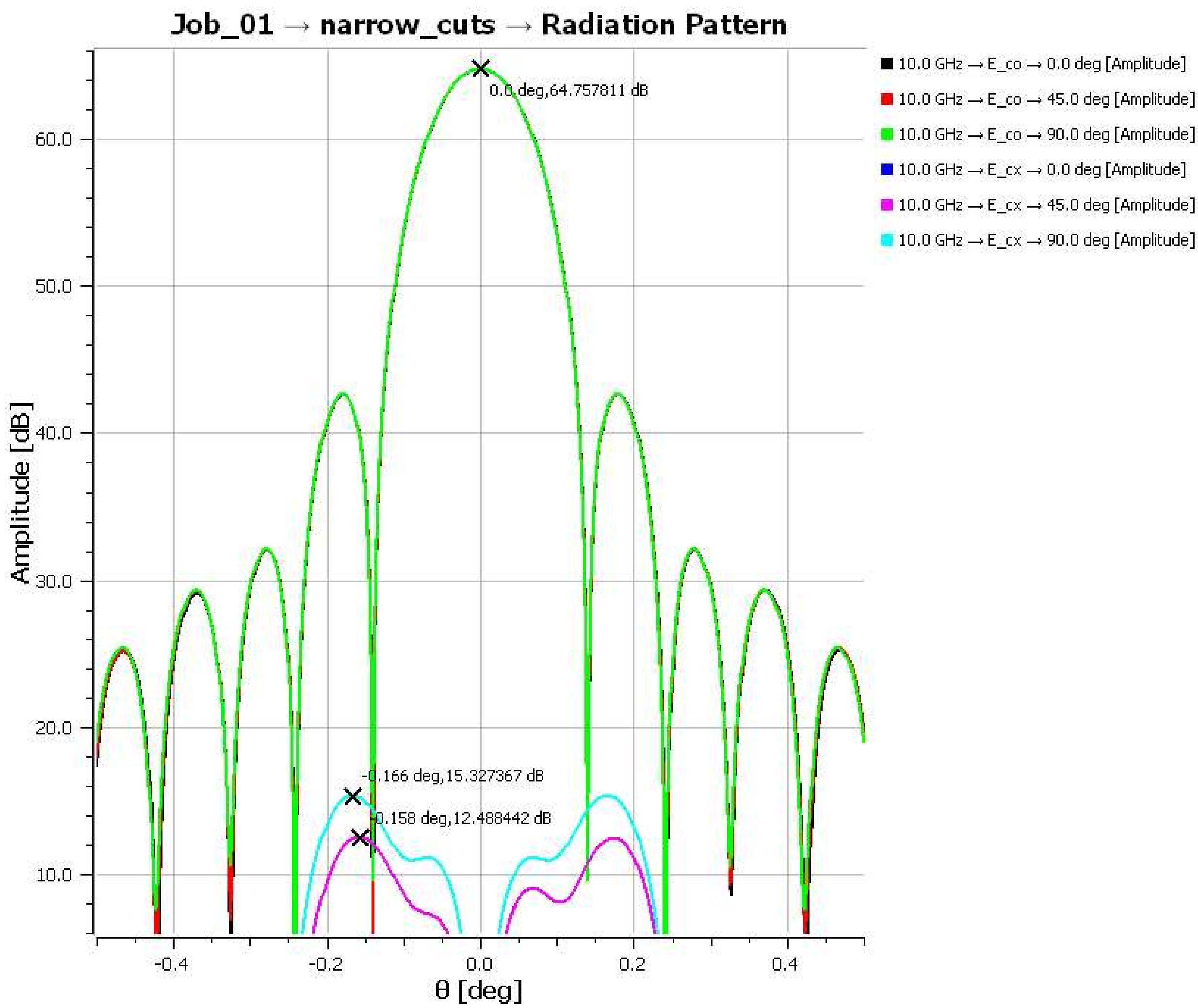


Figure 39 Undistorted Surfaces Beam Pattern 10 GHz

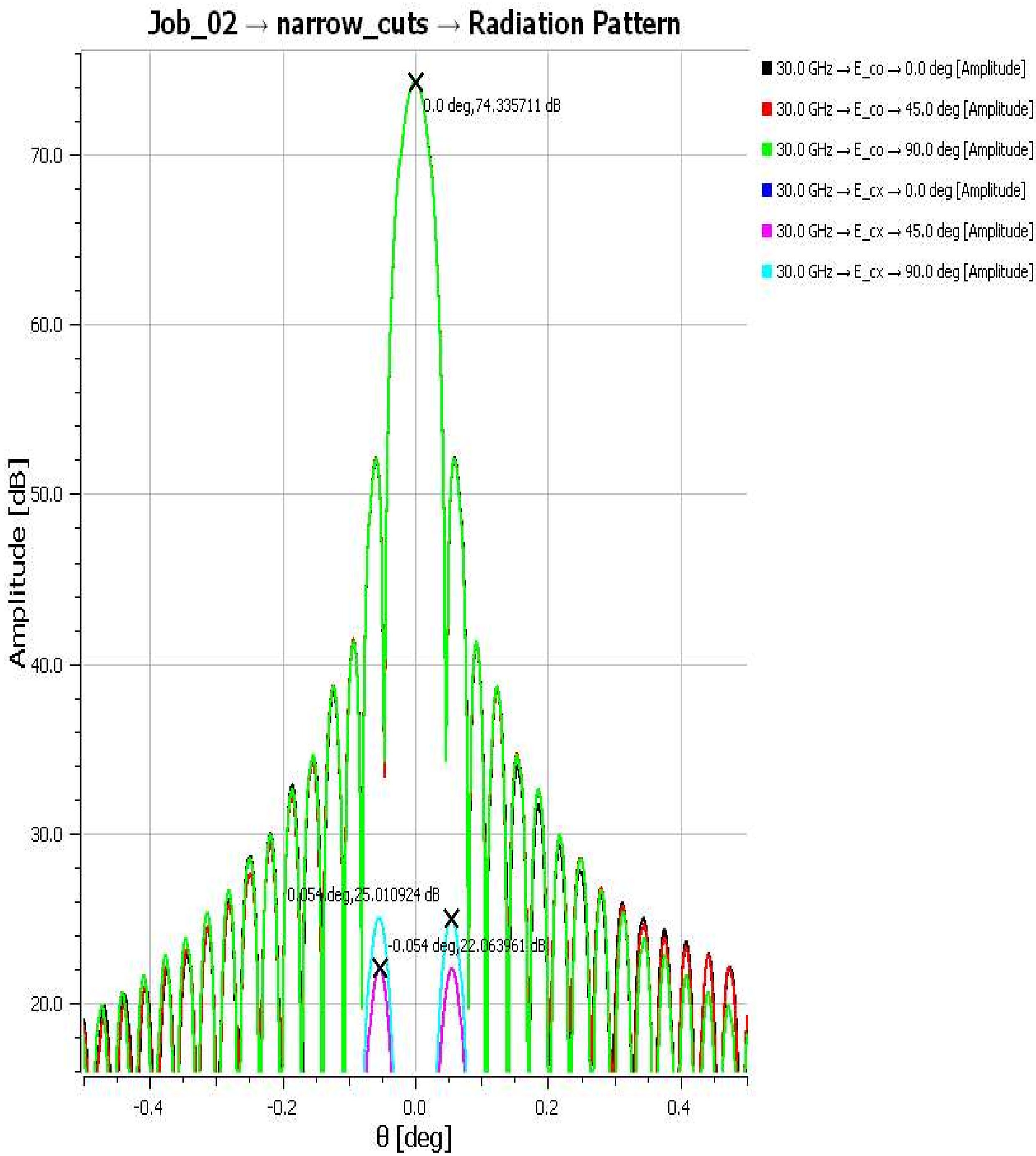


Figure 40 Undistorted Surfaces Beam Pattern 30 GHz

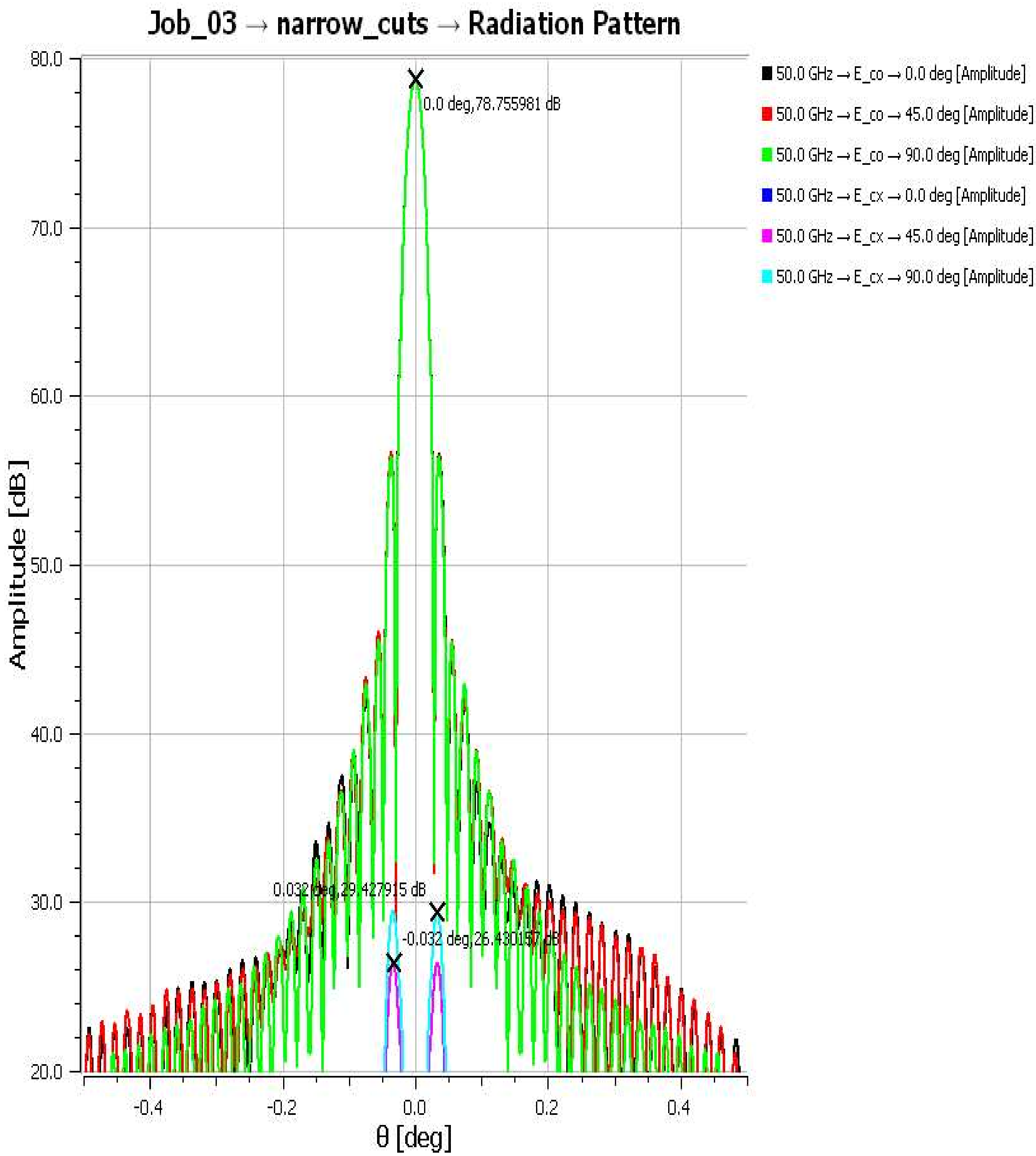


Figure 41 Undistorted Surfaces Beam Pattern 50 GHz

The peak gain is shown in Table 18.

Table 18 Gain for Undistorted Surfaces

Frequency [GHz]	10	30	50
Gain [dB]	64.758	74.336	78.756

The efficiency for the load cases presented from here on will be calculated as;

$$\eta_i = \frac{G_\epsilon}{G_0}$$

Where;

$G_\epsilon = Gain\ for\ Load\ Case$

$G_0 = Gain\ for\ Undistorted\ Case$

6.3.1.1 Gravitational Loading

Two gravitational loading cases were analysed; 15° and 90° elevation angles. Details of the analysis can be found in [RD06]. The results of the GRASP simulations are shown in Figure 42, Figure 43 and Figure 44 for 15° elevation angles at 10, 30 and 50 GHz respectively. Note pointing corrections have been applied to all gravity load case plots.

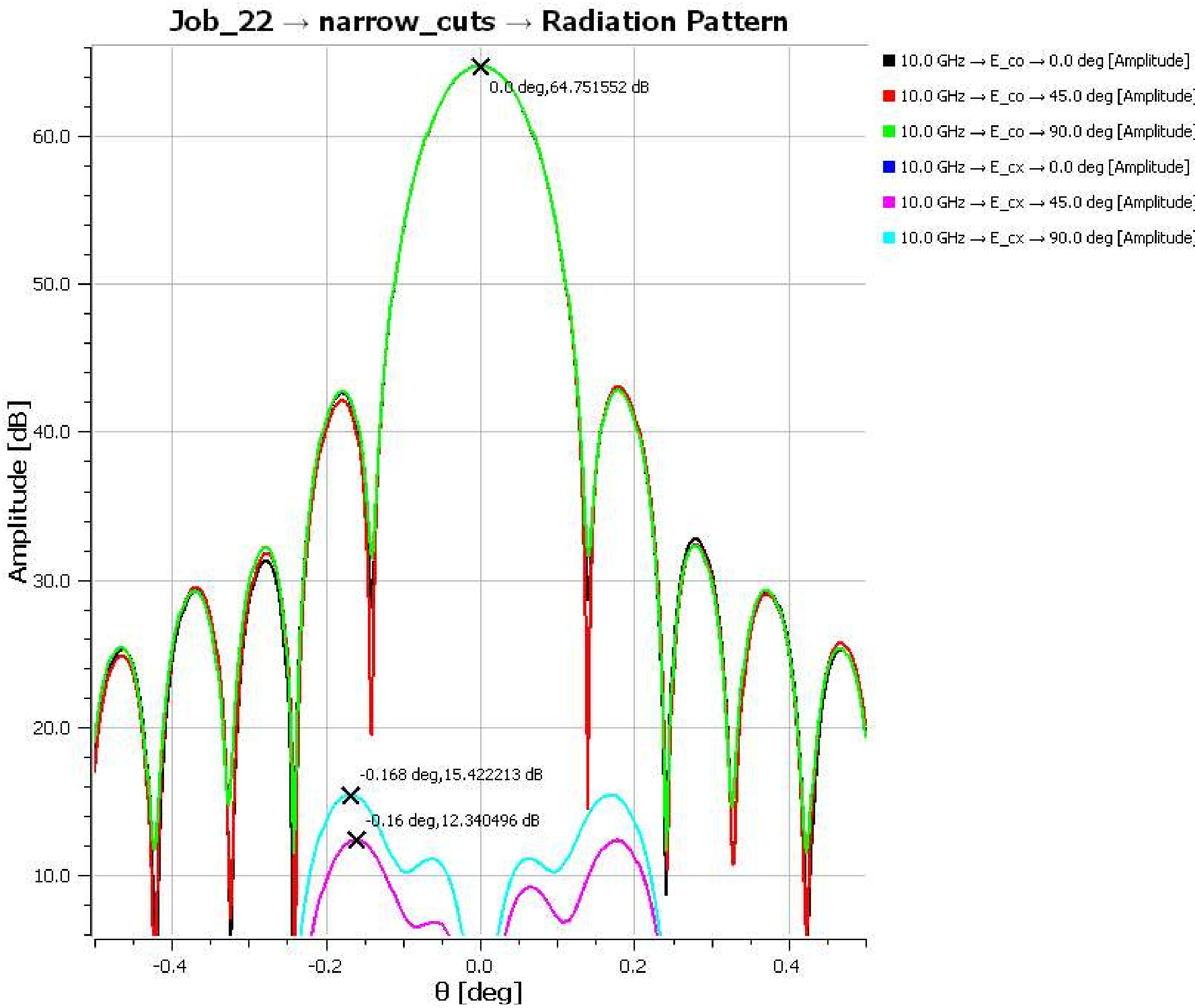


Figure 42 15° Elevation Angle Gravity Loading Case Beam Pattern 10 GHz

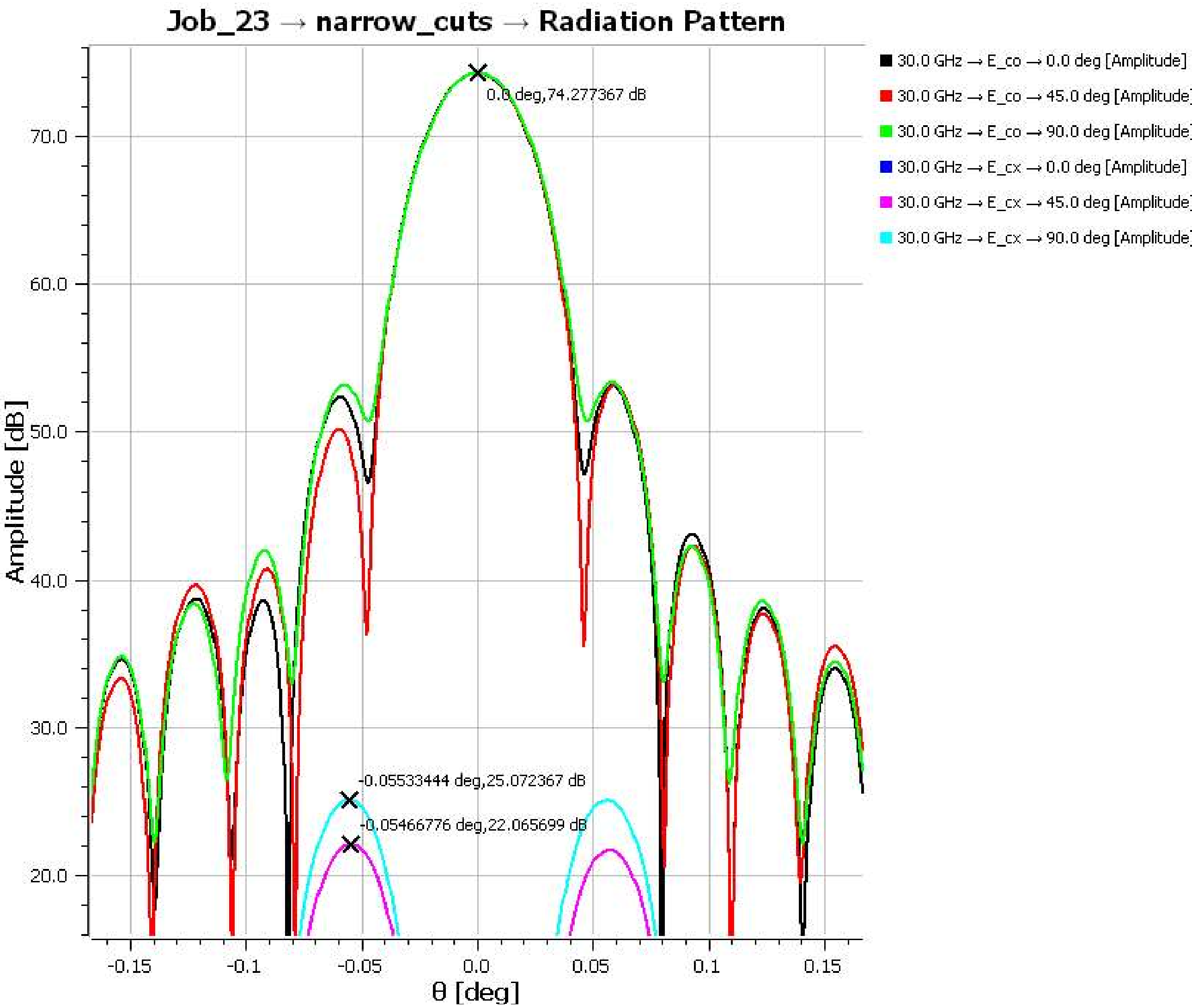


Figure 43 15° Elevation Angle Gravity Loading Case Beam Pattern 30 GHz

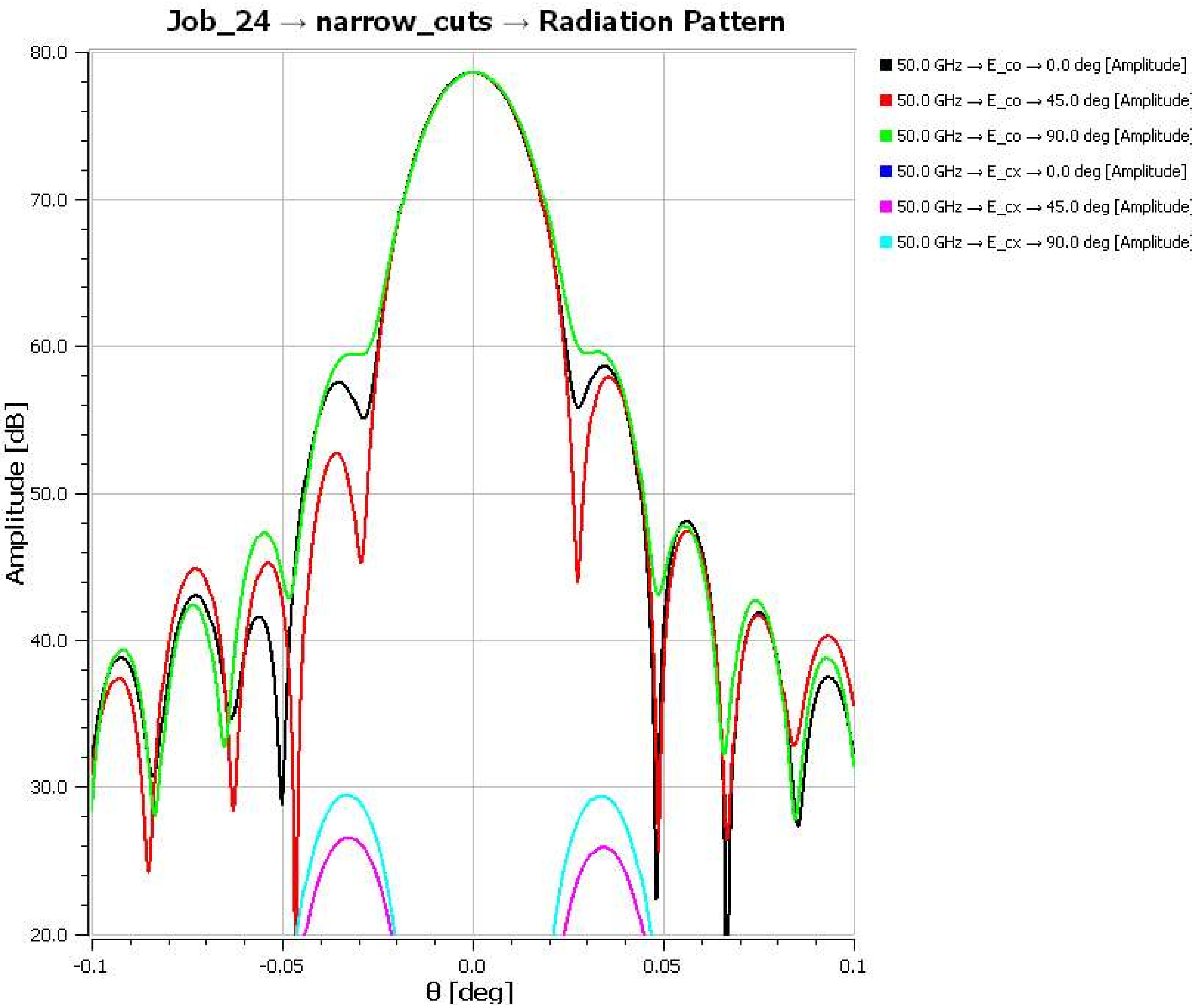


Figure 44 15° Elevation Angle Gravity Loading Case Beam Pattern 50 GHz

The results of the GRASP simulations are shown in Figure 45, Figure 46 and Figure 47 for 90° elevation angles at 10, 30 and 50 GHz respectively.

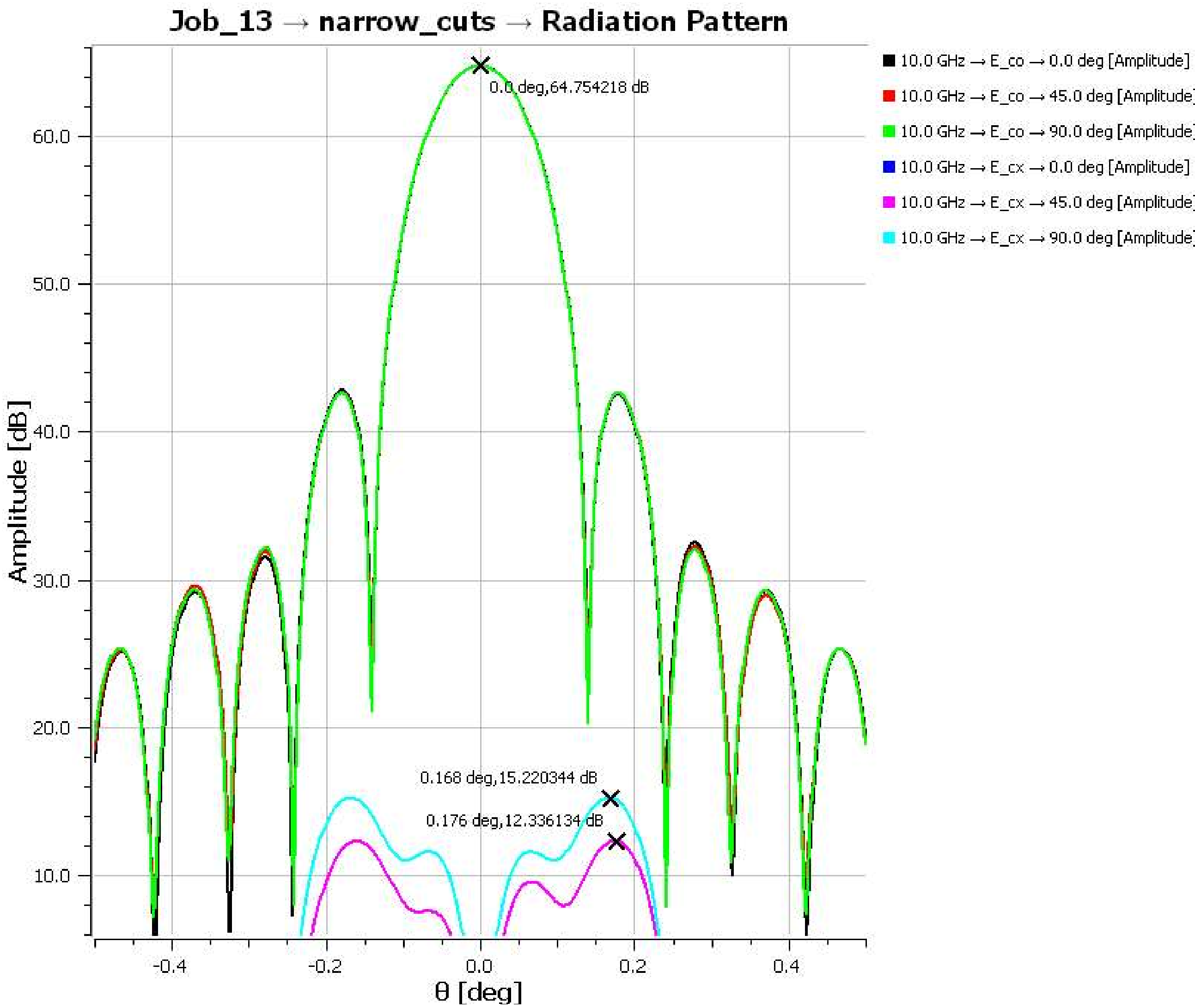


Figure 45 90° Elevation Angle Gravity Load Case Beam Pattern 10 GHz

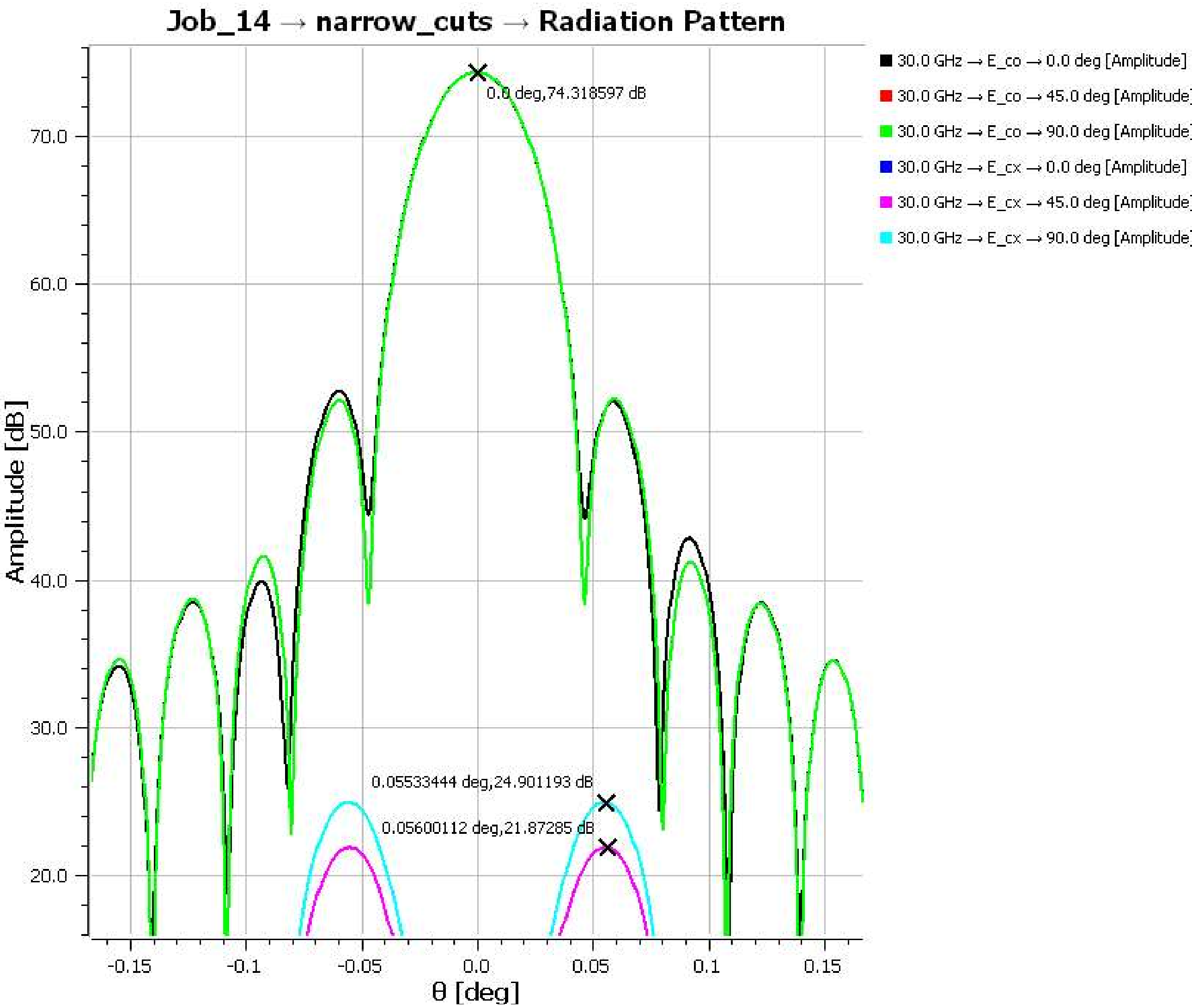


Figure 46 90° Elevation Angle Gravity Load Case Beam Pattern 30 GHz

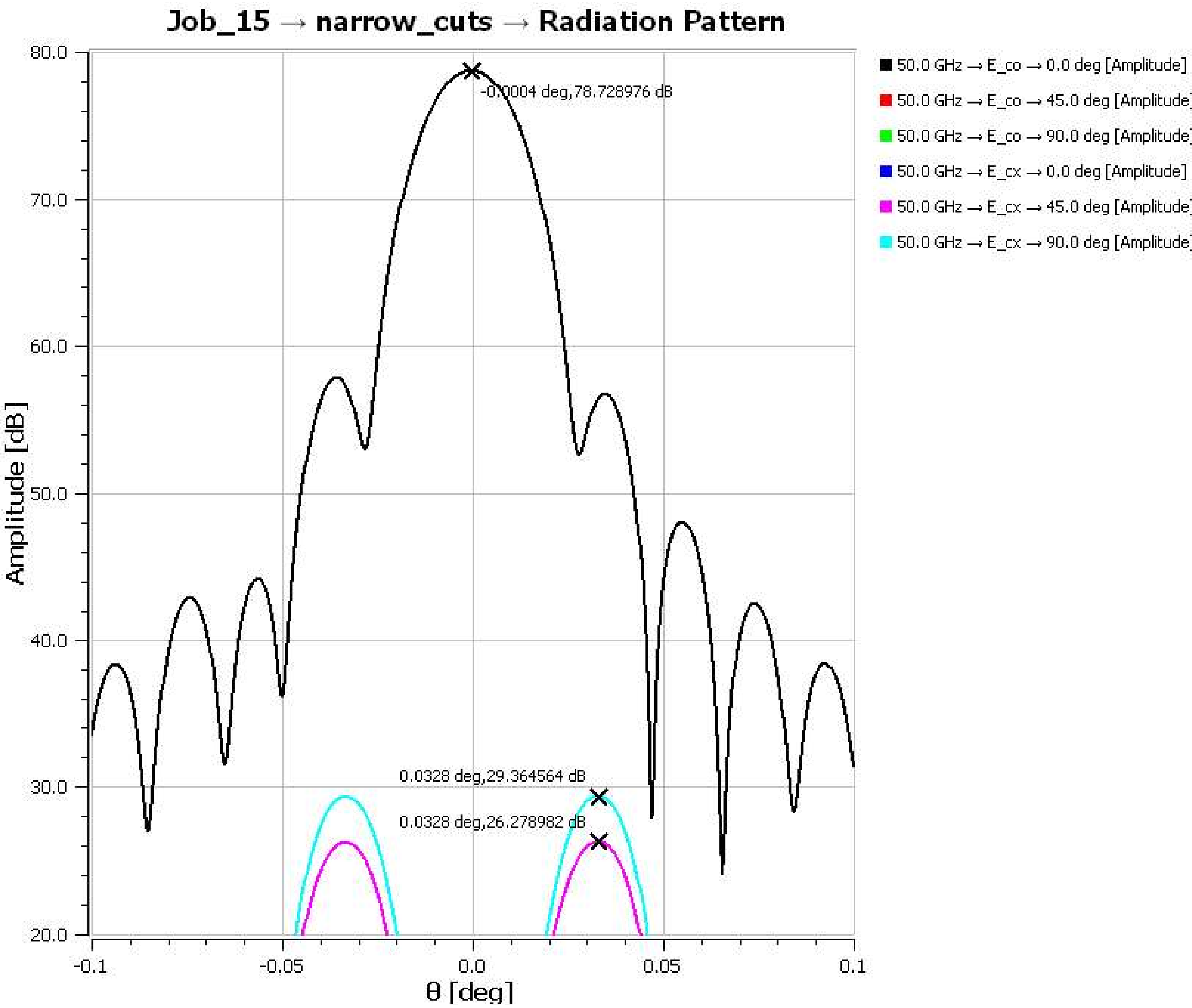


Figure 47 90° Elevation Angle Gravity Load Case Beam Pattern 50 GHz

The peak gain and calculated efficiency for the two gravity load cases is shown in Table 19. Note gravity load cases are the same for precision and normal operating conditions.

Table 19 Gain and Efficiency, Gravity Load Cases

	Frequency [GHZ]	10	30	50
Gravity 15deg	Gain [dB]	64.752	74.277	78.598
	Efficiency	99.9%	98.7%	96.4%
Gravity 90deg	Gain [dB]	64.754	74.319	78.729
	Efficiency	99.9%	99.6%	99.4%

6.3.1.2 Wind Load Deformations

In order to analyse the surface deformations due to wind loading it is necessary to understand what the load on the reflector due to wind will be. In 2010 NRC performed a series of wind loading tests on an offset reflector in the NRC wind tunnel facility at the Institute for Aerospace Research, details of this testing can be found in [RD13]. The output from these tests was a series of wind pressure and wind load coefficients for various reflector configurations at a range of elevation and azimuth angles. The pressure coefficient field results for a feed-low configuration were used for wind load modelling on the ngVLA 18m dish. Two of the worst wind load cases were analysed: 1) 0º Azimuth angle and 16º elevation angle and 2) 90º azimuth angle and 66º elevation angle. The pressure field contour maps for both the cases are shown in Figure 48.

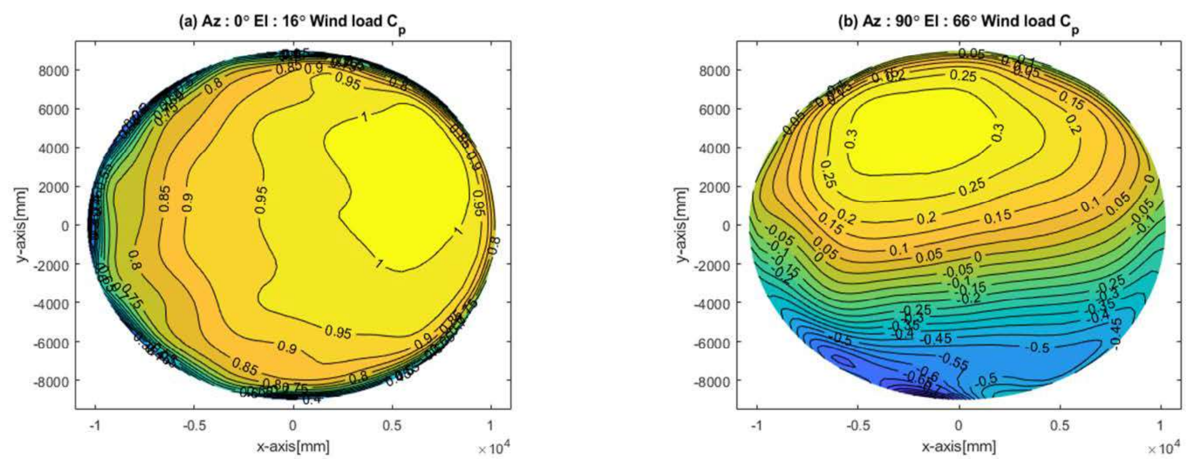


Figure 48 Wind load cases: (a) & (c) are pressure coefficient contour plots at Az: 0° El: 16° and Az: 90° El: 66°.

The two cases were analysed with a wind speed of 5 m/s (precision conditions), details of this analysis can be found in [RD06]. The results of the GRASP simulations for the 15° elevation angle are shown in Figure 49, Figure 50 and Figure 51 at 10 GHz, 30 GHz and 50 GHz respectively.

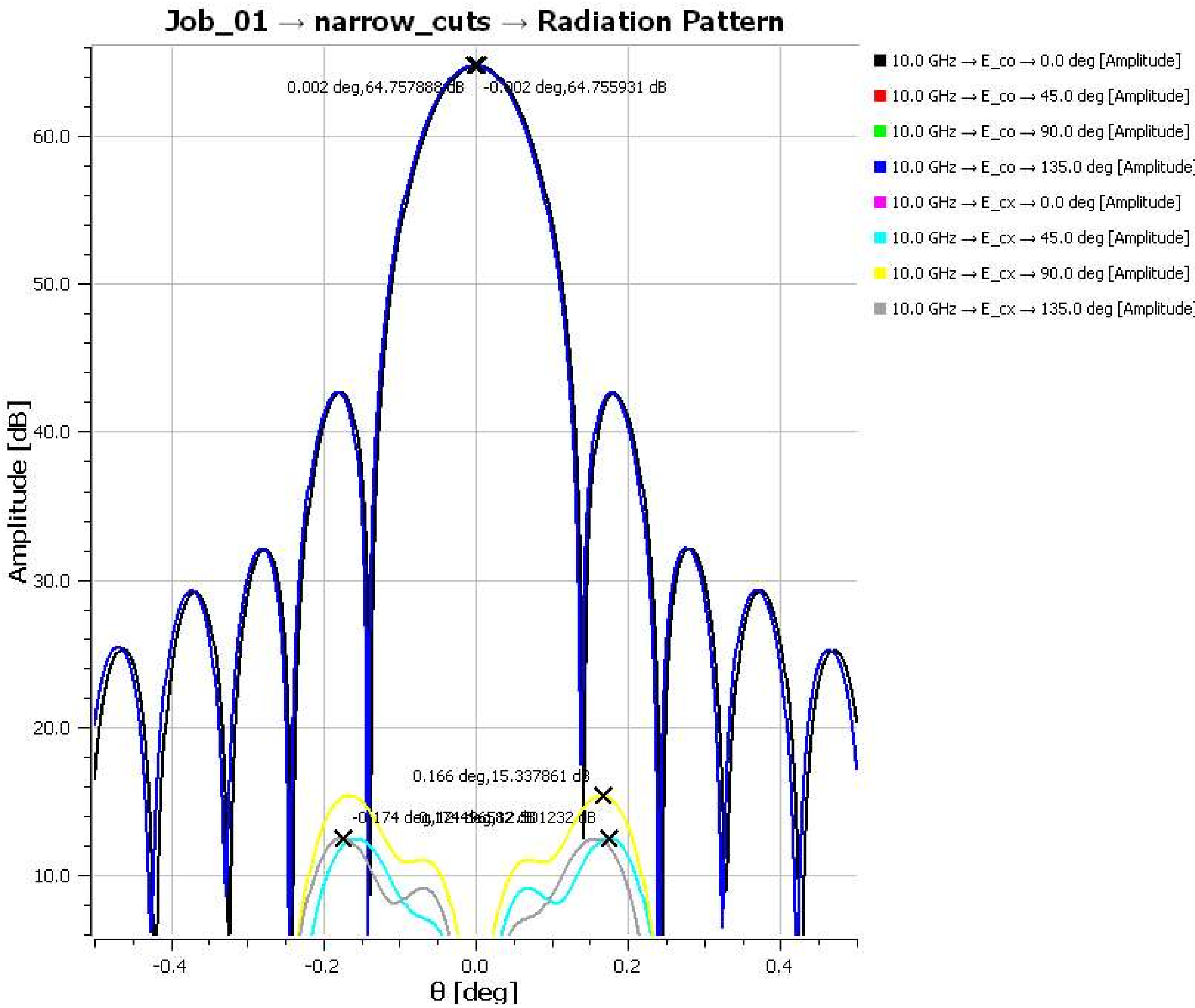


Figure 49 Wind Load Case 1 Beam Pattern 10 GHz

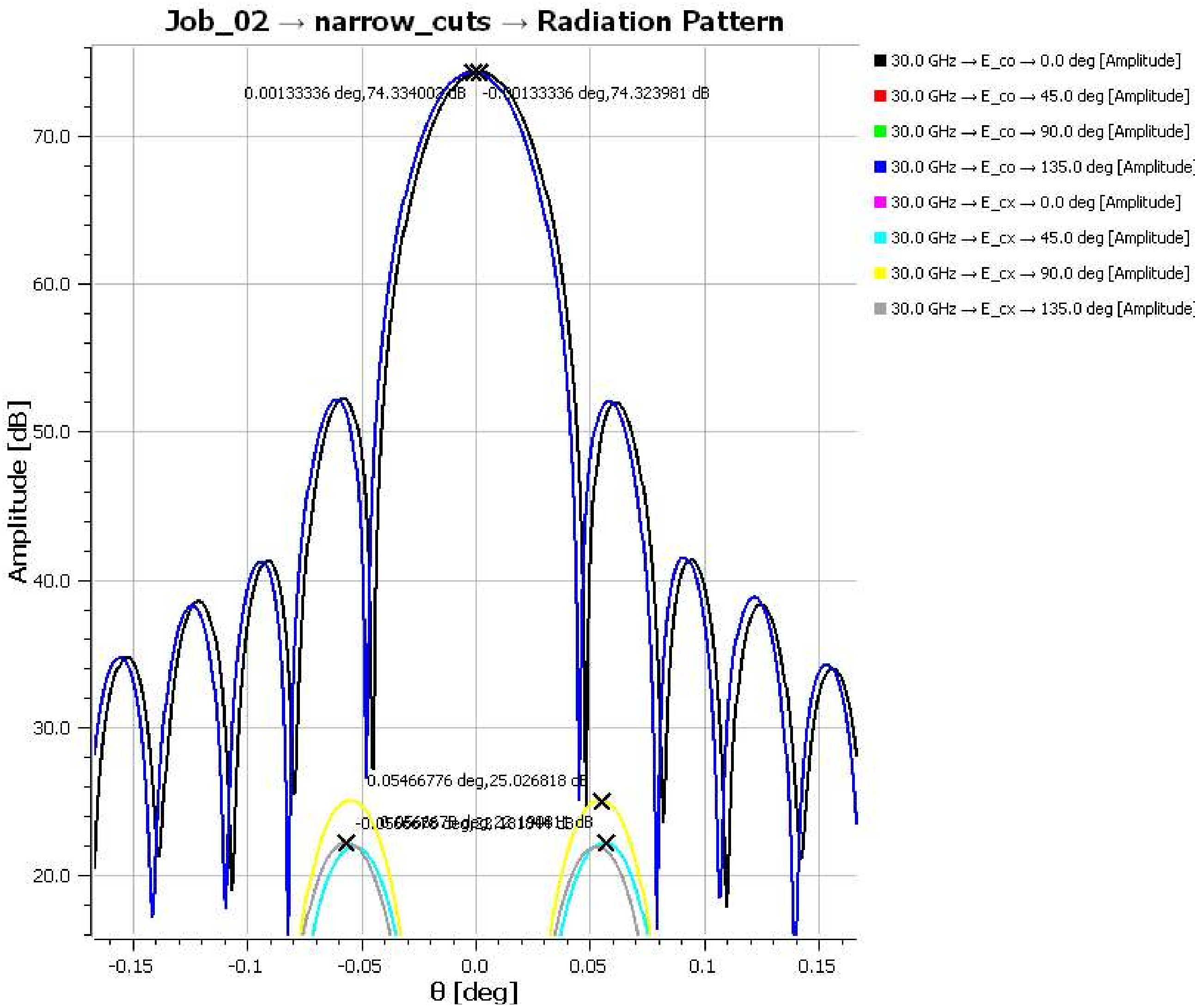


Figure 50 Wind Load Case 1 Beam Pattern 30 GHz

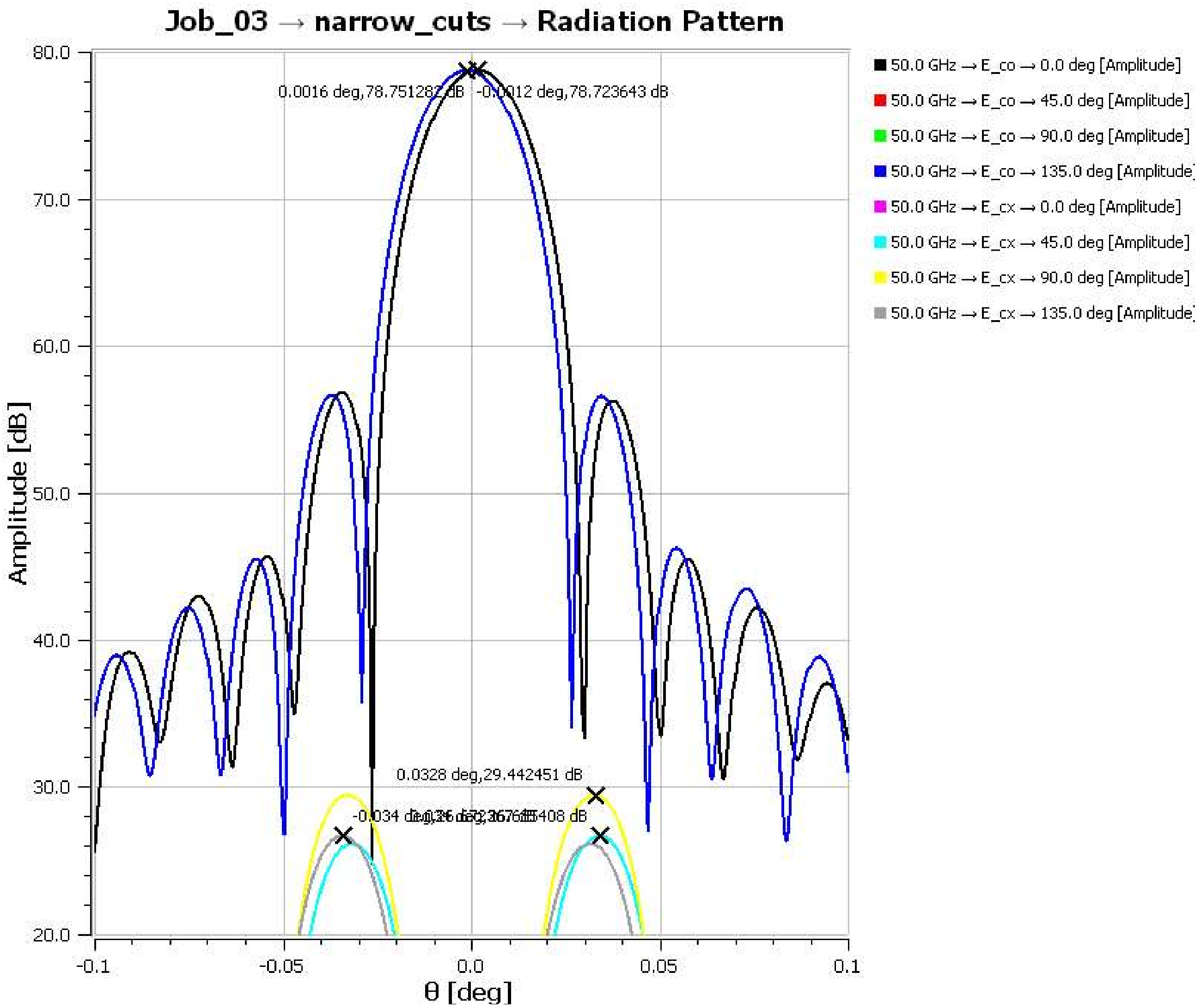


Figure 51 Wind Load Case 1 Beam Pattern 50 GHz

The results of the GRASP simulations for the 90° elevation angle case are shown in Figure 52, Figure 53 and Figure 54 at 10 GHz, 30 GHz and 50 GHz respectively.

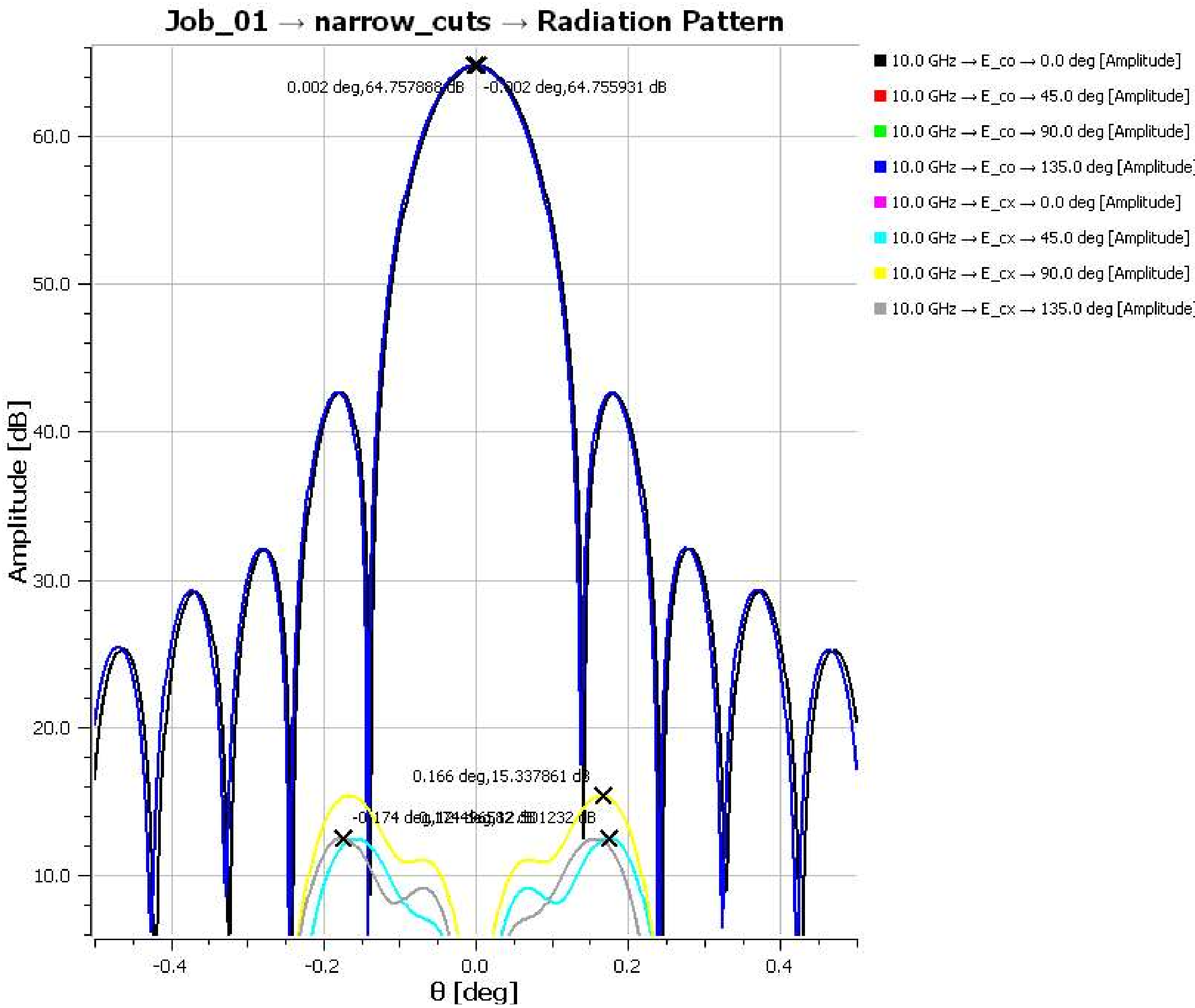


Figure 52 Wind Load Case 2 Beam Pattern 10 GHz

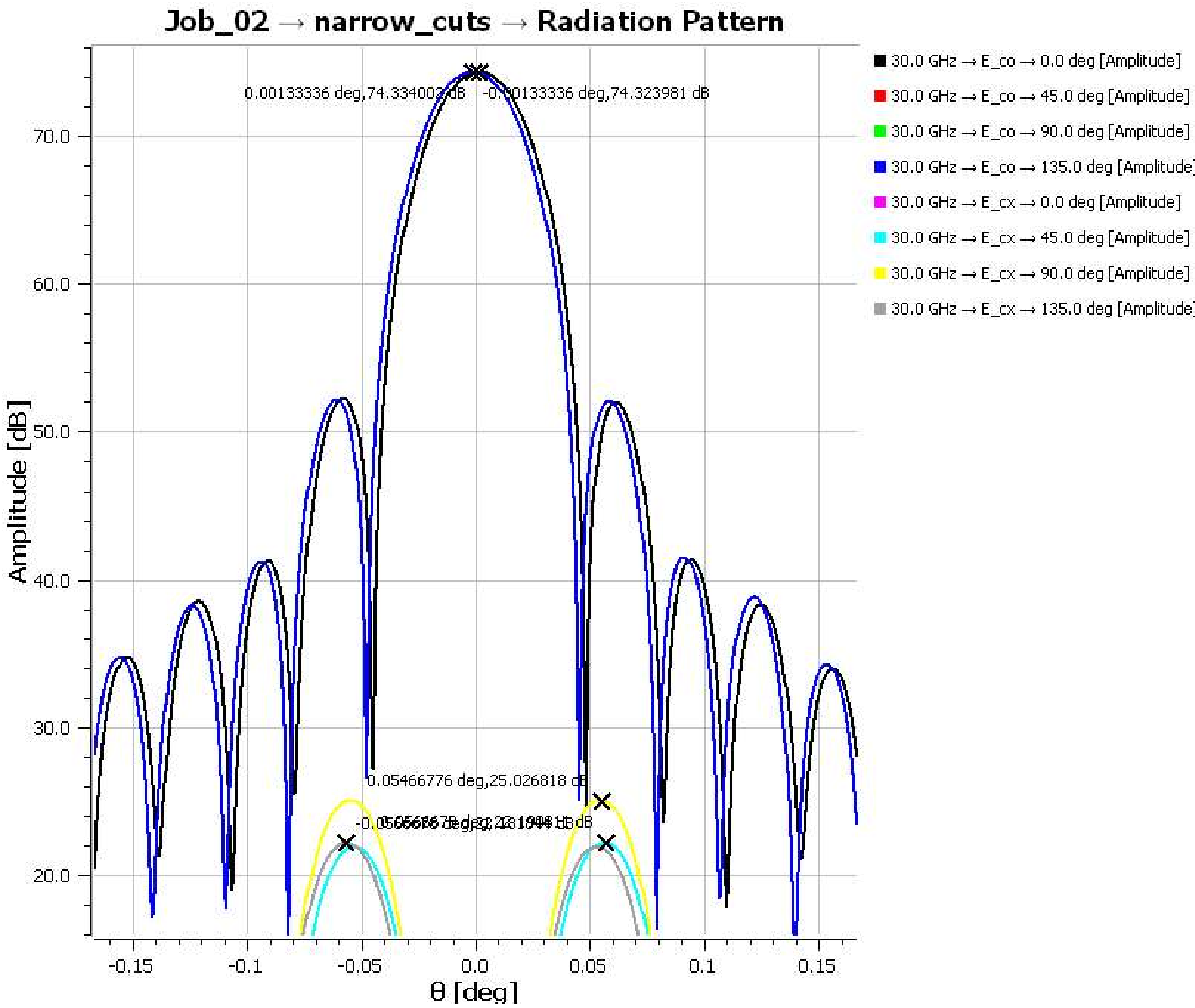


Figure 53 Wind Load Case 2 Beam Pattern 30 GHz

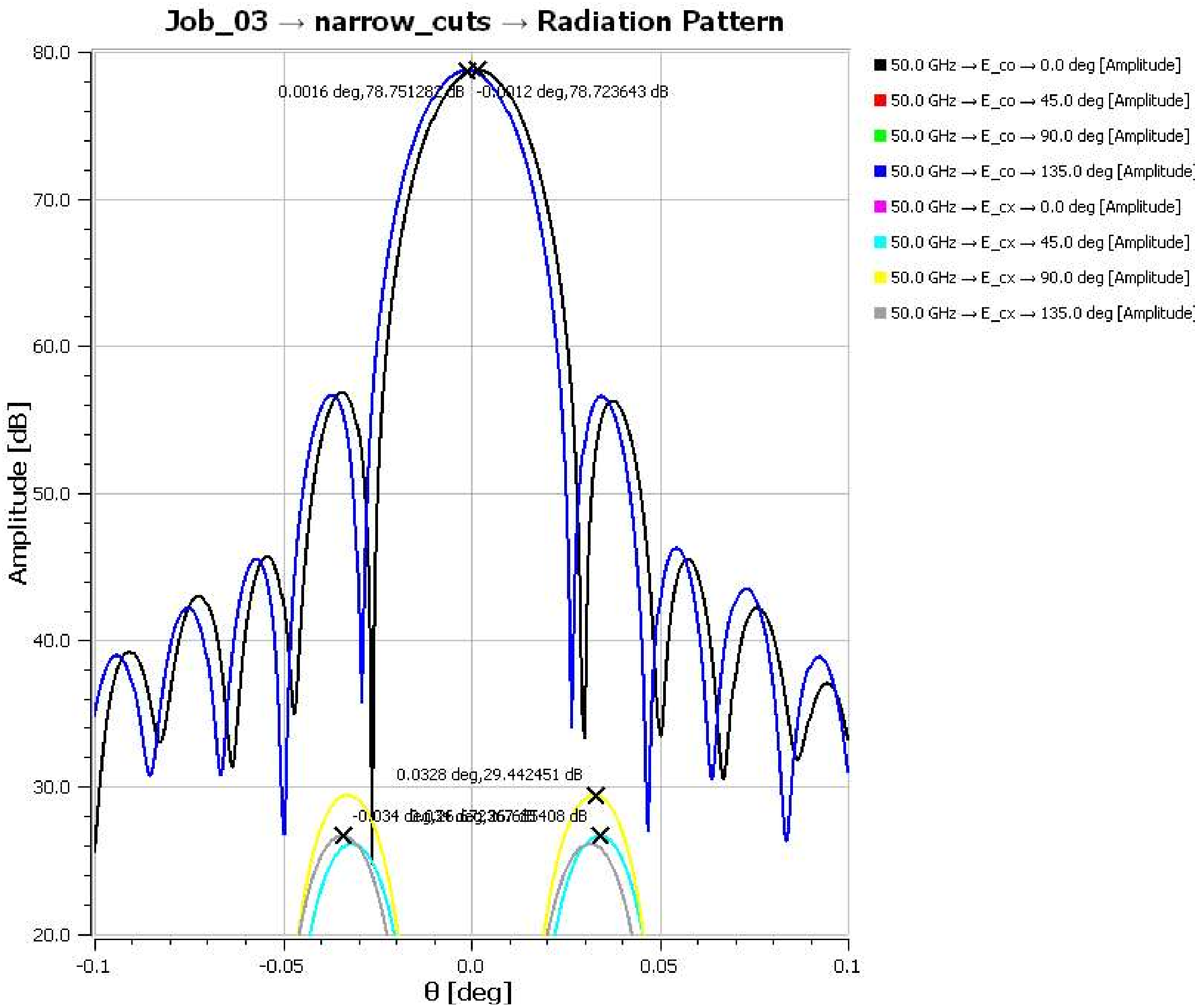


Figure 54 Wind Load Case 2 Beam Pattern 50 GHz

The peak gain and calculated efficiency for the two wind load cases are shown in Table 20.

Table 20 Gain and Efficiency, Wind Load Cases

	Frequency [GHZ]	10	30	50
W01	Gain [dB]	64.758	74.334	78.751
	Efficiency	100.0%	100.0%	99.9%
W07	Gain [dB]	64.758	74.334	78.752
	Efficiency	100.0%	100.0%	99.9%

The reflector models used for the wind tunnel testing have a different BUS configuration than the ngVLA design and therefore in future design phases computational fluid dynamics (CFD) analysis will be performed to refine wind load data.

6.3.1.3 Thermal Deformation

Two key thermal loading cases have so far been considered; thermal bath and thermal gradient.

6.3.1.3.1 Thermal Bath

In Precision operating conditions the requirement is for night time operation so only thermal bath needs consideration however the temperature operating range is large, -15 C ≤ T ≤ 25 C, a reflector that is assembled at 15 C but operated at -15 C must therefore maintain performance over a temperature range of 30 C. The initial analysis had been performed at a ΔT of 20 C but results can be linearly scaled to other temperature ranges.

During night operation the reflector is assumed to be at thermal equilibrium and so distortions due to thermal expansion/contractions will be caused by differences in CTE in different parts of the structure. The CTEs of the major components of the primary reflector structure are shown in Table 21. It is clear from the table that the thermal expansion coefficients vary across the structure.

Table 21 Primary Reflector Component CTEs

Components	Material	CTE [µm/m/ºC]
Reflector Surface	Carbon fibre/epoxy/ reflective material	7.8
Composite materials	Carbon fibre/epoxy	6.1
oBUS	Foam Cored carbon fibre/epoxy	9.2
iBUS	Steel	12

The results of the GRASP simulations are shown in Figure 55, Figure 56 and Figure 57 at 10 GHz, 30 GHz and 50 GHz respectively.

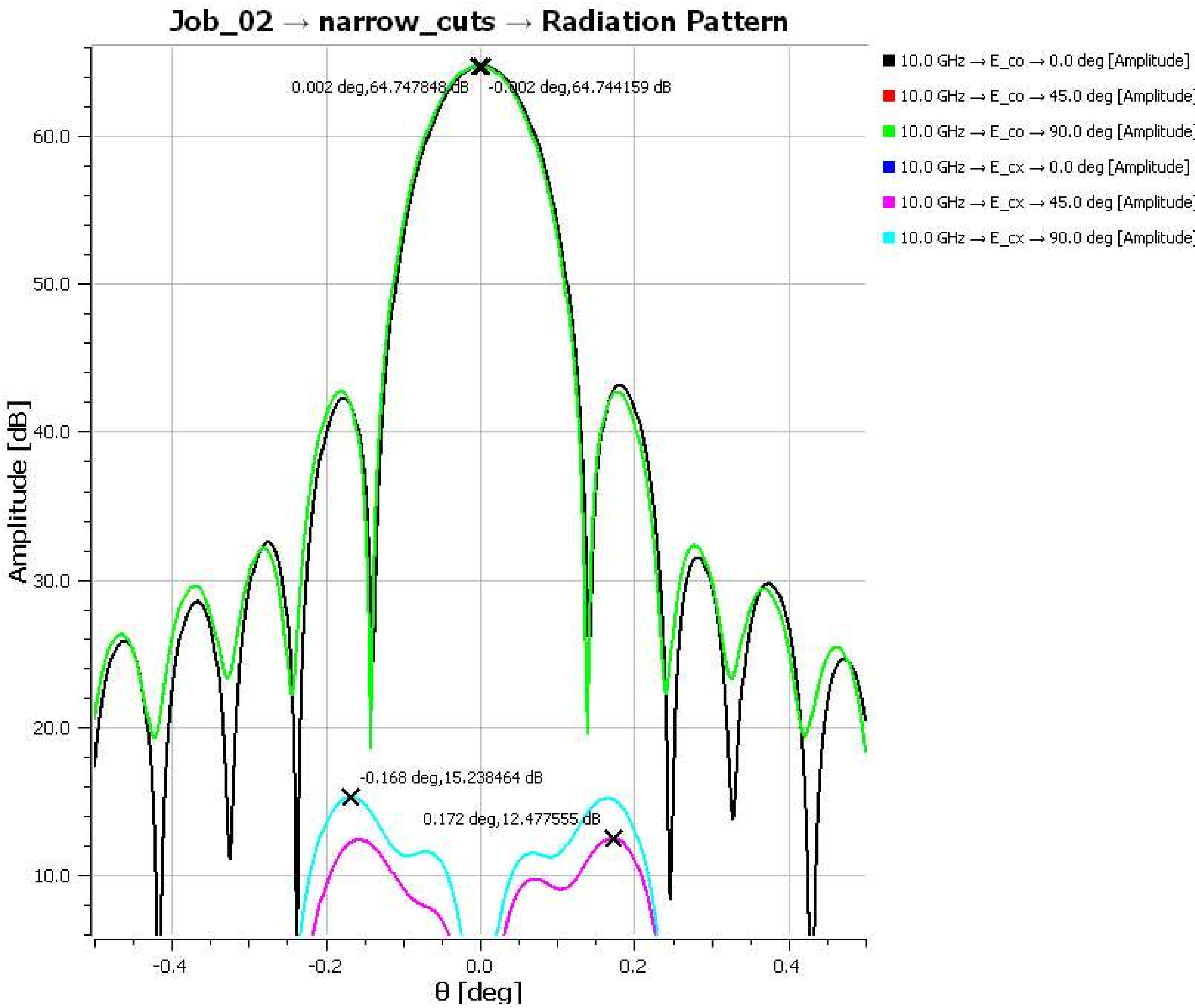


Figure 55 Beam Pattern, Thermal Bath 10 GHZ

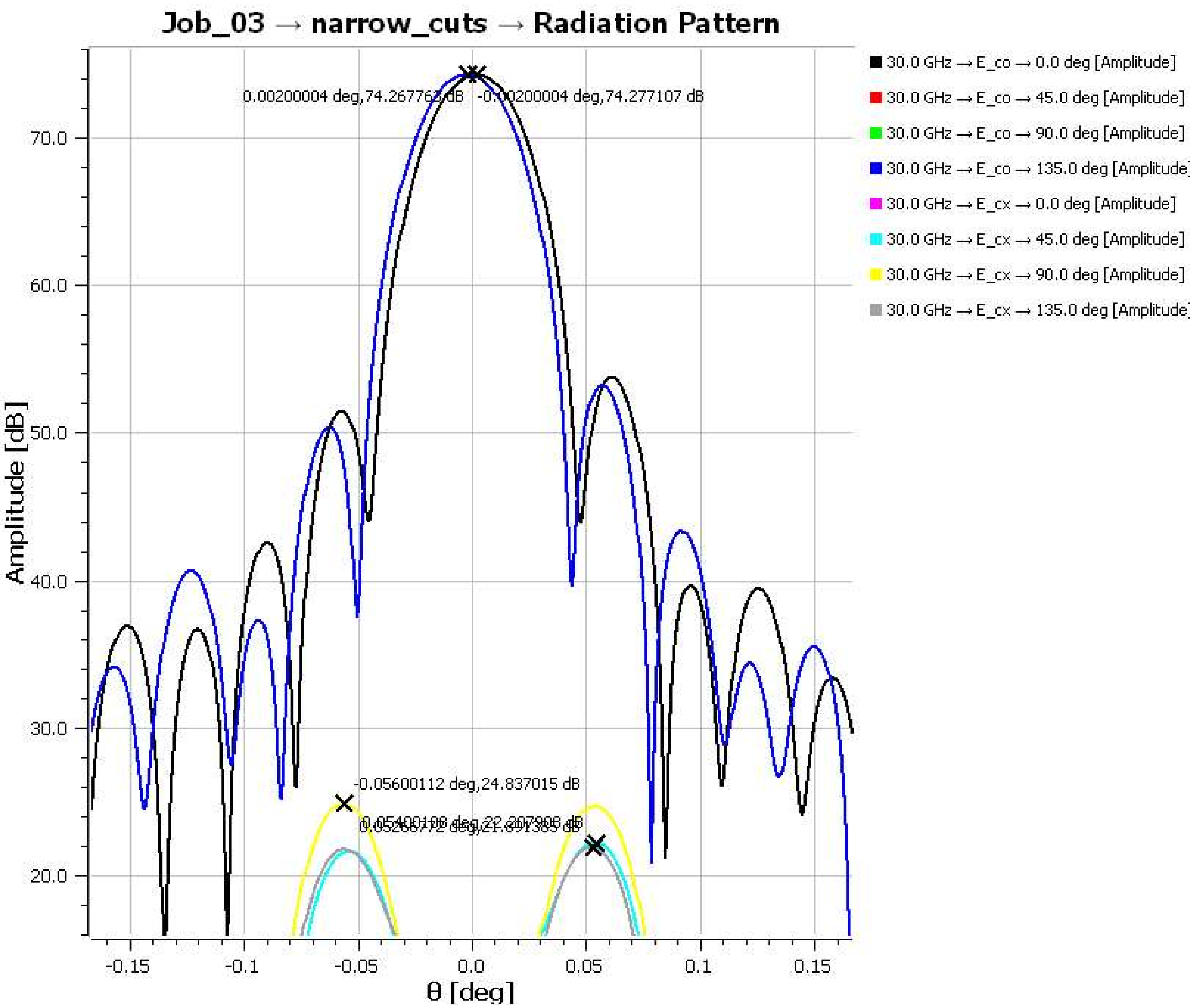


Figure 56 Beam Pattern, Thermal Bath 30 GHZ

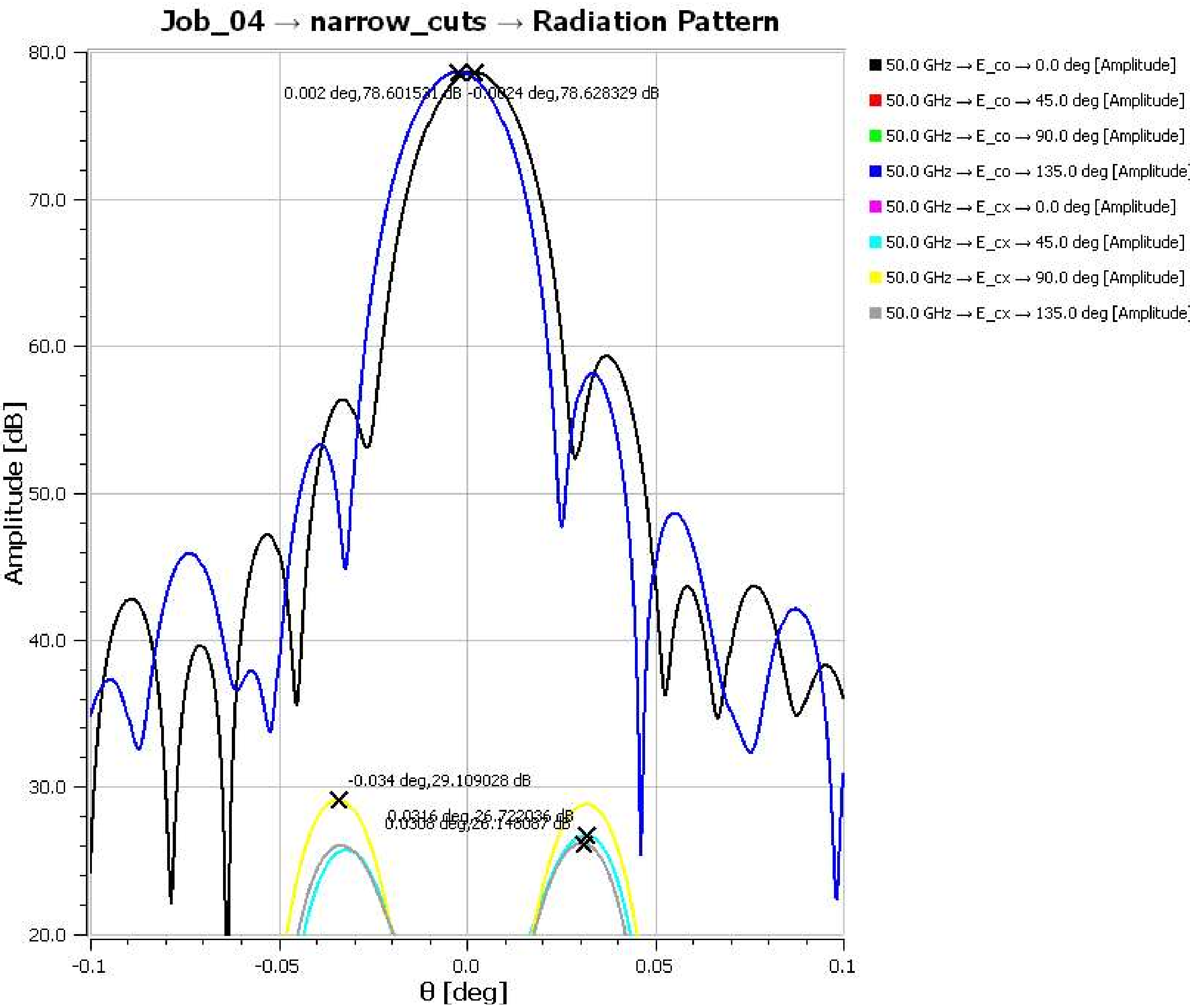


Figure 57 Beam Pattern, Thermal Bath 50 GHZ

6.3.1.3.2 Thermal Gradient

Thermal gradient was also studied with the same FEA model where a 5C temperature variation was introduced on the long axis of the dish. The results of the GRASP simulations are shown in Figure 58, Figure 59 and Figure 60 at 10 GHz, 30 GHz and 50 GHz respectively.

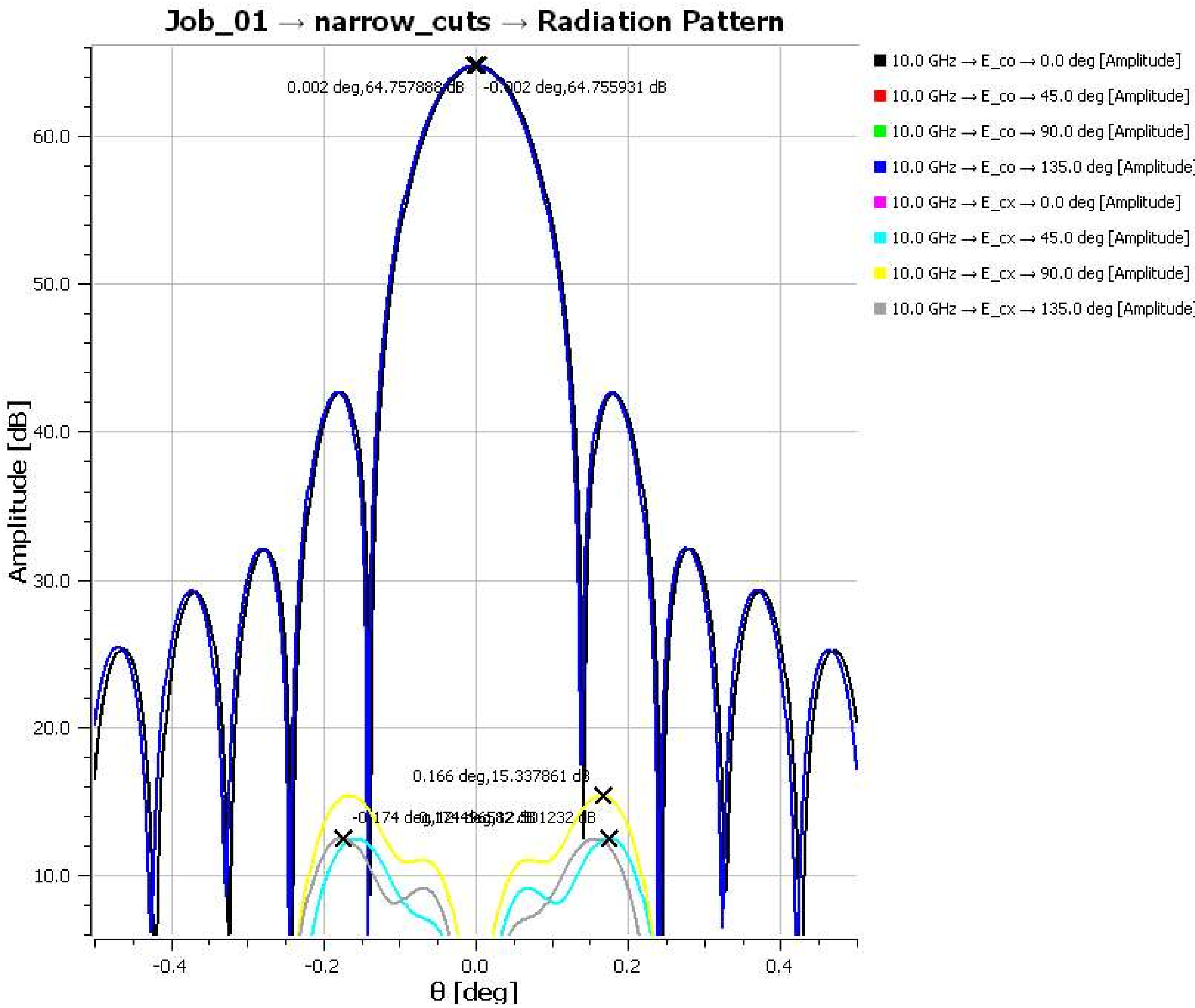


Figure 58 Beam Pattern, Thermal Gradient, 10 GHz

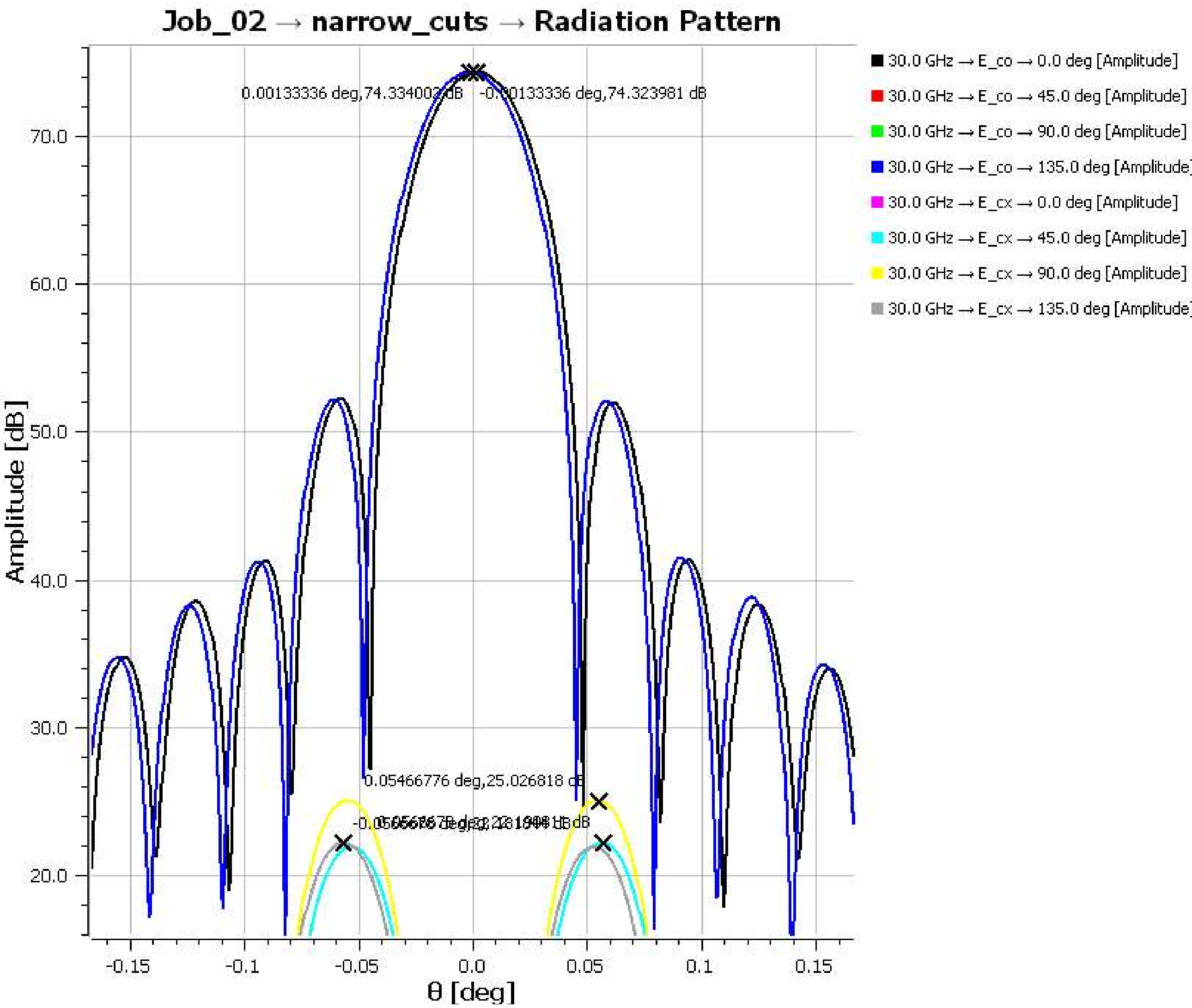


Figure 59 Beam Pattern, Thermal Gradient, 30 GHz

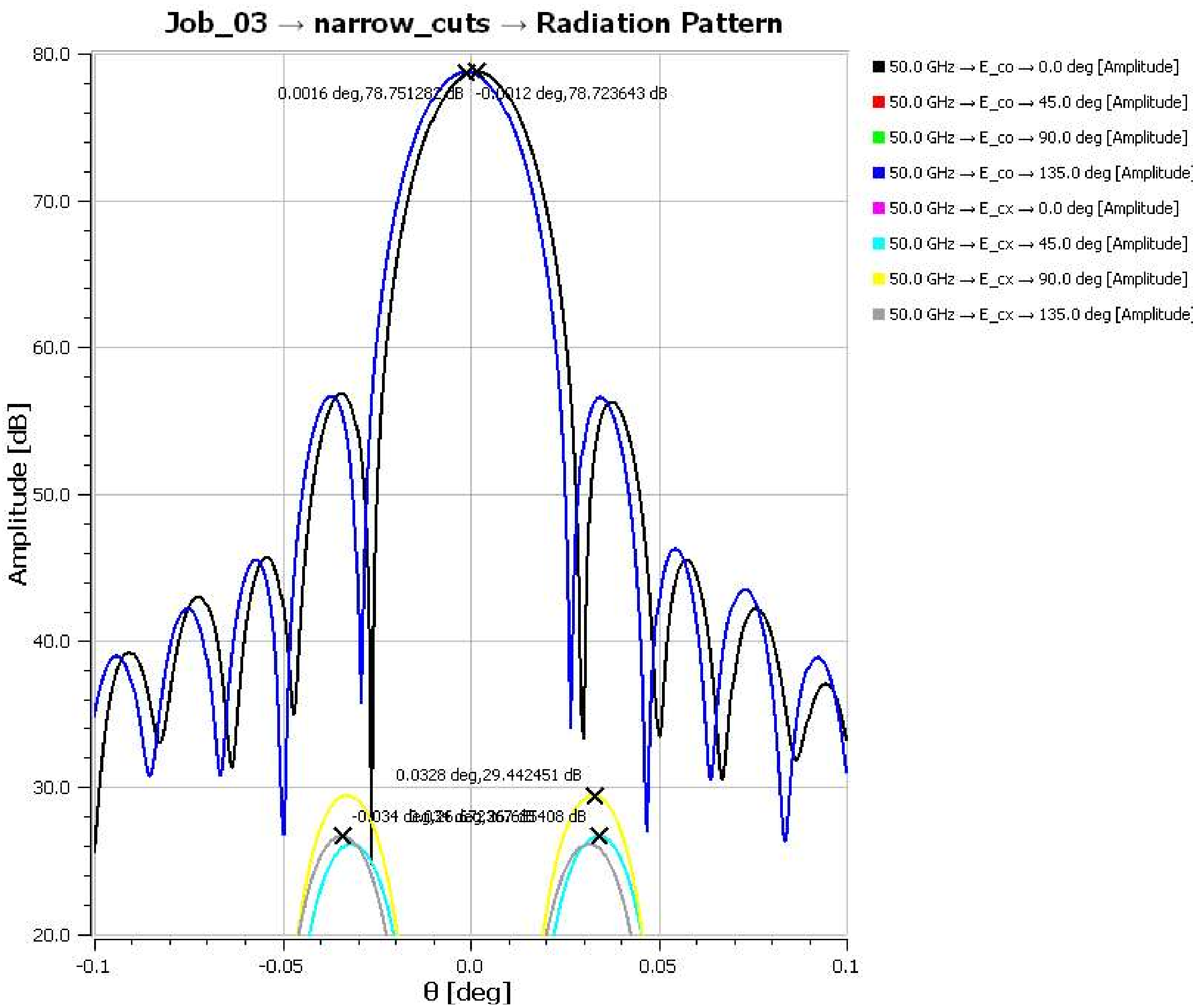


Figure 60 Beam Pattern, Thermal Gradient, 50 GHz

The peak gain and calculated efficiency for the two thermal load cases is shown in Table 22.

Table 22 Gain and Efficiency, Thermal Load Cases

	Frequency [GHZ]	10	30	50
Thermal Bath	Gain [dB]	64.748	74.277	78.628
	Efficiency	99.8%	98.7%	97.1%
Thermal Gradient	Gain [dB]	64.757	74.333	78.752
	Efficiency	100.0%	99.9%	99.9%

6.3.2 Calculated Efficiencies

At this time efficiency losses due to mould accuracy, process induced distortions (PID), aging for both reflectors and the load induced distortions on the secondary are not included in the electromagnetic (EM) simulations. Therefore these must be estimated through use of the Ruze equation and then used in the final overall efficiency calculation. The values assigned to these error sources in surface accuracy error budgets developed for the PDR, Table 23 for precision operating conditions and Table 24 for normal operating conditions, are used to estimate the corresponding efficiencies.

Table 23 Precision Operating Target Surface Accuracy Error Budget

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould	**100**	Mould	50
Process	86	Process	18
Gravitational	53	Gravitational	20
Wind	20	Wind	4
Thermal	45	Thermal	10
Ageing	7	Ageing	2
Total	149	Total	58
Combined Total (RSS)		**160**	[µm RMS]
Requirement		**160**	[µm RMS]

Table 24 Normal Operating Target Surface Accuracy Error Budget

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould	**100**	Mould	50
Process	86	Process	18
Gravitational	53	Gravitational	20
Wind	41	Wind	9
Thermal	68	Thermal	15
Ageing	16	Ageing	3
Total	158	Total	59
Combined Total (RSS)		**169**	[µm RMS]
Requirement		**300**	[µm RMS]

6.3.2.1.1 Secondary Reflector Efficiency

Using the values from Table 23 and Table 24 the surface accuracies of the secondary reflector are calculated, Table 25 and Table 26.

Table 25 Secondary Surface Accuracy Precision

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould		Mould	50
Process		Process	18
Gravitational		Gravitational	20
Wind		Wind	4
Thermal		Thermal	10
Ageing		Ageing	2
Total		Total	58
Combined Total (RSS)		**58**	[µm RMS]

Table 26 Secondary Surface Accuracy Normal

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould	**0**	Mould	50
Process	0	Process	18
Gravitational	0	Gravitation	20
Wind	0	Wind	9
Thermal		Thermal	15
Ageing		Ageing	3
Total		Total	59
Combined Total (RSS)		**59**	[µm RMS]

The Basis Of Estimates (BOE) for values in the budgets are:

a. Mould accuracy is based on experience with the DVA and MeerKat moulds.
b. Process induced distortion is based on experimental measurements, modelling and experience.
c. Gravity, thermal and wind induced distortions based on FEA modelling.
d. Aging is based on study conducted for the ALMA antennas [RD13] that suggested a 10% reduction on elastic modulus (stiffness) for carbon fibre reinforced polymer (CFRP) structures over time. The value used is: the sum of deformations related to stiffness; gravity, thermal and wind, multiplied by 0.1.

From these values using the Ruze equation the efficiency is calculated, Table 27 and Table 28.

Table 27 Secondary Reflector Efficiency Precision

Frequency (GHz)	10	30	50	80	100	120
Surface eff	99.9%	99.5%	98.5%	96.3%	94.3%	91.9%

Table 28 Secondary Reflector Efficiency Normal

Frequency (GHz)	10	30	50	80	100	120
Surface eff	99.9%	99.5%	98.5%	96.2%	94.1%	91.6%

6.3.2.1.2 Calculated Primary Reflector Efficiency Due To Mould, Process and Aging

Using the values from Table 23 and Table 24 the surface accuracies of the primary reflector due to mould, process and aging are calculated.

Table 29 Primary Surface Accuracy Precision

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould	**100**	Mould	
Process	86	Process	
Gravitational		Gravitational	
Wind		Wind	
Thermal		Thermal	
Ageing	7	Ageing	
Total	132	Total	
Combined Total (RSS)		**132**	[µm RMS]

Table 30 Primary Surface Accuracy, Normal

Primary	Value [µm RMS]	Secondary	Value [µm RMS]
Mould	**100**	Mould	
Process	86	Process	
Gravitational		Gravitational	
Wind		Wind	
Thermal		Thermal	
Ageing	16	Ageing	
Total	133	Total	
Combined Total (RSS)		**133**	[µm RMS]

The Basis Of Estimates (BOE) for values in the budgets are;

a. Primary mould accuracy is an engineering estimate based on NRC experience and discussions with the mould vendor.
b. Process induced distortion is based on experimental measurements, modelling and experience.
c. Aging is based on study conducted for the ALMA antennas [RD13] that suggested a 10% reduction on elastic modulus (stiffness) for CFRP structures over time. The value used is: the sum of deformations related to stiffness; gravity, thermal and wind, multiplied by 0.1.

From these values using the Ruze equation the efficiency is calculated, Table 31 and Table 32.

Table 31 Primary Reflector Efficiency Precision

Frequency (GHz)	10	30	50	80	100	120
Surface eff	99.7%	97.3%	92.6%	82.2%	73.6%	64.3%

Table 32 Primary Reflector Efficiency Normal

Frequency (GHz)	10	30	50	80	100	120
Surface eff	99.7%	97.2%	92.5%	82.0%	73.3%	64.0%

6.3.3 Total Efficiency

The total aperture efficiency is calculated by taking the product of the efficiencies of all contributing cases. Cases considered are shown in Table 33.

Table 33 Efficiency Calculation Cases

	Operating Condition	
Load Cases	Precision	Normal
Gravity	Worst case	Worst case
Thermal Bath	Yes	Yes*
Thermal Gradient	No	Yes
Wind	Yes	Yes*
Secondary Reflector	Yes	Yes
Mould, process and aging	Yes	Yes

* Scaled to Normal operating conditions.

The considered load case efficiencies and total aperture efficiencies are shown in Table 34 (precision conditions) and Table 35 (normal conditions).

Table 34 Aperture Efficiency, Precision Operating Condition

Frequency [GHz]	10	30	50
Requirement	**100%**	**95%**	**88%**
Total Precision	**99.3%**	**94.3%**	**85.3%**
Gravity	99.9%	98.7%	96.4%
Thermal	99.8%	98.7%	97.1%
Wind	100.0%	100.0%	99.9%
Secondary	99.9%	99.5%	98.5%
Mould, Process & Aging	99.7%	97.3%	92.6%

Table 35 Aperture Efficiency, Normal Operating Condition

Frequency [GHz]	10	30	50
Requirement	**98%**	**86%**	**66%**
Total Normal	**98.0%**	**85.7%**	**67.6%**
Gravity	99.9%	98.7%	96.4%
Thermal	99.0%	94.1%	87.6%
Wind	99.5%	95.4%	87.9%
Secondary	99.9%	99.5%	98.5%
Mould, Process & Aging	99.7%	97.2%	92.5%

Currently GRASP simulation has only been performed up to 50 GHz due to computational time required. The efficiency at higher frequencies can be estimated by back-calculating an equivalent surface accuracy from the efficiencies in Table 34 and Table 35 and using that to calculate the efficiency. The results of this exercise are shown in Table 36 and Table 37.

Table 36 Estimated Efficiency for All Frequency Bands, Precision

Frequency (GHz)	10	30	50	80	100	120
Surface eff	99.3%	93.7%	83.5%	63.0%	48.6%	35.3%
Requirement	100%	95%	88%	73%	61%	49%

Table 37 Estimated Efficiency for All Frequency Bands, Normal

Frequency (GHz)	10	30	50	80	100	120
Surface eff	98.2%	85.1%	63.8%	31.6%	16.5%	7.5%
Requirement	98%	86%	66%	35%	20%	9%

It can be seen that at this time the design is very close to meeting the requirement. Paths to meeting the requirement are discussed in the Section 6.6.

6.4 Pointing

The pointing error (PE) requirements for the ngVLA 18m antenna are shown in Table 38 andTable 39.

Table 38 Precision Pointing Requirements

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

Table 39 Normal Pointing Requirements

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 a minimum of 15 minutes.	SYS0701, SYS0801

Preliminary pointing analysis has been performed, the results are presented for Precision and Normal conditions. With the development of the integrated FEA model all of the structural PEs are now expressed in a single term (as opposed to one for elevation assembly, one for pedestal, etc.) for a specific load case.

The BOEs of the errors are;

a. Estimate based on experience and other antennas. Typically only used for errors that are fully compensated anyways.
b. From GRASP electromagnetic (EM) analysis of FEA structural analysis results.
c. Gust contributions scaled from constant wind case. Based on method used in ALMA where an equivalent wind that accounts for gusts is used for the constant wind cases and the gust component is then calculated as; $\delta_g = \delta_c * ((\frac{v_e}{v_c})^2 - 1)$. Where; $\delta_g = error\ due\ to\ wind\ gust$, $\delta_c = error\ due\ to\ constant\ wind$, $v_e = equivilant\ wind$, $v_c = constant\ wind$. Assumed $v_e = 1.06 * v_c$ based on ALMA values.
d. Servo modelling results [RD14].

The assumptions made for the level of compensation provided by the Reference pointing model are shown in Table 40.

Table 40 Reference Pointing Model Compensation

Reference Pointing Compensation	
Thermal Soak	90%
Thermal Gradient	50%
Constant Wind	50%
Wind Gusts	0%

The Absolute and Reference pointing errors with only Systematic Pointing Error correction Model (SPEM) compensation are shown in Table 41 (Precision) and **Table 42** (Normal).

Table 41 Pointing Errors; Precision, Uncompensated (except SPEM)

Precision Operating Environment	Elevation angle; 66 Degrees					
	Wind Speed [m/s]	Equivalent Wind Speed w/Gusts [m/s]	Max Wind Gust Speed [m/s]	Thermal Soak [C]	Thermal Gradient [dT]	Thermal Change [C/hr]
	5	5.3	7	20	0	1.8

PE Contributor	Elevation PE Without Compensation (arcsec)	Elevation PE With Compensation (arcsec)	Elevation Applicabilty to Referenced Pointing (%)	Referenced El Pointing Error (arcsec)	XEL PE Without Compensation (arcsec)	XEL PE With Compensation (arcsec)	XEL Applicabilty to Referenced Pointing (%)	Referenced XEL Pointing Error (arcsec)	BOE	Notes
Structure Deformation Due to Gravity	86.40	0.00	100%	0.00	0.00	0.00	100%	0.00	b	Compensated by SPEM
Structure Deformation Due to Thermal Soak	11.00	11.00	10%	1.10	0.00	0.00	10%	0.00	b	Very slow change, assumed 100% compensated in Reference Pointing
Structure Deformation Due to Thermal Gradient	0.00	0.00	50%	0.00	0.00	0.00	50%	0.00	b	Slow change, assumed 75% compensated in Reference Pointing
Structure Deformation Due to Constant Wind	2.00	2.00	50%	1.00	0.00	0.00	25%	0.00	b	Moderate change, assumed 50% compensated in Reference Pointing
Structure Deformation Due to Wind Gusts	0.25	0.25	100%	0.25	0.00	0.00	100%	0.00	c	
Subtotals (RSS + Wind)	97.63	11.23		1.66	0.00	0.00		0.00		
Elevation Assembly										
Orthogonality error, Reflectors to Elevation Axis	10.00	0.00	100%	0.00	10.00	0.00	100%	0.00	a	Compensated by SPEM
Pedestal										
Tower Tilt Fixed	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Othogonality of the Az/El Axes	4.00	0.00	100%	0.00	4.00	0.00	100%	0.00	a	Compensated by SPEM
Subtotals	4.12	0.00		0.00	4.12	0.00		0.00		
Servo										
Encoder Mounting and Gearing With Temp.	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Encoder Calibration error or Fixed Offsets	2.00	0.00	100%	0.00	2.00	0.00	100%	0.00	a	Compensated by SPEM
Wind Gusts	0.59	0.59	100%	0.59	0.00	0.00	100%	0.00	d	
Subtotals (RSS + Wind)	2.31	0.59		0.59	2.24	0.00		0.00		
Foundation										
Foundation change (long-term)	1.00	0.00	0%	0.00	1.00	0.00	0%	0.00	a	Compensated by SPEM
Foundation deformation with Constant Wind	0.50	0.50	50%	0.25	0.50	0.50	50%	0.25	a	Moderate change, assumed 50% compensated in Reference Pointing
Foundation deformation with Wind Gusts	0.48	0.48	100%	0.48	0.06	0.06	100%	0.06	c	
Subtotals (RSS + Wind)	1.40	0.98		0.73	1.15	0.56		0.31		
SPEM Residuals										
SPEM Residuals	0.50	0.50	25%	0.13	0.50	0.50	25%	0.13	a	
Totals and Comparison With Specification										
Total PE (RSS + Wind)	97.75	11.30		1.91	4.85	0.75		0.34		

Total El and XEL Compensated PE (RSS'd)	**11.32**
Non-Repeatable Pointing Error Spec. (arcsec)	18.00
Total EL and XEL Referenced Pointing Error	**1.94**
Referenced Pointing Error Specification	3.00

Table 42 Pointing Errors; Normal, Uncompensated (except SPEM)

Normal Operating Environment **Elevation angle;** 66 Degrees

Wind Speed [m/s]	Equivalent Wind Speed w/Gusts [m/s]	Max Wind Gust Speed [m/s]	Thermal Soak [C]	Thermal Gradient [dT]	Thermal Change [C/hr]
7	7.42	10	30	5	1.8

PE Contributor	Elevation PE Without Compensation (arcsec)	Elevation PE With Compensation (arcsec)	Elevation Applicabilty to Referenced Pointing (%)	Referenced El Pointing Error (arcsec)	XEL PE Without Compensation (arcsec)	XEL PE With Compensation (arcsec)	XEL Applicabilty to Referenced Pointing (%)	Referenced XEL Pointing Error (arcsec)	BOE	Notes
Structure Deformation Due to Gravity	86.40	0.00	100%	0.00	0.00	0.00	100%	0.00	b	Compensated by SPEM
Structure Deformation Due to Thermal Soak	16.50	16.50	10%	1.65	0.00	0.00	10%	0.00	b	Very slow change, assumed 100% compensated in Reference Pointing
Structure Deformation Due to Thermal Gradient	7.20	7.20	50%	3.60	0.00	0.00	50%	0.00	b	Slow change, assumed 75% compensated in Reference Pointing
Structure Deformation Due to Constant Wind	3.92	3.92	50%	1.96	0.00	0.00	25%	0.00	b	Moderate change, assumed 50% compensated in Reference Pointing
Structure Deformation Due to Wind Gusts	0.48	0.48	100%	0.48	0.00	0.00	100%	0.00	c	
Subtotals (RSS + Wind)	104.93	18.53		4.65	0.00	0.00		0.00		
Elevation Assembly										
Orthogonality error, Reflectors to Elevation Axis	10.00	0.00	100%	0.00	10.00	0.00	100%	0.00	a	Compensated by SPEM
Pedestal										
Tower Tilt Fixed	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Othogonality of the Az/El Axes	4.00	0.00	100%	0.00	4.00	0.00	100%	0.00	a	Compensated by SPEM
Subtotals	4.12	0.00		0.00	4.12	0.00		0.00		
Servo										
Encoder Mounting and Gearing With Temp.	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Encoder Calibration error or Fixed Offsets	2.00	0.00	100%	0.00	2.00	0.00	100%	0.00	a	Compensated by SPEM
Wind Gusts	1.34	1.34	100%	1.34	0.00	0.00	100%	0.00	d	
Subtotals (RSS + Wind)	2.61	1.34		1.34	2.24	0.00		0.00		
Foundation										
Foundation change (long-term)	1.00	0.00	0%	0.00	1.00	0.00	0%	0.00	a	Compensated by SPEM
Foundation deformation with Constant Wind	0.98	0.98	50%	0.49	0.50	0.50	50%	0.25	a	Moderate change, assumed 50% compensated in Reference Pointing
Foundation deformation with Wind Gusts	1.02	1.02	100%	1.02	0.06	0.06	100%	0.06	c	
Subtotals (RSS + Wind)	2.24	2.00		1.51	1.15	0.56		0.31		
SPEM Residuals										
SPEM Residuals	0.50	0.50	25%	0.13	0.50	0.50	25%	0.13	a	
Totals and Comparison With Specification										
Total PE (RSS + Wind)	105.07	18.70		5.07	4.85	0.75		0.34		

Total El and XEL Compensated PE (RSS'd)	18.71
Non-Repeatable Pointing Error Spec. (arcsec)	35.00
Total EL and XEL Referenced Pointing Error	5.09
Referenced Pointing Error Specification	5.00

The pointing requirements under precision conditions have been met and almost met under normal conditions. Having said that there are still many items that are estimated and will need to be confirmed by modelling, example or testing. In addition the method of calculating the PE due to wind gust components should be discussed and an agreed upon method adopted for future design work.

6.5 Survivability

At this time the elevation rotating assembly has been analysed for one survival wind load case; wind angles Az = 90°, El = 66°, wind velocity = 50m/s. The analysis included linear buckling analysis of the composite surfaces. The results indicate that the elevation assembly will survive under these conditions, for details see [RD06].

Further analysis of the complete structure will be required in the next phases.

6.6 Potential Areas of Improvement

6.6.1.1 Structural Improvements

The yoke structure is currently one of the biggest contributors to PE and has an effect on the surface accuracy of the primary reflector. An initial optimization of this structure shows there is some potential for improvement, see [RD06] for further details.

The current secondary/feed support structure attaches to the primary reflector BUS at four points and causes distortions in the primary surface around these locations. A new secondary/feed support structure is being considered that attaches to the primary BUS at six points in order to spread the load and decrease the resulting distortions in the primary surface.

6.6.1.2 Manufacturing Errors

The SRC reflectors are manufactured as the name implies in one piece on a mould. The as-manufactured surface accuracy depends on: materials selection, mould accuracy, composite layup design, process design and process control.

Unlike small machined or formed panels it is nearly impossible to actually measure just the as-manufactured surface accuracy on a large single piece reflector surface. As soon as the part is removed from the mould it is subject to gravitational and thermal effects, it cannot be put in a temperature controlled room, supported ideally and measured on a coordinate measuring machine (CMM) as can be done with panels.

Attainable mould accuracy has increased considerably over time with new machines and methods developed by industrial entities such as Janicki Industries. The 15m DVA2 mould was reworked to 210 micron RMS from the DVA1 mould that had been designed to meet the 500 micron RMS requirements of a 10 GHz reflector. The structure was a steel back structure with a fibreglass faceplate and putty surface which is not very thermally stable and suffered from differential thermal expansion effects between the face structure (putty and fibreglass) and the back structure. A 100 micron RMS accuracy for machined all carbon mould on an isothermal steel base in a thermally stable environment is believed to be achievable.

NRC has conducted extensive research into minimizing process induced distortion with large gains being made through laminate design, material selection and process control to the point where small length scale surface process induced distortion has been minimized. In fact extremely fine surface features present in the mould are reproduced on the part.

For the DVA1 project NRC contracted Convergent Technology to conduct a study of the process induced distortions (PID) in the 15m reflector infusion process. The study [RD10] involved a combination of test, measurement and finite element modelling and resulted in several significant design changes to reduce PID. The modelling predicted a 69 micron RMS surface accuracy due to PID [RD11], [RD12]. Unfortunately it is extremely difficult to verify this as any measurement of the produced surface includes gravity, thermal and adjustment effects. In addition no measurement was conducted on the DVA1 before it suffered damage in transport. The primary source of PID is the volumetric shrinkage of the resin during cure. In an effort to further decrease PID in the DVA2 the resin was changed from vinyl ester (~8%-11% shrinkage) to epoxy resin (~2% shrinkage). The budgeted value of 86 microns for PID in the ngVLA 18m reflector is based on the DVA1 modelled value of 69 microns reduced by 15% (estimated) to account for resin change and then scaled by the squares of reflector diameters ($18^2/15^2$). A study of the proposed 18m primary surface will be commissioned with Convergent to confirm this number.

The DVA1 reflector surface was removed from the mould, flipped over, mounted on the steel backup structure, and then adjusted. For DVA2 the moulded reflector surface was released but not removed from the mould before installation of the steel tube BUS. The surface and BUS assembly was then removed from the mould and adjustment of the BUS performed to reach the final surface accuracy. In both cases it is unknown how much of the deformation being adjusted out was process induced, how much was gravitational and how much was due to manufacturing tolerances in the BUS. Efforts are underway to attempt to extract a value from the measurement data of the DVA antennas.

For the ngVLA the plan is to attempt to “capture” the surface shape by installing the oBUS on to the surface before it is released from the mould. For serial production it is easy to justify a jig to accurately align the oBUS to the moulded part during installation. Final adjustments can then be made if necessary to reach the final accuracy requirement once the complete assembly is removed from the mould.

6.6.1.3 Surface Adjustment

The nature of the SRC reflector is such that the surface deformations are generally large scale and greater around the rim of the reflector. Small scale deformations are governed by the mould smoothness. Experience with the DVA1 and 2 reflectors has shown that adjustment at the rim of the reflector is very effective in smoothing large scale deformations. The adjustment scheme outlined in section 5.2.1 provides radial adjustment tangential to the reflector surface at many points around perimeter of the surface. Initial modelling [RD06] shows that this is effective at reducing large scale deformations due to gravity or to compensate for manufacturing tolerances in the oBUS. Simply applying adjustments at four locations shown in Figure 61 was shown to reduce the surface error by ~5microns.

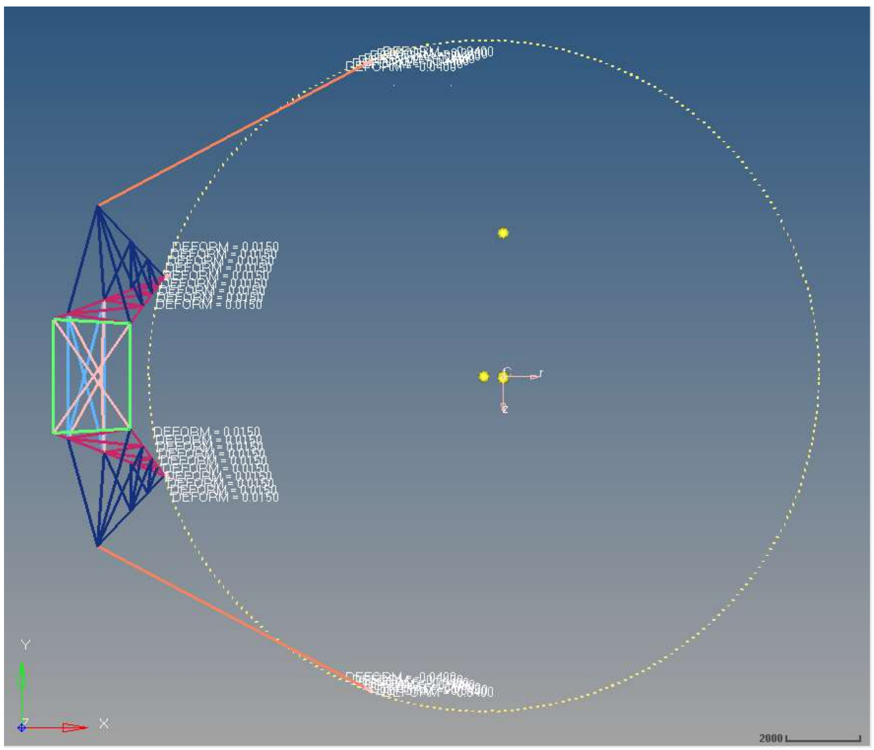


Figure 61 Deforms at the secondary support locations

No optimization of the adjustment was applied at this point so further reduction can be expected. Using this model NRC is developing a method of determining required adjustment from a given deformed shape. The goal is to be able to determine adjustments from a measured surface and feed them into a semi-automated adjustment tool similar to that used for the ALMA antennas.

7 MAINTENANCE, RELIABILITY AND LIFETIME

At this early stage of the design cycle it is difficult to provide definitive information regarding the maintenance, reliability and life cycle of the final product. It is possible to speak to the concepts that will be applied in order to minimize required maintenance and to maximize reliability and lifetime.

7.1 Maintenance and Reliability

The maintenance requirements for the ngVLA antennas are given in Table 43 [AD01]. At this point in the design cycle it is premature to assign numbers to the maintenance intervals and efforts required. However it is possible to illustrate the approach being taken to satisfy these requirements.

Table 43 Maintenance 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

With the very large number and the wide geographical locations of antennas in the ngVLA the maintenance requirements of the antennas are a major concern. In the design of bespoke and selection of commercial-off-the-shelf (COTS) components for the NRC ngVLA antenna both low preventative maintenance and high reliability have been considered. As the design matures maintenance requirements will be analysed in greater depth to ensure maintenance costs are kept to a minimum. Examples of components and design elements being considered include:

- Direct drives
- Modular design
- Azimuth bearing oil bath

Appropriate consideration will be given to implementation of condition-based maintenance by incorporating sensors and self-test procedures that will allow remote monitoring of the condition of the antenna. Condition-based maintenance reduces cost by reducing unnecessary time-based preventative maintenance while allowing necessary maintenance to be planned and scheduled as a change in a component or system’s condition is identified.

Particular attention will be paid to auxiliary mechanisms such as stow pins and cable wraps which if not well designed can “nickel and dime” a project. Where possible and appropriate, accelerated life testing of components and systems will be carried out early in the development.

7.2 Design Life

The design life requirements of the ngVLA antennas are shown in Table 44 [AD01].

Table 44 Design Life Requirements

Parameter	Req. #	Value	Traceability
Design Life	ANT1801	The antenna shall be designed to require no major overhaul work for 20 years.	
Life Cycle Optimization	ANT1802	The antenna design shall minimize its life-cycle cost for 20 years of operation.	

The 20 year design life and life cycle optimization requirements for the ngVLA antennas should not be difficult to achieve. A large portion of the mount is based on mature technology (steel fabrications, rolling element bearings, etc.) for which the life cycles are well understood. Two areas that will require greater attention in future phases are the direct drives and the composite structures.

Direct drives have been in use in optical telescopes for 20 years for almost 10 years; for example, in the Very Large Telescope (VLT) and in radio telescopes such as ALMA. The drives have no moving parts to wear out and no limited lifetime electrolytic capacitors so achieving 20 years life should easily be possible. A part of the planned trade study between direct drives and traditional gear train drives will include both lifecycle and maintenance aspects.

Composite structures have been employed in the marine and other industries for over 50 years and some have been in service for that entire time. The key to making them last is to provide protection from the sun’s ultra violet (UV) and from moisture ingress, both of which can be achieved with well applied, high quality paint, and high quality material choices and structural design. However for the composite structures employed in the ngVLA antenna design, a key aspect is long-term shape stability. Although this is not unique to radio telescopes the degree to which it is required is; so it is not possible to satisfy this by example. Recognizing this NRC has initiated a series of studies involving both test and analysis to investigate the long-term shape stability of the structures in question.

8 FUTURE WORK

8.1 Design and Analysis

The following design and analysis tasks will be performed in the next phase.

8.1.1 Drive System Trade Study

Direct drive vs direct pinion/gear drive will be studied for both azimuth and elevation drives with consideration of performance and cost, both capital and maintenance.

8.1.2 iBUS to oBUS Connection

The connection between the inner and outer BUS structures will be detailed. Emphasis will be on providing a stiff connection while providing accommodation for reasonable manufacturing tolerances for the large structures.

8.1.3 Surface Adjusters

Detail design of surface adjusters.

8.1.4 Feed/Secondary Support Structure

The new Feed/Secondary Support Structure concept requires detailed analysis to ensure adequate performance and further design detailing for volume manufacture.

8.1.5 Feed Indexer

Little attention has been paid to the feed indexer at this time due to resource limitations as it is seen as low risk. Design and analysis effort will be required in the next phase.

8.1.6 Complete Integrated FEA Model

The secondary reflector surface will be incorporated into the integrated antenna FEA in the next phase to allow EM modelling of the complete optical system under various load cases.

8.1.7 Yoke Structure Optimization

An initial topology optimization has been performed on the yoke structure and shows promise to reduce PE and improve surface accuracy. The rationalization of the optimized shape has been started and will be completed and integrated into the FEA model for future analysis.

8.1.8 Multi-piece Primary Reflector Concept

Development of the MRC design will continue including development of a cost model.

8.2 Logistics

Work will continue on the production planning and transport aspects of the project.

8.3 Prototyping and Testing

Several aspects of the design will be prototyped in order to retire associated risks.

8.3.1 Surface Adjusters

Surface adjusters can be prototyped in isolation and/or on a small diameter reflector.

8.3.2 Process Induced Distortion Study

A contract for an updated analysis of the process induced distortion for the design presented here will be issued. The new analysis will consider the 18m diameter design and incorporate changes in materials and other design elements (i.e. no rim in dish surface infusion).

8.3.3 Multi-piece Concepts

Several aspects of the proposed MRC design can be prototyped on a smaller scale. In particular the joint connections to determine ease of manufacture and accuracy after reassembly.

8.4 Materials Analysis and Testing

A feature of composite materials is the ability to vary the properties by changing the type of fibres, resin and process used. The down side of this is that the only way to precisely know the properties of a particular material is through testing. As part of the ngVLA antenna design project NRC will be carrying out the following analysis and testing of materials;

- Coefficient of Thermal Expansion – the layup of the reflector surface proposed for the ngVLA has changed somewhat from that of the DVA dishes. The reflective material, resin and some of the fibre materials have changed. All of these changes should result in a slightly reduced CTE so samples of the proposed dish surface layup along with layups representing other parts of the structure such as the OBUS will be measured in-house and/or sent out to an external testing lab for CTE measurement.
- Weathering – in order to address risk 101-R6 the long term stability of the surface accelerated aging tests will be conducted on the proposed materials well as modelling of the materials and aging mechanisms.
- Peel test – peel tests will be conducted to address 101-R3 the bond strength of the reflective material to the structural laminate analysis.
- A comprehensive new set of coupon testing for mechanical properties of laminates intended for the ng-VLA telescope. Initial design work is typically done with existing material property values from earlier work as well as estimates done with micromechanics where test results don't exist, but as the design progresses confirmation of material properties for each proposed laminate in each separate orthogonal direction must be measured.
- Small scale structural tests – structural testing on the scale of fabricated sub-components such as the rim connector to dish edge connection would be tested. Other structural components such as the glue joints between the oBUS components, and the strength of the oBUS to iBUS point load strap-type connectors would also be tested.

Short Baseline Array Antenna: Preliminary Technical Requirements

020.47.05.00.00-0001-REQ-A-SBA_ANTENNA_TECH_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
R. Selina	Electronics Div., NRAO	2019-07-23
D. Dunbar	ngVLA/NM-Ops, NRAO	2019-07-23

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.23 10:36:25 -06'00'	Electronics Division, NRAO	2019-07-23
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.23 14:04:17 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-23

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.23 14:04:32 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-23

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.

Table of Contents

1 Introduction 6
1.1 Purpose 6
1.2 Scope 6
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 7
3 Overview of SBA Antenna Technical Specifications 8
3.1 Document Outline 8
3.2 Project Background 8
3.3 General SBA Antenna Description 8
3.4 Summary of SBA Antenna Requirements 9
4 SBA Antenna Functional and Performance Requirements 10
4.1 Operating Frequency Range 10
4.2 Optical and Mounting Geometry 10
4.3 Allowable Design Volume and Mass 12
4.4 Number of Antennas 12
4.5 Reflector Construction and Accuracy 12
4.6 Pointing Accuracy 13
4.6.1 Pointing Accuracy in Precision Operating Environment 13
4.6.2 Pointing Accuracy in the Normal Operating Environment 13
4.7 Focus Stability 14
4.8 Range of Motion 14
4.9 Axis Rates 14
4.10 Stow Positions 15
4.11 System Noise Contributions 15
4.12 Solar Observations 16
4.13 Spurious Signals/Radio Frequency Interference Generation 16
4.14 Environmental Conditions 16
4.14.1 Precision Operating Conditions 17
4.14.2 Normal Operating Conditions 17
4.14.3 Limits to Operating Conditions 17
4.14.4 Survival Conditions at Stow Position 18
4.14.5 Lightning Protection Requirements 18
4.14.6 Seismic Protection Requirements 19
4.14.7 Site Elevation 19
4.14.8 Vibration 19
4.15 Maintenance and Reliability Requirements 19
4.16 Monitor and Control Requirements 20
4.17 Motion Limiting Features 21
4.18 Lifecycle Requirements 21
5 Interface Requirements 22
5.1 Interface to the Foundation/Station 22
5.2 Interface to the Electrical Infrastructure 22
5.3 Interface to the Fiber Optic Transmission System 23
5.4 Interface to Other External Cables and Piping 23

5.5 Interface to the Receiver Enclosure/Front-End Electronics ... 23
5.6 Interface to the Back-End Electronics ... 24
5.7 Interface to Internal Cables and Piping ... 24
5.8 Interface to the Cryogenic System ... 24
5.9 Interface to the Monitor and Control System ... 24
6 Subsystem Requirements ... 25
7 Safety ... 26
7.1 General ... 26
7.2 Hazard Analysis ... 26
7.2.1 Hazard Severity ... 26
7.2.2 Hazard Probability ... 26
7.2.3 Hazard Risk Acceptability Matrix ... 27
7.2.4 Requirements on Operational Hazards ... 27
7.2.5 Hazard Analysis ... 27
7.3 Safety Design Requirements ... 28
7.3.1 Fire Safety ... 28
7.3.2 Mechanical Safety ... 28
7.3.3 Electrical Safety ... 28
7.3.4 Hydraulic and Pneumatic Safety ... 29
7.3.5 Handling, Transport, and Storage Safety ... 29
7.3.6 Toxic Substances ... 29
7.3.7 Confined Space ... 29
7.4 Physical Security ... 29
8 Requirements for Design ... 30
8.1 Analyses and Design Requirements ... 30
8.1.1 Finite Element Structural Analyses ... 30
8.1.2 Thermal Modeling and Analysis ... 31
8.1.3 Stress Analysis and Load Combination ... 31
8.1.4 Antenna EM Analysis Support ... 31
8.1.5 Control Loop Design and Analysis ... 33
8.1.6 Reliability, Availability, Maintainability Analysis ... 33
8.2 Electromagnetic Compatibility Requirements ... 33
8.3 Materials, Parts, and Processes ... 34
8.3.1 Type of Steel ... 34
8.3.2 Stress Relieving ... 34
8.3.3 CFRP ... 34
8.3.4 Fasteners ... 34
8.3.5 Paints ... 34
8.3.6 Surface Treatment ... 34
8.3.7 Thermal Insulation ... 34
8.3.8 Rodent Protection ... 34
8.3.9 Name Plates and Product Marking ... 34
8.3.10 Labels ... 35
9 Documentation Requirements ... 36
9.1 Technical Documentation ... 36
9.2 Software and Software Documentation ... 36
10 Verification and Quality Assurance ... 37

11 Key Performance Parameters 39
12 Appendix 41
12.1 Abbreviations and Acronyms 41
12.2 Coordinate System 42
12.2.2 Main Reflector (MR) Coordinate System 42
12.2.3 Secondary Reflector (SR) Coordinate System 43
12.2.4 Focal Plane Coordinate system 44
12.2.5 Antenna Azimuth 44
12.2.6 Antenna Elevation 44
12.3 Maintenance Definitions 45
12.3.1 Maintenance Approach 45
12.3.2 Periodic Preventive Maintenance 45
12.3.3 Overhaul 45

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.

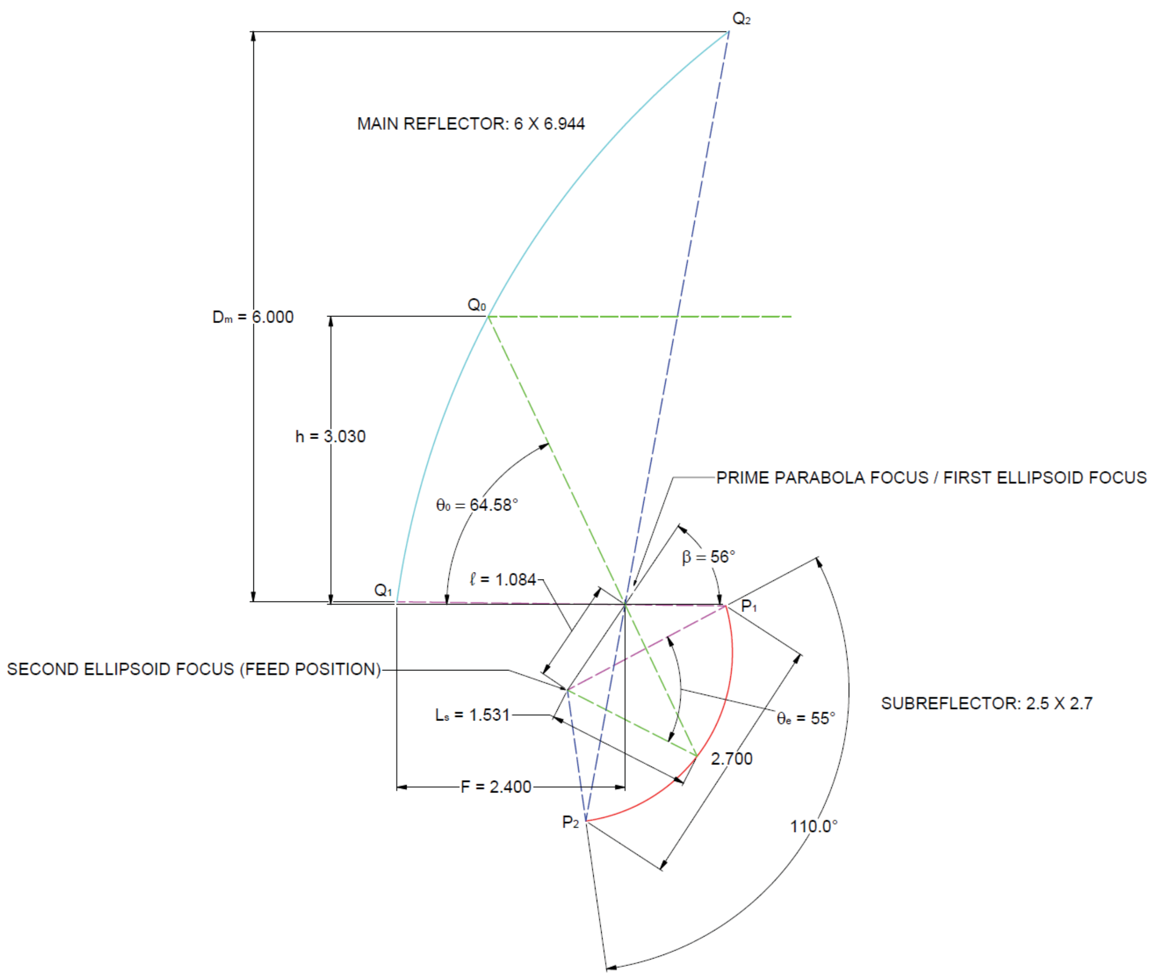


Figure 1 - Cross-section of the optical geometry through the plane of symmetry for unshaped (paraboloid ellipsoid) reflectors. Values may be refined in the design.

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 ≥20mm (focus) and Y_F ≥1000mm (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 ≤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.

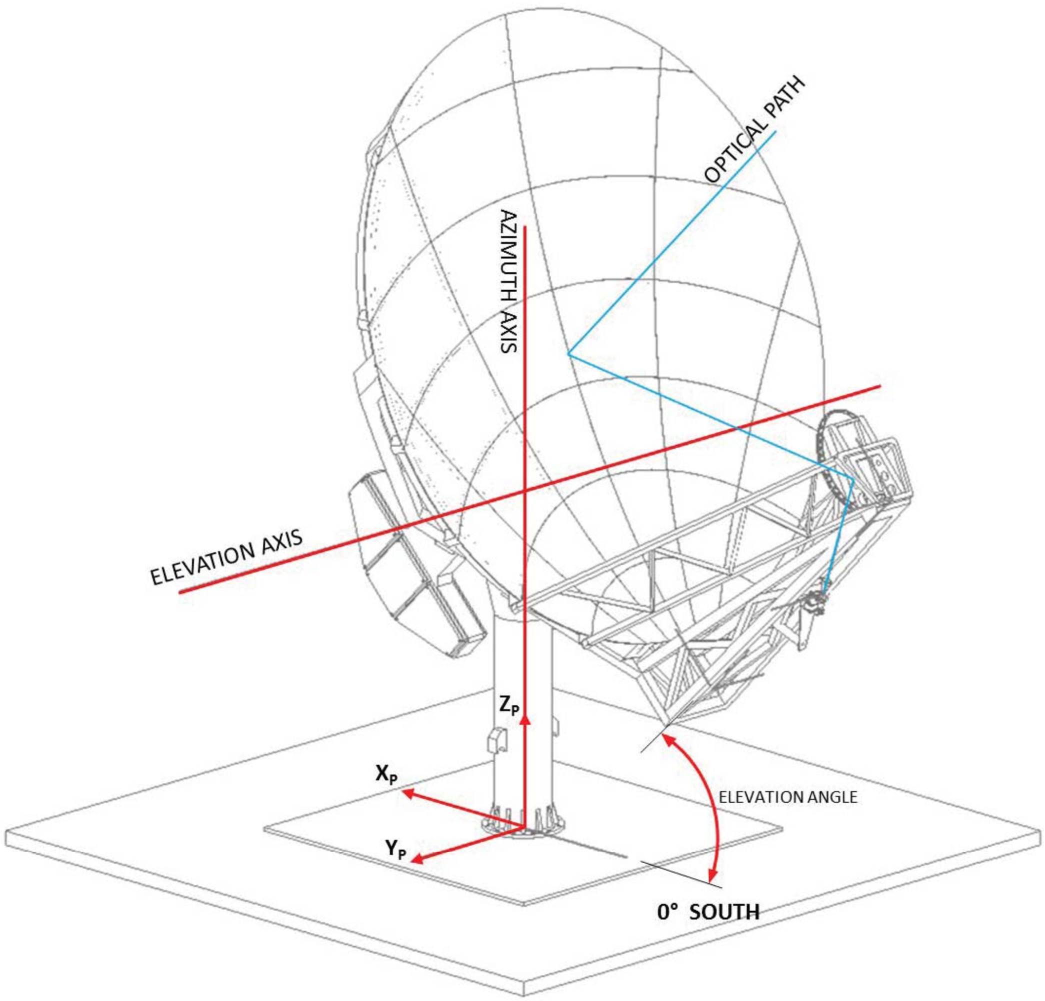


Figure 2 - Diagram of the antenna pad coordinate system and major axes. Separate Cartesian reference frames define each mirror surface, the focus, and the pad respectively. Antenna design is diagrammatic only.

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).

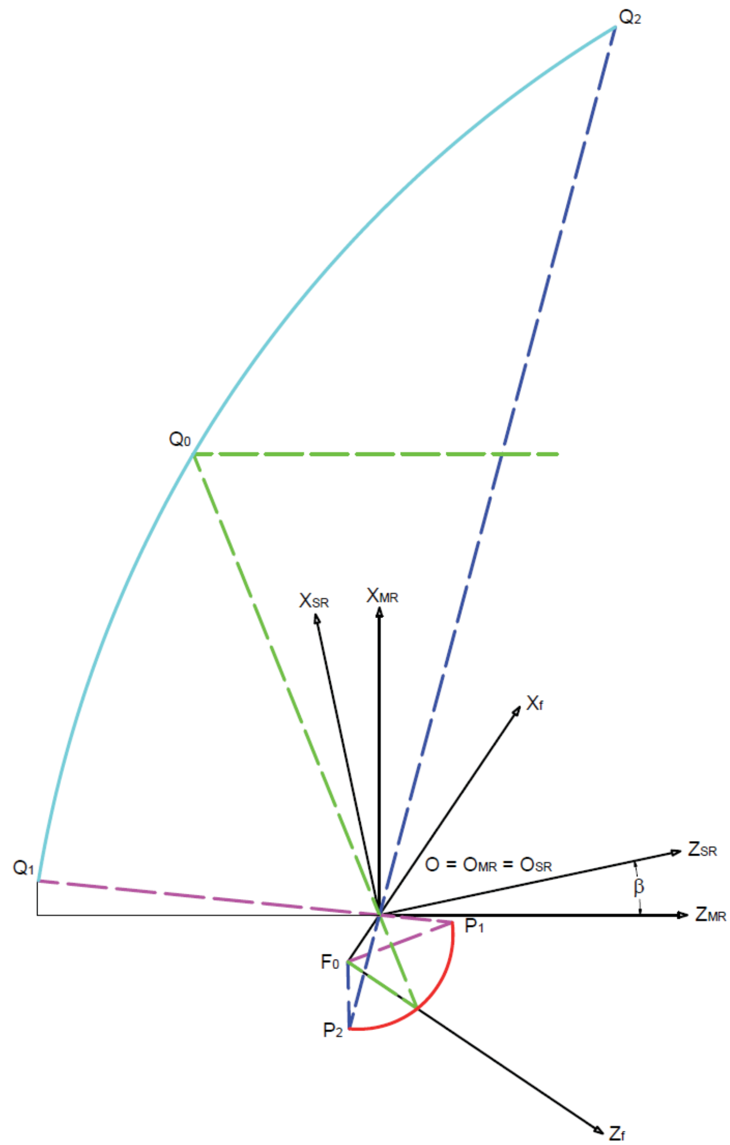


Figure 3 - Antenna optical coordinate system. Separate Cartesian reference frames define each reflector surface and the secondary focus.

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.

ngVLA 6m Antenna Concept Design Document

Document Number 102-0000-001-CDD-001
Revision: 1
Author .... Dean Chalmers
Date 2019-07-25
Status .... Released
Classification .... Unrestricted

Prepared By	Name	Dean Chalmers	Signature	
	Organisation	NRC		
Reviewed By	Name	Gordon Lacy	Signature	Gordon Lacy (Jul 29, 2019)
	Organisation	NRC		
	Name		Signature	
	Organisation			
	Name		Signature	
	Organisation			
Approved By	Name	Scott Roberts	Signature	Scott Roberts (Jul 30, 2019)
	Organisation	NRC		
Issued By	Name	Donna Morgan	Signature	
	Organisation	NRC		

[This document describes concept design for the ngVLA 6m Antenna Design project.]

DOCUMENT HISTORY

Revision	Date	Change Request	Change Description
A	04July2018		Initial draft for comment
1	25July2019		Approved for release

DOCUMENT SOFTWARE

Application		Version	Filename
Wordprocessing	MSWord		102-0000-001-CDD-001_CoDesignDoc_A_2019-07-25.docx

ORGANISATION DETAILS

Designation	Name	Organisation
Primary Author and Responsible Organisation	Dean Chalmers	NRC
Contributors	G. Lacy	NRC
	M. Islam	NRC
	M. Fleming	Minex
	M. Wessel	SED Systems
	R. Osterried	SED Systems
	R. Hellyer	NRC

TABLE OF CONTENT

1 **INTRODUCTION** **7**
1.1 Purpose of Document 7
1.2 Scope of Document 7
1.3 Intended Audience 7
1.4 Design Context 7

2 **APPLICABLE AND REFERENCE DOCUMENTS** **8**
2.1 Applicable Documents 8
2.2 Reference Documents 8

3 **OPERATIONAL CONTEXT** **9**
3.1 Operational Environment 9

4 **RISKS** **12**
4.1 Risks 12

5 **DESIGN OVERVIEW** **15**
5.1 Design Overview 16
5.1.1 Elevation Rotating Assembly 16
5.1.2 Mount 24

6 **ERROR BUDGETS** **25**
6.1 Surface Accuracy Error Budget 25
6.2 Pointing Error Budget 27

7 **PERFORMANCE** **29**
7.1 System Noise Contribution 29
7.2 Aperture Efficiency 30
7.2.1 Gravitational Deformations 31
7.2.2 Results 34
7.2.3 Manufacturing Errors 37
7.2.4 Surface Adjustment 37
7.3 Pointing 37
7.4 Survivability 38
7.5 Drives 38
7.5.1 Elevation Drive 38
7.5.2 Azimuth Drive 41

8 PRODUCTION LOGISTICS 44
8.1 Primary Reflector Transport 44

9 FUTURE WORK 45
9.1 Design and Analysis 45
9.1.1 iBUS Design 45
9.1.2 Feed/Secondary Support Structure 45
9.1.3 Mount Design 45
9.1.4 Integrated FEA Model 45

LIST OF TABLES

Table 1 Applicable Documents 8
Table 2 Reference Documents 8
Table 3 Precision Operating Conditions [AD01] 9
Table 4 Normal Operating Conditions [AD01] 10
Table 5 Limit to Operating Conditions [AD01] 10
Table 6 Survival Conditions [AD01] 11
Table 7 Project Risks 13
Table 8 Product Risks 14
Table 9 Antenna Surface Accuracy Error Budget – Precision Operating Conditions 26
Table 10 Antenna Surface Accuracy Error Budget – Normal Operating Conditions 26
Table 11 Example Pointing Error Budget from 18m 28
Table 12 System Noise Contributions Requirement 29
Table 13 Aperture Efficiency Related Requirements [AD01] 30
Table 14 Precision Pointing Requirements 37
Table 15 Normal Pointing Requirements 38
Table 16 Elevation Drive Loads 39
Table 17 Elevation Drive Performance Matrix 41
Table 18 Azimuth Drive Loads 41

LIST OF FIGURES

Figure 1 NRC ngVLA 6m Antenna Design Concept 15
Figure 2 Primary surface edge adjuster tab concept 17
Figure 3 Primary surface edge adjuster with oBUS 17
Figure 4 Assembled oBUS structure 18
Figure 5 oBUS components in colour 19
Figure 6 Cross Section of Antenna at Low (12º) Elevation Angle 20
Figure 7 6m iBUS structure 21
Figure 8 6m Secondary Support Structure. 22
Figure 9 Stiffening Ribs on Primary Reflector to Support Secondary Support Structure 23
Figure 10 Secondary and Feed Support Structure for 6m dish 23
Figure 11 Complete 6m telescope with mount 24
Figure 12 Reflector Surface Noise Measurement Results 29
Figure 13 6m Reflector Assembly 31
Figure 14 6m oBUS 32
Figure 15 Primary surface Laminate schedule (blue layer: carbon qiso, red layer: triaxial carbon). 32
Figure 16 oBUS Laminate schedule (blue layer: carbon qiso, pink layer: foam core) 33
Figure 17 oBUS rib Laminate schedule (green layer: carbon qiso, pink layer: foam core) 33
Figure 18 Cone back-primary laminate schedule and foam core (blue layer: carbon QISO, magenta layer: carbon uni, grey layer: foam core). 34
Figure 19 ngVLA 6m FE model constraints 35
Figure 20 ngVLA 6m surface RMS error under Gravity load cases (a) 15° and (b) 90° elevation angle. 35
Figure 21 Surface RMS error under Gravity load cases for ngVLA 18m (a) 15° and (b) 90° elevation angles and ngVLA 6m (c) 15° and (d) 90° elevation angles. 36
Figure 22 Elevation Drive Configuration 40
Figure 23 Azimuth Drive Options 42
Figure 24 Example direct drive configuration 42
Figure 25 Example Direct Pinion Drive 43

LIST OF ACRONYMS AND ABBREVIATIONS

BUS	BackUp Structure
CTE	Coefficient of Thermal Expansion
DVA	Dish Verification Antenna
ERA	Elevation Rotating Assembly
FE	Finite Element
FEA	Finite Element Analysis
iBUS	Inner Backup Structure
ngVLA	next generation Very Large Array
NRAO	National Radio Astronomy Observatory (USA)
NRC	National Research Council (Canada)
oBUS	Outer Backup Structure
PE	Pointing Error
QISO	Quasi-Isotropic
RMS	Root Mean Square
SPEM	Systematic Pointing Error correction Model
SRC	Single-piece Rim-supported Composite
VLA	Very Large Array
XEL	Cross-elevation

1 INTRODUCTION

1.1 Purpose of Document

The purpose of this document is to describe the Conceptual Design of the National Research Council of Canada (NRC) Next Generation Very Large Array (ngVLA) 6m Antenna Design as called out in Statement of Work NRC ngVLA 6m Antenna Study, [AD02].

1.2 Scope of Document

This document describes the operational context of the design and the operating conditions as defined in the ngVLA Antenna: Preliminary Technical Specifications, [AD01].

- The project assumptions and risks are presented with their status and mitigation plans.
- Methods of accounting for system budgets are described, example budgets and initial analysis results for key performance requirements are presented.
- Production logistics concepts are described for on-site manufacturing and assembly.
- Finally a summary of the key future tasks is provided.

1.3 Intended Audience

This document is expected to be used by the NRC ngVLA Antenna Design Team, National Radio Astronomy Observatory (NRAO) Antenna Integrated Product Team and Management Teams, and the ngVLA System Engineering and Management Team.

1.4 Design Context

NRC is conducting two design studies in parallel for the ngVLA; one for the 6m antenna, the focus of this document, and one for the 18m antenna. Due to the relative cost impacts for the project, 214 18m antenna could constitute ~50% of the overall project cost vs <5% for the 19 6m antennas, a much greater emphasis has been put on the 18m design. The 6m antenna design presented here is based on the extensive development work that has been performed at NRC for the 18m ngVLA antenna. The ngVLA 6m and 18m antennas, essentially, must meet the same requirements (other than optical surface sizes); however, designing the 18m antenna to meet these requirements is much more difficult than the 6m. Given limited resources the bulk of design and analysis effort has therefore been put into the 18m design with the understanding that there will very low risk in meeting the requirements with the 6m design by the application of the same design concepts. Therefore this document contains a minimal amount of analysis of the performance of the 6m. Its ability to meet the requirements is inferred by analogy to the 18m design.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The following documents at their indicated revision form part of this document to the extent specified herein.

Table 1 Applicable Documents

Ref No	Document/Drawing Number	Document Title	Revision
AD01	020.47.05.00.00-0001-SPE	ngVLA Short Baseline Array SBA Antenna: Preliminary Technical Specifications	2
AD02	020.05.40.05.01-0002-SOW	Statement of Work, NRC ngVLA 6m Antenna Study	
AD03	101-0000-001-CDD	ngVLA 18m Antenna Concept Design Document	A

2.2 Reference Documents

The following documents provide useful reference information associated with this document. These documents are to be used for information only. Changes to the date and/or revision number do not make this document out of date.

Table 2 Reference Documents

Ref No	Document/Drawing Number	Document Title	Revision
RD01		“Fabry-Perot Resonator Design for the Measurement of Surface Reflectivity,” D. Henke et al. in 9th Global Symp. on Millimeter-Waves., Espoo, Finland, Jun. 6–8, 2016.	
RD02		“Measurements of Composite Reflectors across Q-Band (33–50 GHz) and W-Band (75–115 GHz),” D. Henke et al. [*accepted*] in *18th Int. Symp. Antenna Technol. Appl. Electromagn. (ANTEM)*, Aug. 19–22, 2018.	
RD03	101-0000-001-REG-001	ngVLA 6m Antenna Risk Register	A
RD04	9P033REP01	ngVLA ngVLA Report Main Drive Axes	
RD05	101-0000-004-PLN	ngVLA 18m Antenna Preliminary Production Plan	A

3 OPERATIONAL CONTEXT

The ngVLA array will consist of 214 x 18m antennas and 19 x 6m antennas. The 6m antennas will be deployed on the Plains of San Agustin in New Mexico at the core of the array with baselines from 11 to 60m, [AD01]. All antennas will be fixed position, the array will not be reconfigurable.

The project has defined four functional regimes;

1. Precision Operating: low wind speed, at night, low temperature rate of change and no precipitation.
2. Normal Operating: moderate wind speed, day/night, moderate temperature rate of change and no precipitation.
3. Limit to Operations: higher wind speed, low and high temperature limits and precipitation resulting in ice build-up.
4. Survival Conditions: high winds, extreme temperatures, snow and/or ice accumulation and hail.

Additionally, requirements are identified for seismic and lightning strike events.

3.1 Operational Environment

The defined operating conditions for the antennas are shown in Table 3, Table 4, Table 5 and Table 6.

Table 3 Precision Operating Conditions [AD01]

Parameter	Req. #	Value	Traceability
Solar Thermal Load	SBA1411	Night time only; no solar thermal load within last 2 hours.	SYS2411
Wind Speed	SBA1412	0 ≤ W ≤ 7 m/s average over 10 min time. 10 m/s peak gusts.	SYS2412
Temperature	SBA1413	-15 C ≤ T ≤ 25 C	SYS2413
Temperature Rate of Change	SBA1414	1.8 °C/Hr.	SYS2414
Precipitation	SBA1415	No precipitation.	SYS2415

Table 4 Normal Operating Conditions [AD01]

Parameter	Req. #	Value	Traceability
Solar Thermal Load	SBA1421	Exposed to full sun.	SYS2421
Wind Speed	SBA1422	W ≤ 10 m/s average over 10 min time. 15 m/s peak gusts.	SYS2422
Temperature	SBA1423	-15 C ≤ T ≤ 35 C	SYS2423
Temperature Rate of Change	SBA1424	3.6 ° C/Hr.	SYS2424
Precipitation	SBA1425	No precipitation.	SYS2425

Table 5 Limit to Operating Conditions [AD01]

Parameter	Req. #	Value	Traceability
Wind	SBA1431	W ≤ 15 m/s average over 10 min. W ≤ 20 m/s gust.	SYS2432
Temperature	SBA1432	-20 C ≤ T ≤ 45 C	SYS2433
Precipitation	SBA1433	Any precipitation rate that does not result in accumulation of ice on the antenna structure.	SYS2434

Table 6 Survival Conditions [AD01]

Parameter	Req. #	Value	Traceability
Wind	SBA1441	0 m/s ≤ W ≤ 50 m/s average.	SYS2441
Temperature	SBA1442	-30 C ≤ T ≤ 50 C	SYS2442
Radial Ice	SBA1443	2.5 cm	SYS2443
Snow Load	SBA1444	25 cm	SYS2444
Hail Stones	SBA1445	2.0 cm	SYS2445
Antenna Orientation	SBA1446	Stow-survival, as defined by designer	

4 RISKS

4.1 Risks

Risks have been categorized into either Project or Product risks. Project risks are those that might impact the completion of the design work on budget and schedule, product risks are those that might impact the ability of the design to meet the requirements. Both project and product risks are further categorized as to the nature of the impact; Budget, Schedule, Logistical or Technical. All identified risks are tracked in the project risk register, [RD03].

Table 7 Project Risks

Risk#	Description	Status	Type	Category	Mitigation Plan	Probability	Impact
102-R5	Work delay due to unexpected loss of resources	Open	Project	Schedule		30%	2
102-R6	Procurement delays related to contracts	Open	Project	Schedule		50%	2
102-R7	Loss of personnel due to retirement and employees seeking employment elsewhere	Open	Project	Schedule		10%	2

Table 8 Product Risks

Risk#	Description	Status	Type	Category	Mitigation Plan	Probability	Impact
102-R1	Production cost exceeds ngVLA expectations	Open	Product	Budget	Initiate cost evaluation early in project and update often to track cost.	20%	2
102-R2	Bond between reflective material and surface structure is not strong enough	Open	Product	Technical	Send material structure samples for lifecycle testing.	30%	2
102-R3	Repeatability of single piece reflector surface accuracy during production cannot be proven.	Open	Product	Technical	Provide quality assurance protocols for production. Compliant connection between primary surface and BUS with adjustment is being investigated during concept design phase.	20%	3
102-R4	Long term surface accuracy stability cannot be proven.	Open	Product	Technical	Review and re-issue of report done produced for SKA project. Investigate accelerated life testing.	75%	2
102-R8	Surface accuracy requirement cannot be met.	Open	Product	Technical	Minimize deformation due to environmental effects to allow maximum allocation to as-manufactured errors.	20%	3
102-R9	Tangential surface adjusters cannot reduce distortions to meet surface requirement.	Open	Product	Technical	Model and prototype at an early stage.	50%	2
102-R10	Strength, stiffness and long-term endurance of surface adjusters are unproven.	Open	Product	Technical	Model, prototype and test adjusters at an early stage.	50%	2
102-R11	Durability of surface reflective material is compromised by moisture ingress.	Open	Product	Technical	Provide quality control measures for production and repair procedures for operations.	20%	1

5 DESIGN OVERVIEW

The preliminary design for the ngVLA 6m antennas is a Single-piece Rim-supported Composite (SRC) Reflector on a steel yoke and pedestal mount, Figure 1.

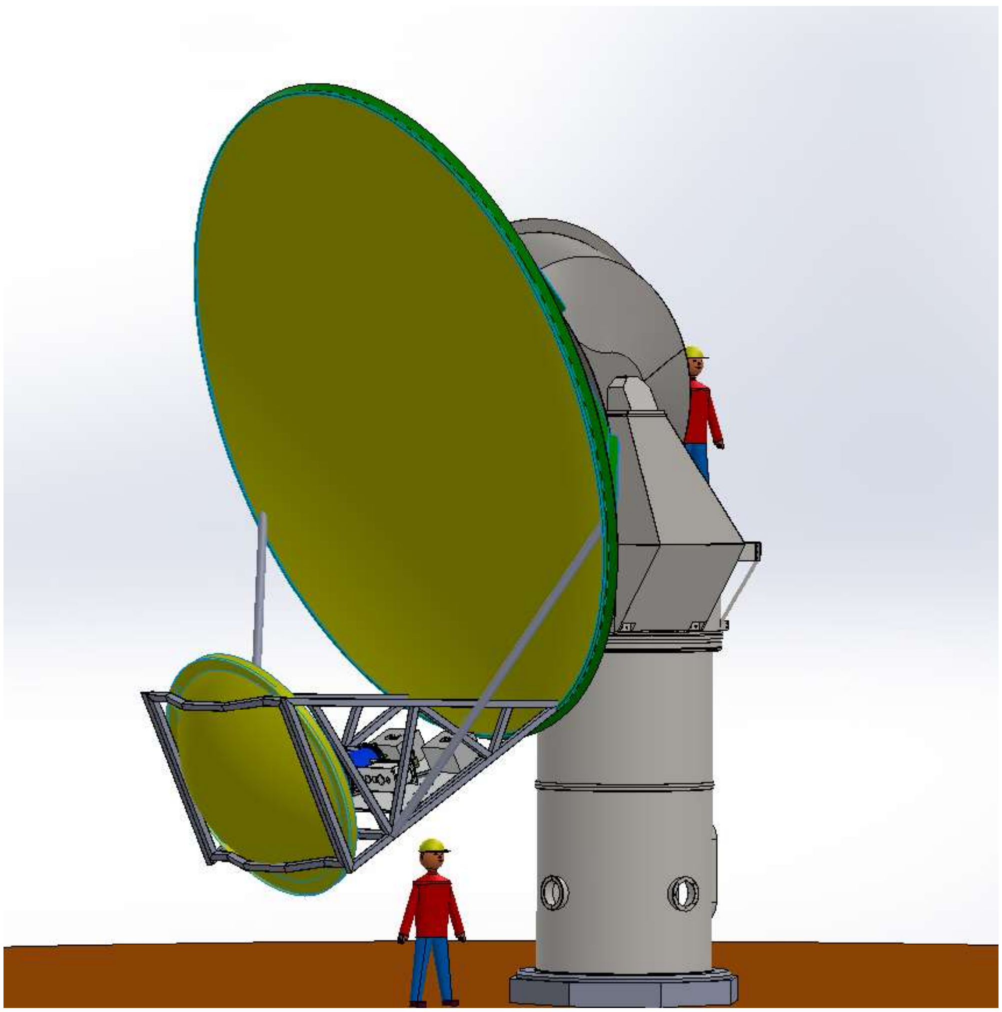


Figure 1 NRC ngVLA 6m Antenna Design Concept

5.1 Design Overview

5.1.1 Elevation Rotating Assembly

The Elevation Rotating Assembly (ERA) design features a SRC primary reflector surface supported by a composite shell outer BackUp Structure (oBUS) which attaches to a fabricated steel inner BUS (iBUS). The 6 metre iBUS differs from the 18 metre design principally in the fact that it will be built from steel plate rather than from tubes. A composite space frame secondary support structure attaches to the oBUS at the rim of the primary reflector and supports the feed package and secondary reflector.

5.1.1.1 Primary Reflector Surface

The primary reflector surface manufacturing technique is based on the vacuum infused carbon fibre/epoxy resin layup process used in the fabrication of the Dish Verification Antenna (DVA) antennas. The surface is ~4mm thick and consists of 5 layers of quasi-isotropic carbon fibre fabric, a copper reflective layer and protective layers of thin fibreglass veil. This is nearly identical to that used in the 18m design except it will be slightly thinner. The primary surface infusion is of uniform thickness and does not include a rim or other features that may result in process induced distortions. The exception is the surface adjuster tabs which will be infused with the surface. These will be designed to result in minimal distortions and are located around the perimeter in a small band of the surface outside of the optical surface. Figure 2 shows a concept sketch for the adjuster tabs (this concept will be virtually identical to the one proposed on the 18m). The metal spool would be added at the edge of the layup, then overwrapped around its perimeter with a pre-cured carbon-fibre ‘fan’ as illustrated in the figure. The green zone in the figure represents the 100mm wide extension to the primary surface which is outside of the aperture. The carbon fibre ‘fan’ would be incorporated into the centre of the layup (through-thickness) during the primary layup and in this way would form an integral part of the structure.

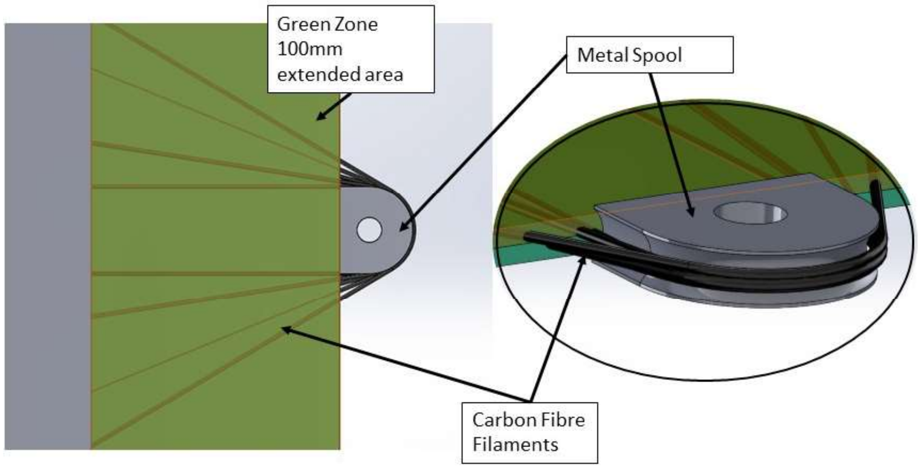


Figure 2 Primary surface edge adjuster tab concept

Figure 3 shows the primary surface edge adjuster concept in context with the oBUS edge structure. The primary surface (left hand panel) is suspended from the oBUS by the primary surface edge adjuster tabs shown in Figure 2 together with a clevis and stud arrangement. Nuts and washers located on each side of the oBUS flange on the studs will allow for the adjustment of the perimeter tension loads on the surface and, in turn, the shape of the surface.

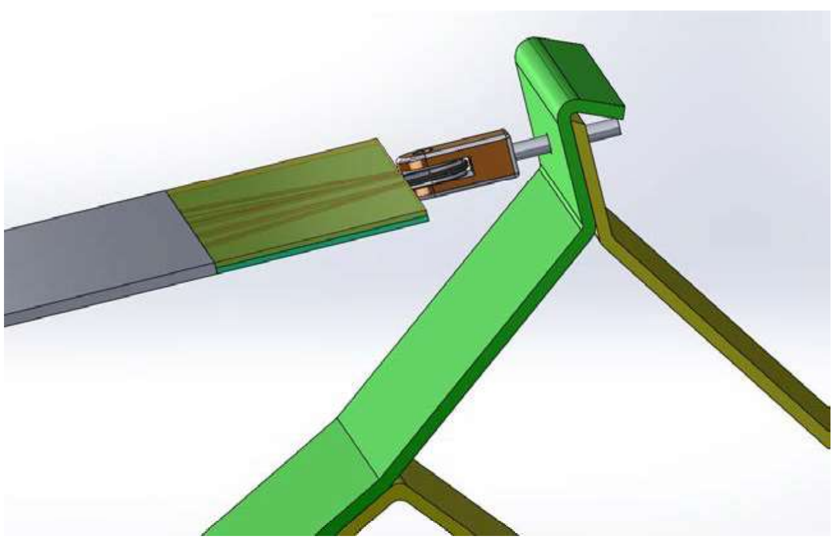


Figure 3 Primary surface edge adjuster with oBUS

5.1.1.2 Outer Backup Structure

The oBUS is comprised of 7 panels, and 7 ribs, and is really a scaled down version of the 18m version. The complete oBUS structure is depicted in Figure 4.

Figure 4 Assembled oBUS structure

The component dimensions are designed to enable standard transport to site. Because the 6m is so much smaller than the 18m design, the oBUS panels can be larger relative to the total size of the oBUS. For this reason the full circumference of the 6m reflector can be completed with 7 panels instead of the 22 required for the 18m. The panels and ribs are carbon fibre/epoxy composite layup similar to that used in the surface (without the reflective layer). The ribs provide stiffening at the panel joints as well as load paths from the feed/secondary support structure connections to the iBUS. The outer or top edge of the structure is stiffened by the circumferential rim beam. Figure 5 depicts an assembled oBUS with the components that make up the structure shown in different colours. The 7 panels that make up the oBUS are shown with 6 panels in green and one in grey (the grey panel shows you the extent of one panel). The top edge circumferential beam is shown in red and the radial beams in blue. The panels and beams would be built off site and trucked in. The green (and grey) panels would be assembled on a jig very similar to the one shown in the 18m fabrication document, but of course sized for this structure. Once the panels are in place the red rim beam would be bonded in place (in sections), and finally the blue radial beams would be bonded in place.

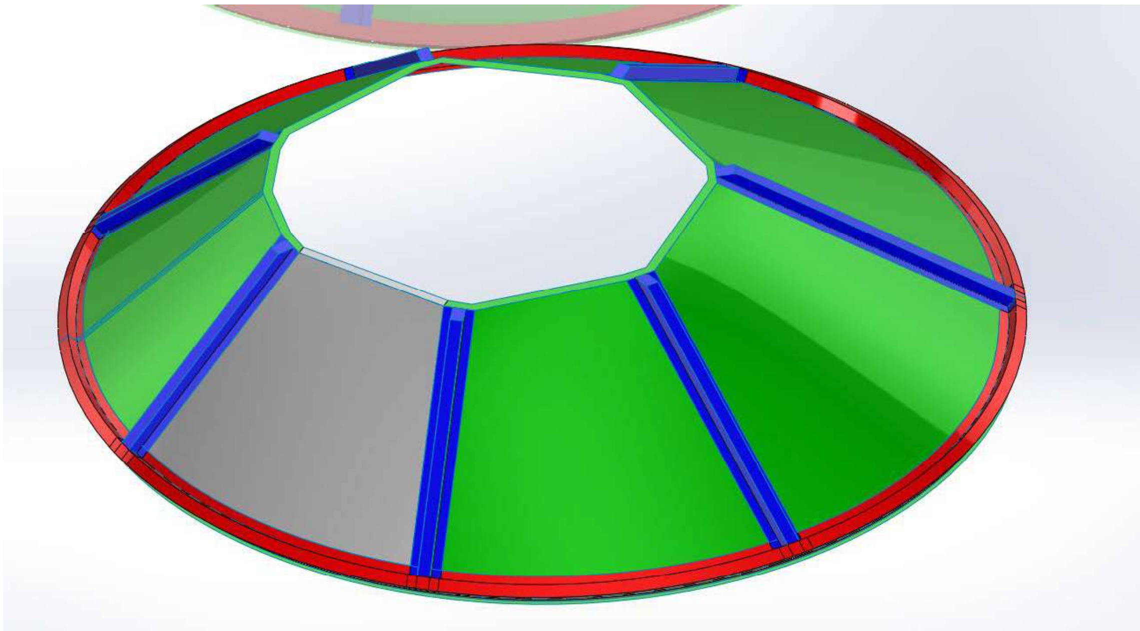


Figure 5 oBUS components in colour

The resulting structure is very stiff in shear between the reflector surface and iBUS. This is of particular importance for the feed-down configuration because the reflector will spend most of its time oriented in a vertical or near vertical orientation where the shear stiffness of the oBUS will provide the larger portion of necessary support for the primary surface (imagine the reflector surface being dragged downward by gravity) in Figure 6.

The oBUS is connected to the iBUS through bolted connections between the bonded-in metal connectors located at the lower end of each radial beam on the oBUS and connection points defined at the same locations on the iBUS. This will be at 7 discrete points directly over the 7 corners defined by the radial (blue) beams shown in Figure 5. When the iBUS and oBUS are combined, they will provide the stiffness required to achieve the pointing and surface accuracy. Figure 6 shows the centre-plane cutaway view of the 6m dish.

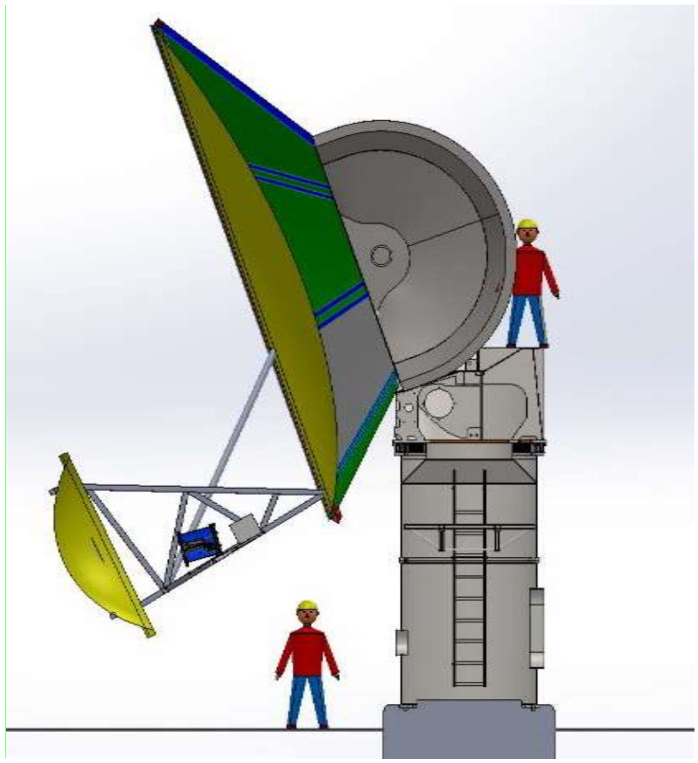


Figure 6 Cross Section of Antenna at Low (12°) Elevation Angle

5.1.1.3 Inner Backup Structure

The iBUS provides the interface and transfers drive loads between the reflector assembly and the yoke. It is an assembly of machined and fabricated steel components. The iBUS for the 6m antenna will likely be quite different than that suitable for the 18m. Figure 7 illustrates the current working solution. As can be seen this is not a tubular space frame concept, but rather a plate structure which is more suitable for the smaller size of the 6m design. The central band represents the drive magnet arc required for a linear motor. The 6m iBUS is conceptual at this time, development of a steel plate structure is seen as low risk and so design resources have been concentrated on other higher risk aspects.

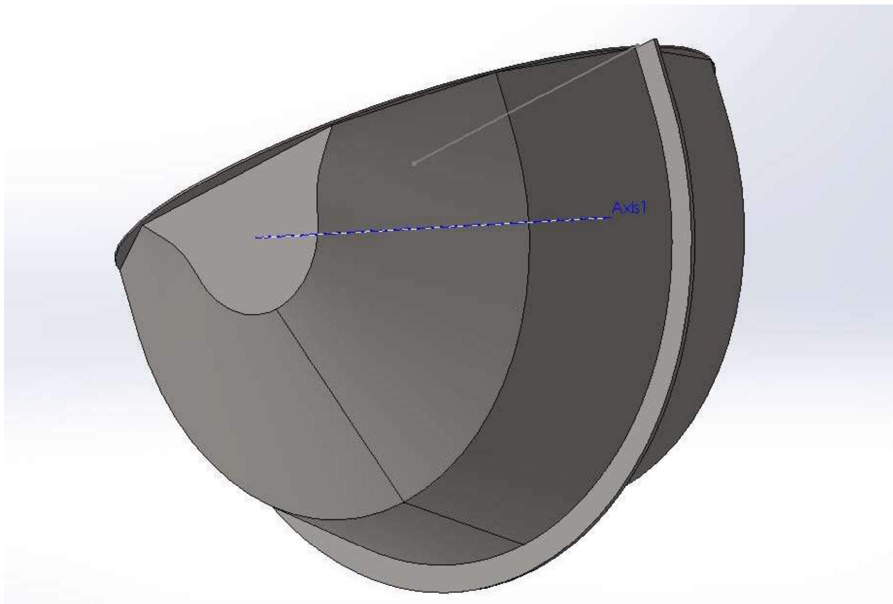


Figure 7 6m iBUS structure

Once assembled, the iBUS will be lifted into position onto the yoke-tower assembly. The primary reflector assembly will be lifted by crane and the connection between the oBUS and iBUS made once in position.

5.1.1.4 Secondary Support

The secondary support structure is a carbon fibre truss to minimize weight and coefficient of thermal expansion (CTE), and maximize stiffness. Figure 8 shows the general arrangement.

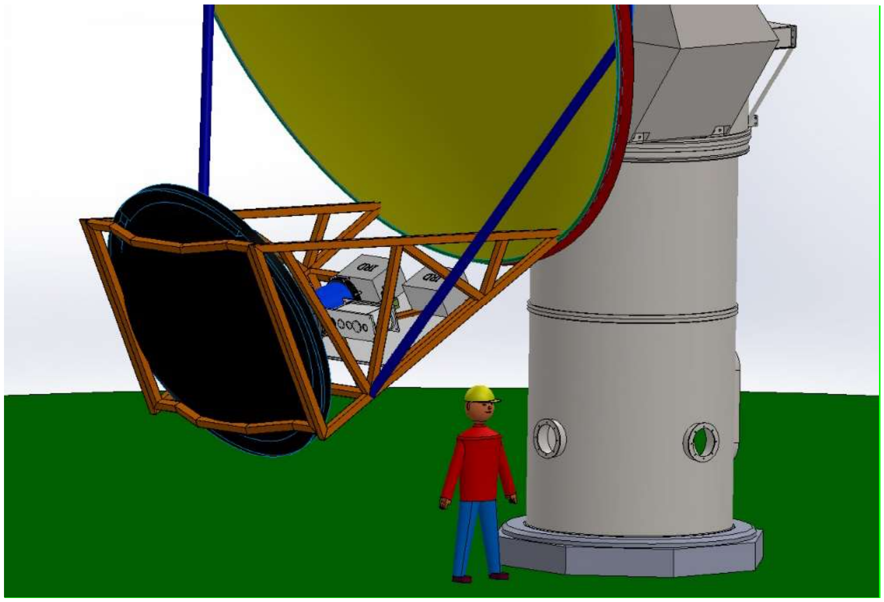


Figure 8 6m Secondary Support Structure.

The primary truss structures (orange) support the secondary reflector (black) and attach to the rim of the primary reflector at two points. A carbon tube on each side (blue in Figure 8) connects to the rim of the primary reflector as far around the rim as practical while still staying out of the optical path and keeping the tube length down below practical limits. The design is similar to that proposed for the 18m, although the reduced size of the optics does help reduce the overall complexity. The feed package and indexer are shown as a series of components (grey and blue in the rendering), and are placeholders ready for further development.

Stiffening ribs integrated into the oBUS transfer the loads from the secondary legs to the iBUS, Figure 9.

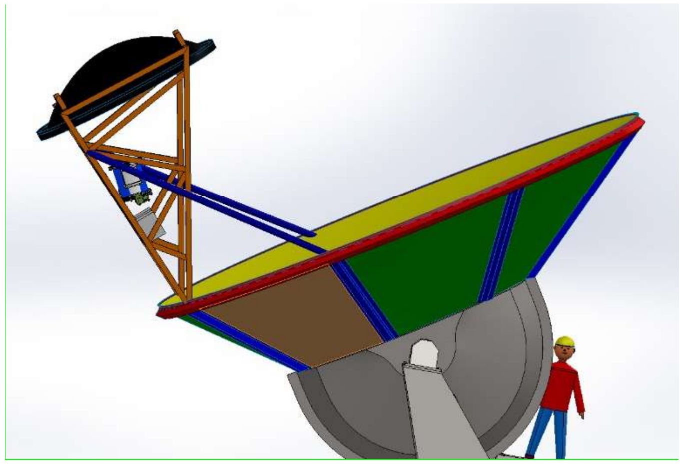


Figure 9 Stiffening Ribs on Primary Reflector to Support Secondary Support Structure

Figure 10 shows a close-up view of the feed and secondary support structure. The different colours indicate separate shippable parts. On-site assembly would occur, with a combination of glue-bonded and bolted connections.

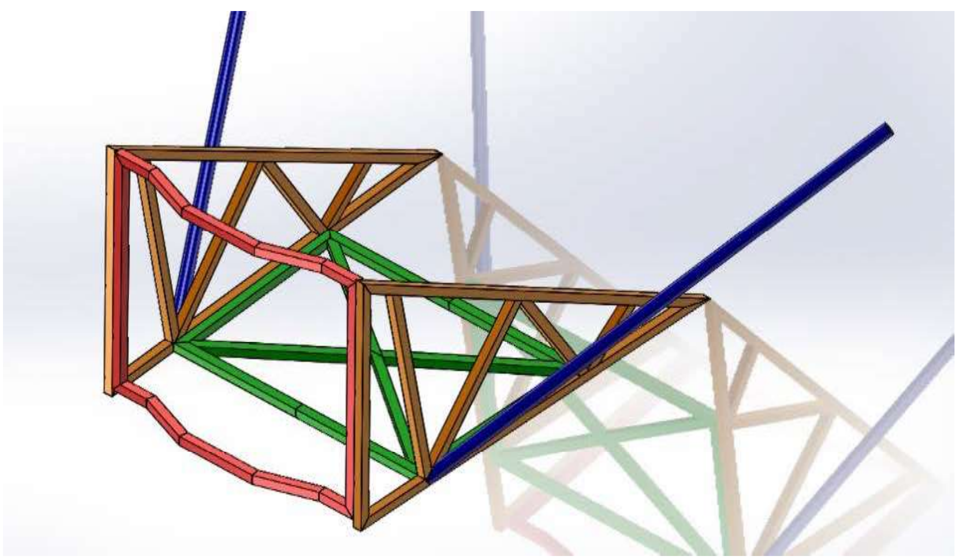


Figure 10 Secondary and Feed Support Structure for 6m dish

5.1.2 Mount

A pedestal mount based on a modified commercial product has been selected for this early design study. The mount was designed as a 10m symmetric satcom antenna intended to operate at up to 50 GHz and in winds up to 28 m/s. The principle modifications are: reducing the height of the tower to match the 6m requirement, modifying the yoke arms, and adapting the turn-head to accommodate the linear drive. Figure 11 shows the general configuration of the mount.

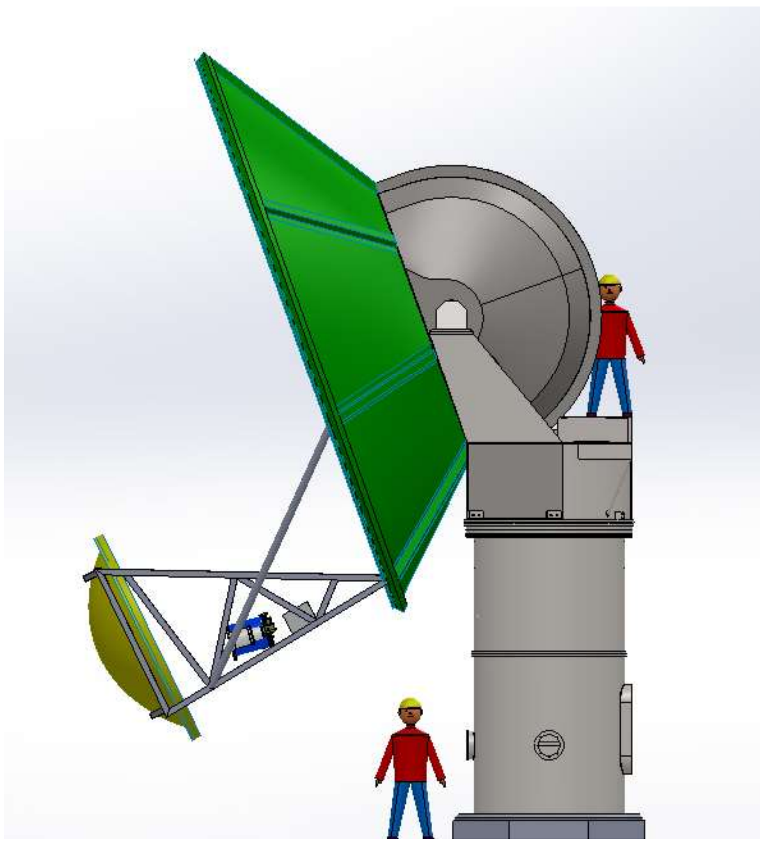


Figure 11 Complete 6m telescope with mount

Although no detailed analysis has been performed on the mount with the 6m ngVLA reflector, given that it was designed for a 10m reflector and to operate in extreme conditions, there is a high level of confidence that with minimal further development the design will meet the ngVAL requirements.

6 ERROR BUDGETS

6.1 Surface Accuracy Error Budget

Surface accuracy is defined as the deviation of the manufactured reflector surface from the designed surface profile. The accuracy can be stated either in the plane tangent to the reflector surface or in the main aperture plane normal to the boresight direction (the main reflector optical axis). For the ngVLA the surface accuracy specifications are stated in the main aperture plane (see Table 13 below). The specifications are for different operating conditions (precision or normal).

Surface error can be caused by the manufacturing process (mould accuracy, part separation from the mould, tensioning of the reflector) or by dynamic wind, gravity, and thermal effects (differential rates of thermal expansion/contraction, or thermal gradients set up by solar irradiation). The dynamic effects will deform the reflectors and the mounting structure, which will cause surface error.

The surface accuracy error budget identifies sources of surface error for both the primary and secondary reflectors, allocates error amounts to the sources and both reflectors, and defines the calculation of overall error using the allocated amounts. The budget is used both to determine compliance with the specifications when the achievable accuracy is known or estimated for each error source, and to estimate the available error margin in a source using the total allowed error in the specification. Surface accuracy budgets with the most recent accuracy data and estimates are shown in Table 9 for precision operating conditions and Table 10 for normal operating conditions. The tables include manufacturing error derived from the mould surface accuracy and the accuracy ratio of the mould and the part built from it. Totals for primary and secondary reflector surface accuracy and overall combined accuracy are shown, as well as antenna efficiency at selected frequencies across the operational band (calculated from the total surface accuracy).

Table 9 Antenna Surface Accuracy Error Budget – Precision Operating Conditions

Precision						
Wind	5	m/s	Night	Temperature	20	C min
Requirement	160	micron RMS				
Primary				**Secondary**		
Mold	**0.080**			Mold	0.05	
Manufacturing	0.100	mm rms		Manufacturing	0.030	mm rms
Gravitational	0.042	mm rms		Gravitational	0.02	mm rms
Wind	0.01	mm rms		Wind	0.01	mm rms
Thermal	0.02	mm rms		Thermal	0.01	mm rms
Ageing	0.01			Ageing	0.01	
Total	0.137	mm rms		Total	0.064	mm rms
Combined Total (RSS)		**0.151**	mm rms			
Frequency (GHz)	**2**	**10**	**30**	**80**	**100**	**116**
Surface eff	100.0%	99.6%	96.4%	77.3%	66.9%	58.2%

Table 10 Antenna Surface Accuracy Error Budget – Normal Operating Conditions

Normal						
Wind	7	m/s	Day/night	Temperatur	30	C min
Requirement	300	micron RMS				
Primary				**Secondary**		
Mold	**0.100**			Mold	0.05	
Manufacturing	0.100	mm rms		Manufactur	0.030	mm rms
Gravitational	0.042	mm rms		Gravitationa	0.02	mm rms
Wind	0.02	mm rms		Wind	0.020	mm rms
Thermal	0.08	mm rms		Thermal	0.05	mm rms
Ageing	0.02			Ageing	0.01	
Total	0.170	mm rms		Total	0.082	mm rms
Combined Total (RSS)		**0.189**	mm rms			
Frequency (GHz)	**2**	**10**	**30**	**80**	**100**	**116**
Surface eff	100.0%	99.4%	94.5%	67.0%	53.5%	43.1%

6.2 Pointing Error Budget

Pointing error is defined as the angular difference between the commanded antenna pointing direction and the resulting main lobe peak gain. Pointing error specifications are for different operating conditions (precision or normal) and whether the pointing currently falls within an angular offset and time offset of a calibration source location that is suitable for a pointing error measurement. The specifications are shown in Table 14 and Table 15.

Pointing error can be repeatable or non-repeatable. Repeatable pointing error can be compensated to some degree. Residual error or error introduced by compensations are treated as non-repeatable pointing error in this document. Systematic pointing errors due to mechanical misalignments and gravity are compensated by using a systematic pointing error correction model (SPEM) as the basis of a compensation. The SPEM model coefficients are determined from a least squares determination according to measurements of pointing error from calibration sources. Other means of correcting systematic pointing error include atmospheric refraction correction, tiltmeters, temperature measurements, and antenna modelling for strain induced by gravity, wind, and thermal effects.

The pointing error budget identifies sources of pointing error in the bias (systematic) and random categories, allocates error amounts to the different sources, and defines the calculation of total pointing error from the allocated amounts. The budget is used both to determine compliance with the specifications when the achievable pointing error contribution for each source is known or estimated, and to determine the available error margin in a source using the allowed total pointing error from the specification.

An example pointing error budget from ngVLA 18 m antenna is shown in Table 11. Both elevation and cross-elevation (XEL) errors are included. Each error is given for absolute pointing (pointing directly to a commanded direction) with and without compensation, and for referenced pointing (pointing relative to a well-known pointing “landmark”) as an applicable fraction of the absolute pointing error contribution. Contributions are divided into categories as they apply to the major components of the antenna system (elevation assembly, pedestal, servo system, and foundation). Examples of error sources include errors in alignment and perpendicularity of the antenna components and deformation by gravity, wind, and thermal expansion/contraction.

Table 11 Example Pointing Error Budget from 18m

Precision Operating Environment **Elevation angle;** 66 Degrees

Wind Speed [m/s]	Equivalent Wind Speed w/Gusts [m/s]	Max Wind Gust Speed [m/s]	Thermal Soak [C]	Thermal Gradient [dT]	Thermal Change [C/hr]
5	5.3	7	20	0	1.8

PE Contributor	Elevation PE Without Compensation (arcsec)	Elevation PE With Compensation (arcsec)	Elevation Applicabilty to Referenced Pointing (%)	Referenced El Pointing Error (arcsec)	XEL PE Without Compensation (arcsec)	XEL PE With Compensation (arcsec)	XEL Applicabilty to Referenced Pointing (%)	Referenced XEL Pointing Error (arcsec)	BOE	Notes
Structure Deformation Due to Gravity	86.40	0.00	100%	0.00	0.00	0.00	100%	0.00	b	Compensated by SPEM
Structure Deformation Due to Thermal Soak	11.00	11.00	10%	1.10	0.00	0.00	10%	0.00	b	Very slow change, assumed 100% compensated in Reference Pointing
Structure Deformation Due to Thermal Gradient	0.00	0.00	50%	0.00	0.00	0.00	50%	0.00	b	Slow change, assumed 75% compensated in Reference Pointing
Structure Deformation Due to Constant Wind	2.00	2.00	50%	1.00	0.00	0.00	25%	0.00	b	Moderate change, assumed 50% compensated in Reference Pointing
Structure Deformation Due to Wind Gusts	0.25	0.25	100%	0.25	0.00	0.00	100%	0.00	c	
Subtotals (RSS + Wind)	97.63	11.23		1.66	0.00	0.00		0.00		
Elevation Assembly										
Orthogonality error, Reflectors to Elevation Axis	10.00	0.00	100%	0.00	10.00	0.00	100%	0.00	a	Compensated by SPEM
Pedestal										
Tower Tilt Fixed	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Othogonality of the Az/El Axes	4.00	0.00	100%	0.00	4.00	0.00	100%	0.00	a	Compensated by SPEM
Subtotals	4.12	0.00		0.00	4.12	0.00		0.00		
Servo										
Encoder Mounting and Gearing With Temp.	1.00	0.00	100%	0.00	1.00	0.00	100%	0.00	a	Compensated by SPEM
Encoder Calibration error or Fixed Offsets	2.00	0.00	100%	0.00	2.00	0.00	100%	0.00	a	Compensated by SPEM
Wind Gusts	0.59	0.59	100%	0.59	0.00	0.00	100%	0.00	d	
Subtotals (RSS + Wind)	2.31	0.59		0.59	2.24	0.00		0.00		
Foundation										
Foundation change (long-term)	1.00	0.00	0%	0.00	1.00	0.00	0%	0.00	a	Compensated by SPEM
Foundation deformation with Constant Wind	0.50	0.50	50%	0.25	0.50	0.50	50%	0.25	a	Moderate change, assumed 50% compensated in Reference Pointing
Foundation deformation with Wind Gusts	0.48	0.48	100%	0.48	0.06	0.06	100%	0.06	c	
Subtotals (RSS + Wind)	1.40	0.98		0.73	1.15	0.56		0.31		
SPEM Residuals										
SPEM Residuals	0.50	0.50	25%	0.13	0.50	0.50	25%	0.13	a	
Totals and Comparison With Specification										
Total PE (RSS + Wind)	97.75	11.30		1.91	4.85	0.75		0.34		

Total El and XEL Compensated PE (RSS'd)	**11.32**
Non-Repeatable Pointing Error Spec. (arcsec)	18.00

Total EL and XEL Referenced Pointing Error	**1.94**
Referenced Pointing Error Specification	3.00

7 PERFORMANCE

7.1 System Noise Contribution

Table 12 System Noise Contributions Requirement

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.	

NRC has conducted tests of its reflecting material to determine the system noise contributions. The test method is detailed in RD01 and the latest results are detailed in RD02 and presented in Figure 12**Error! Reference source not found.**. Samples A1/2 are the materials developed for DVA1, B1/2 material developed for DVA2 and the most recent material developed for the ngVLA project is C1/2. Gains were made between DVA1 and 2 by switching from aluminium to copper and further gains to the most recent material were due to material configuration changes.

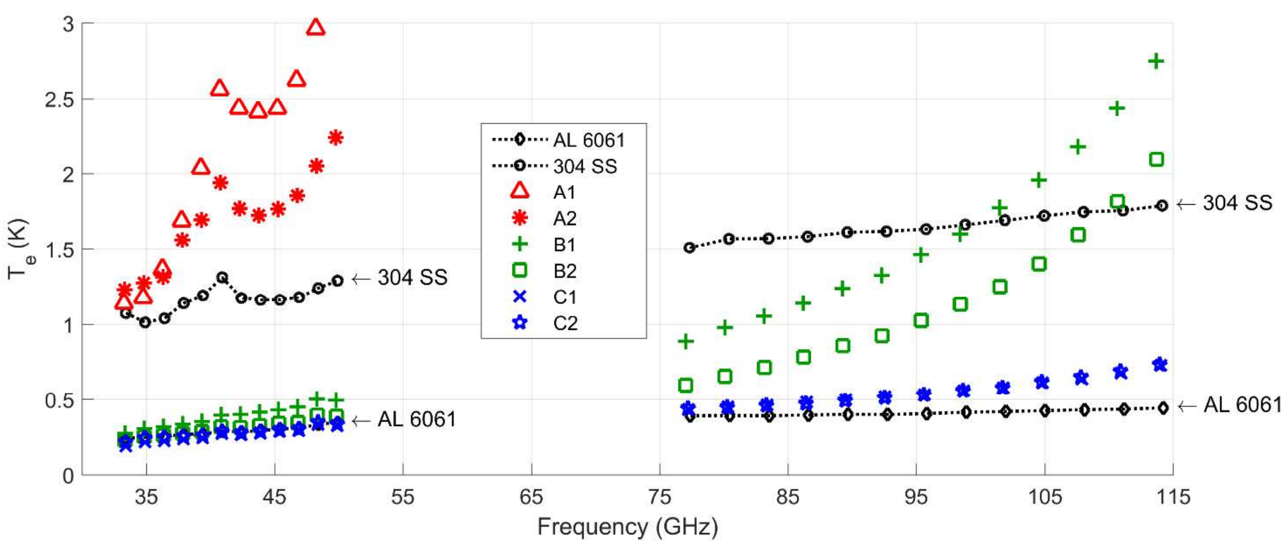


Figure 12 Reflector Surface Noise Measurement Results

The worst case noise temperature contribution from the surface for the C materials is ~0.75 K @ 115 GHz. The resistive loss is calculated as follows:

$$\%loss = \left[1 - \frac{1}{\left(\frac{Tn}{290} + 1\right)}\right] * 100\% = \left[1 - \frac{1}{\left(\frac{0.75}{290} + 1\right)}\right] * 100\% = 0.3\%$$

7.2 Aperture Efficiency

The key requirements for aperture efficiency relate to surface accuracy and reflector surface continuity, Table 13.

Table 13 Aperture Efficiency Related Requirements [AD01]

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 operating in the Normal operating environment.	SYS0501
Reflector Construction	SBA0503	Each reflector 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.	

7.2.1 Gravitational Deformations

Analysis of the gravitational deformations of the 6m reflector assembly, Figure 13, was performed early in the design cycle after which resources were focused on the greater challenge of the 18m design. The results presented here are for the earlier design which did not incorporate many of the features developed for the 18m. They are presented here with the intent to show that the required accuracy will be achievable for the 6m. Design elements from the 18m study will be incorporated in the future only as required to meet performance targets while keeping costs in mind.

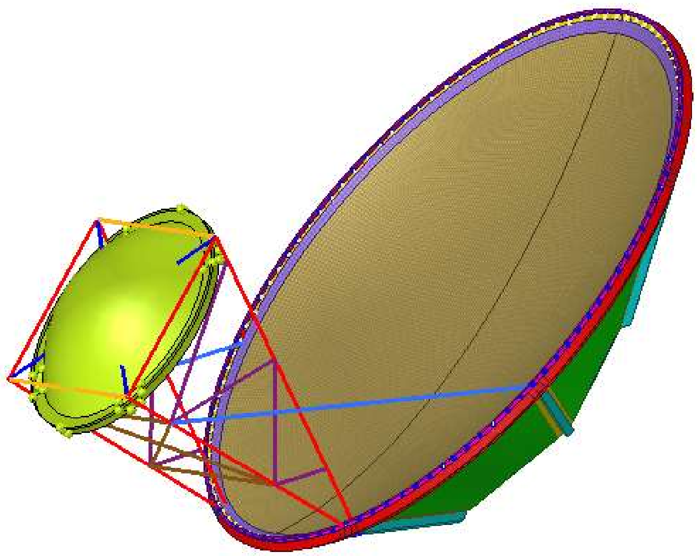


Figure 13 6m Reflector Assembly

The carbon composite cone back structure was reinforced using 6 height optimized ribs with unidirectional fibers to improve the bending stiffness Figure 14.

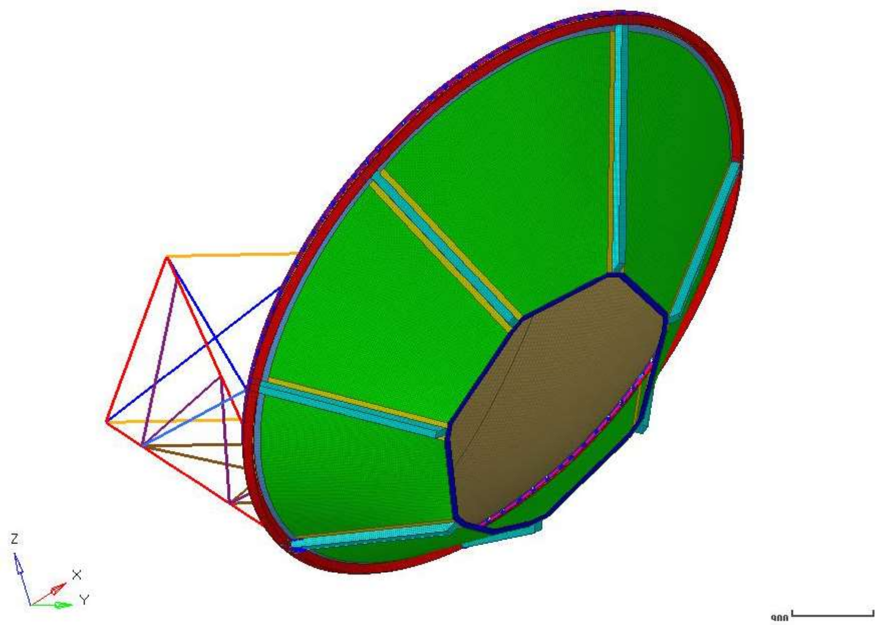


Figure 14 6m oBUS

7.2.1.1 Laminate schedule

The primary surface laminate features of 6 layers of carbon Quasi-Isotropic (QISO) carbon fibre, Figure 15.

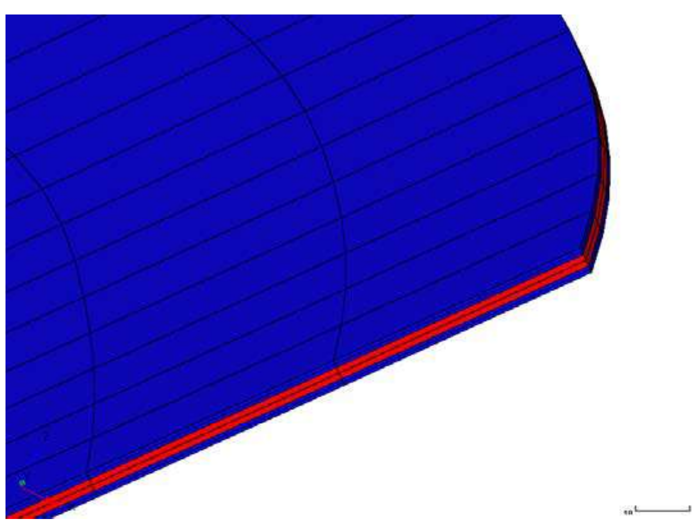


Figure 15 Primary surface Laminate schedule (blue layer: carbon qiso, red layer: triaxial carbon).

The oBUS laminate features of 8 layers of carbon Quasi-Isotropic (QISO) carbon fibre, Figure 16.

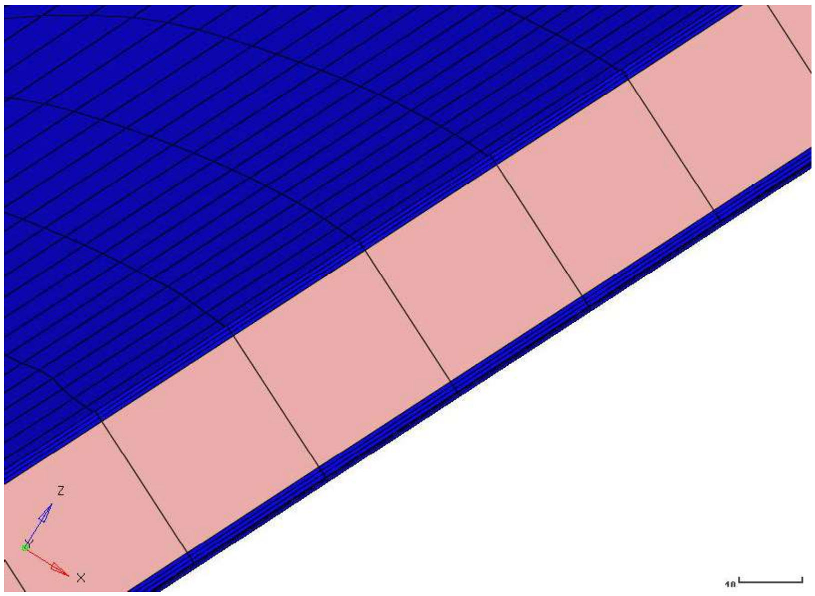


Figure 16 oBUS Laminate schedule (blue layer: carbon qiso, pink layer: foam core)

The oBUS rib laminate features of 4 layers of carbon Quasi-Isotropic (QISO) carbon fibre and two layers of unidirectional carbon fibre, Figure 17.

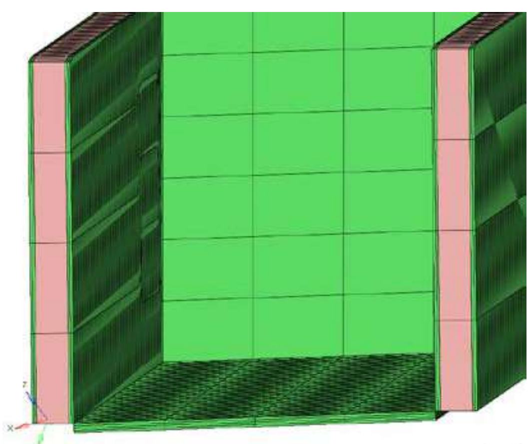


Figure 17 oBUS rib Laminate schedule (green layer: carbon qiso, pink layer: foam core)

The rim laminate features of 3 layers of carbon Quasi-Isotropic (QISO) carbon fibre and 2 layers of unidirectional carbon and one inch thick foam core to improve the rim stiffness, Figure 18.

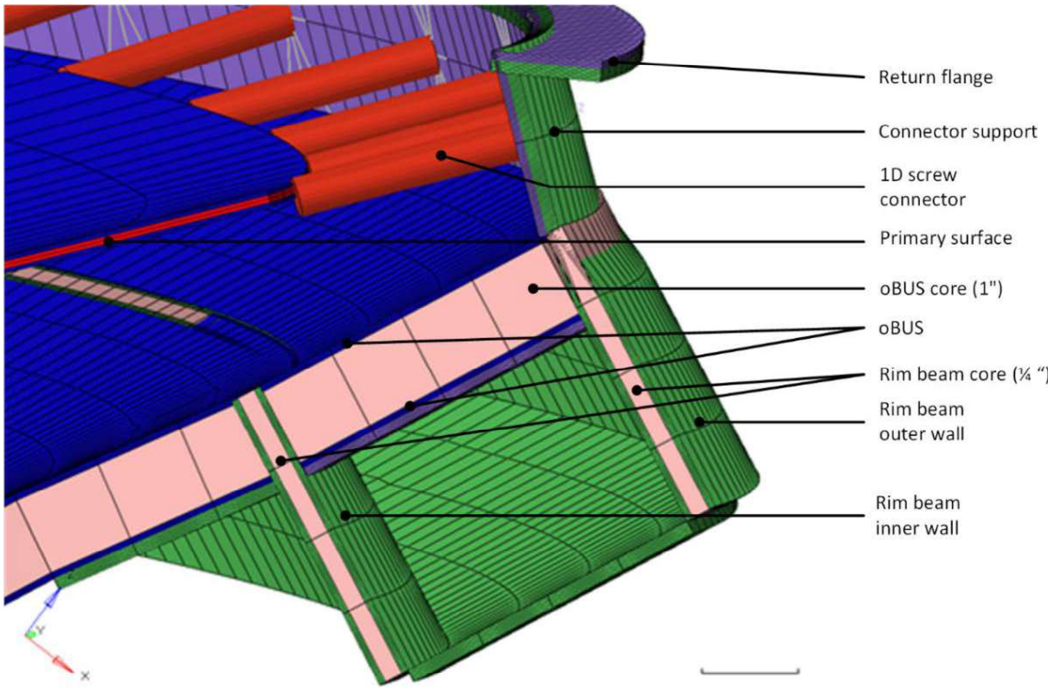


Figure 18 Cone back-primary laminate schedule and foam core (blue layer: carbon QISO, magenta layer: carbon uni, grey layer: foam core).

7.2.2 Results

Under the gravity load case, FE Analysis was performed for 15 degree and 90 degree elevation angles. The FE model is constrained at the bottom of the oBUS structure at 7 locations shown in Figure 19. The iBUS structure is notional at this point and further design is required for the 6m.

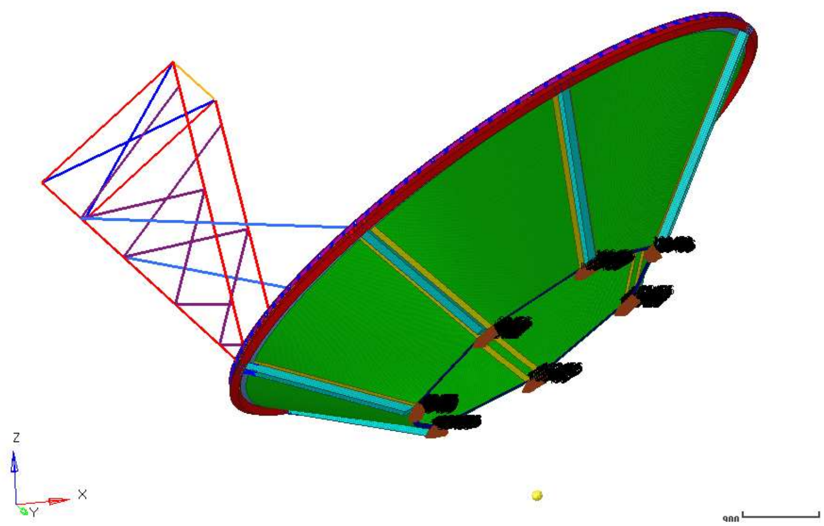


Figure 19 ngVLA 6m FE model constraints

The secondary surface is modelled as a lumped mass supported by four points. The feed is also modelled as lumped mass in the analysis. The surface RMS errors are presented in Figure 20.

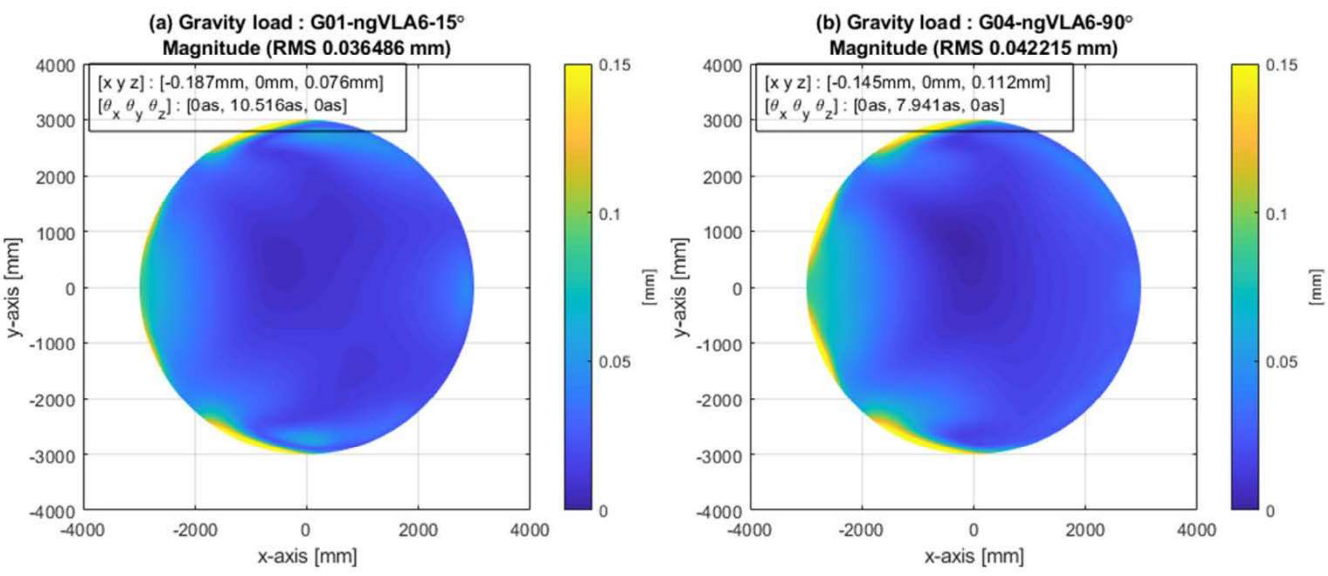


Figure 20 ngVLA 6m surface RMS error under Gravity load cases (a) 15° and (b) 90° elevation angle.

The 6m gravity load case results are then compared with 18m analysis. It is important to note that for proper comparison, the 18m design is also constrained at the bottom of the oBUS structure. Also, the oBUS structure in the 6m design uses 1” thick core while in the 18m design the core thickness is 1.5”.

The secondary tube sizes are similar although the 6m design is lot more compact than the 18m design. The comparison is presented in Figure 21.

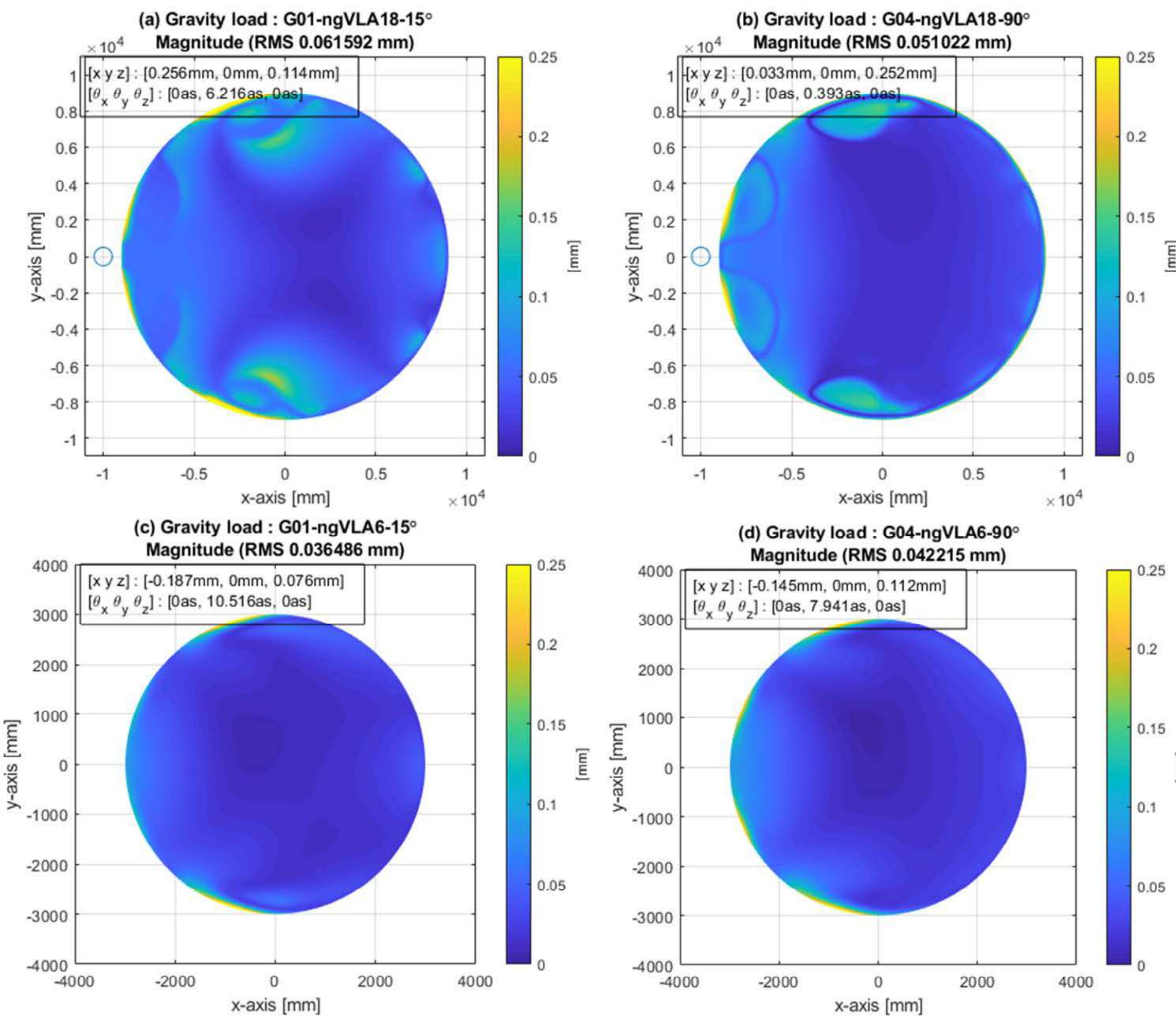


Figure 21 Surface RMS error under Gravity load cases for ngVLA 18m (a) 15° and (b) 90° elevation angles and ngVLA 6m (c) 15° and (d) 90° elevation angles.

It is important to note that for the 18m dish structure, there are some additional carbon composite patches attached. This helps to reduce the surface distortion due to the secondary load (at the connection points) on the primary and visible in the surface RMS error plots (Figure 21 (a) and (b)). The 6m design is very compact in comparison to the 18m design. Hence, no additional patches are not attached in the primary surface. However, further investigation is required to obtain optimal size and shape of the secondary support structures.

7.2.3 Manufacturing Errors

The SRC reflectors are manufactured as the name implies in one piece on a mould. The as-manufactured surface accuracy depends on; mould accuracy, process design and process control. As illustrated in the Surface Error Budget, Table 9, the required as-manufactured accuracy will depend on the values achieved through design for the deformation due to gravity, wind and thermal loads. The values shown in Table 9 represent the current status of the surface accuracy and indicate that the required as-manufactured accuracy will be ~132µm Root Mean Square (RMS) (80 microns RMS mould error and 105 microns RMS process induced error added in RSS).

As with the 18m the plan is to attempt to “capture” the surface shape by installing the oBUS on the surface before it is released from the mould. For serial production it is easy to justify a jig to accurately align the oBUS to the moulded part during installation. Small adjustments will then be made to reach the final accuracy requirement.

7.2.4 Surface Adjustment

The same surface adjustment scheme as proposed for the 18m will be used for the 6m. Details can be found in [AD03].

7.3 Pointing

The pointing requirements for the ngVLA 6m antenna are shown in Table 14 and Table 15.

Table 14 Precision Pointing Requirements

Parameter	Req. #	Value	Traceability
Non-repeatable Pointing Error	SBA0611	54 arc sec RMS.	SYS0801
Referenced Pointing Error	SBA0612	9 arc sec RMS, within 4º of the target position and 15 minutes of time.	SYS0701, SYS0801

Table 15 Normal Pointing Requirements

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 a minimum of 15 minutes.	SYS0701, SYS0801

At this time a comprehensive pointing analysis has not been performed, this will be a priority in the next phase.

7.4 Survivability

Survivability analysis has not been performed at this time, based on the DVA1/2 experience it is not seen to be a risk but will be analysed in the next phase.

The DVA1/2 design did have a failure mode in survival conditions which was buckling of the surface due to high wind from the back of the reflector. At the end of the reflector opposite the feed and secondary the surface has less shape and therefore less stiffness. With the open BackUp Structure (BUS) of the DVA1/2 the surface is exposed to wind directly from the rear. Plans to mitigate that risk with those designs included adding stiffeners to the back of the surface (not desirable as they might print through under operational loading) or shielding attached to the BUS. With the proposed ngVLA design the back side of the reflector is well shielded by the oBUS panels and so the back of the surface will not be exposed to direct wind and the buckling failure should not occur. Analysis to confirm this will be performed in the next phase.

7.5 Drives

7.5.1 Elevation Drive

A preliminary elevation drive design has been performed by Phase USA based on the mechanical configuration and loading scenarios provided by NRC, [RD04]. Loads, based on the NRC wind tunnel data scaled for the reflector size and wind speeds of the ngVLA, are shown in Table 16.

Table 16 Elevation Drive Loads

Max Elevation Drive Loads [kNm]			
Precision	Normal	Limit	Survival
0.7	1.3	10.5	65.7

The elevation drive design is a three-Phase, sinusoidal, double-airgap axial-field motor with:

- Distributed drives, embedded in motor sectors
- Dual gap section distributed on a 1.83m arc radius with 130mm stack, 2.8mm air gap per side
- Natural convection cooling
- Rotor consisting of 4 double sided segments
- Windings encapsulated under vacuum in thermal conductive epoxy resin
- Exposed surface is protected with a carbon fiber sheet applied during encapsulation

The initial drive sizing is performed based on the Limit condition (with a 20% oversizing margin) under which the antenna must be driven to the stow position where brakes and/or stow pins are deployed. The drive configuration is shown in Figure 22.

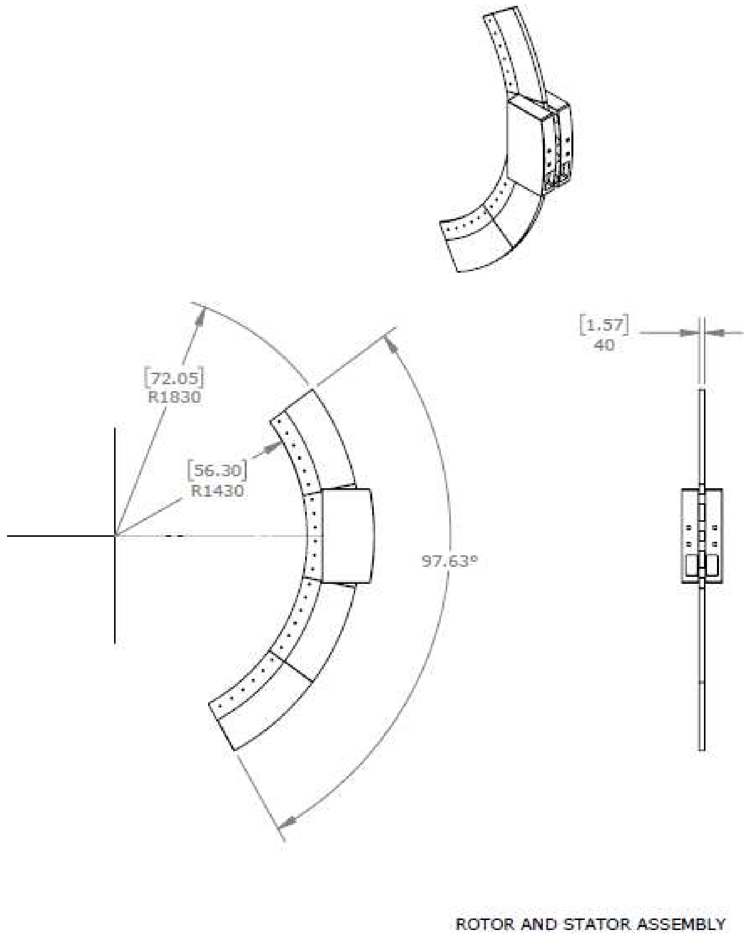


Figure 22 Elevation Drive Configuration

Table 17 Elevation Drive Performance Matrix

perf =

"Tracking , 10m/s"	"Tracking, 18 m/s"	" Survival, peak"	"Pointing, acc."	" WORKING POINT"
1240	6700	11800	6400	" Motor Torque (Nm)"
0.06	0.06	0.75	1	"Shaft Speed (deg/sec)"
4.86	4.86	62.5	83.33	" Speed Nominal % "
0	0.01	0.15	0.11	"Shaft Power (kW)"
0.64	3.24	5.67	3.1	"Tot. Motor Current (Arms)"
12.17	56.97	114.73	75.46	"Motor Voltage (Vrms)"
0	0	0	0	"Id Current (Arms)"
0.64	3.24	5.67	3.1	"Iq Current (Arms)"
1	1	0.99	0.99	"Motor Power Factor"
0	0	0	0	"Core Loss HiFreq (kW)"
0.09	0.09	1.2	1.61	"Core Loss fund.(W)"
0.09	0.09	1.21	1.61	"Tot stator core loss (W)"
0	0	0.01	0.01	"Rotor Loss HiFreq (W)"
12.03	312.59	958.27	285.61	"Copper loss (W)"
0	0	0	0	"Mechanical loss (W)"
12.12	312.69	959.48	287.23	"Overall Motor Loss (W)"
0.09	0.02	0.14	0.28	"Motor efficiency"
20.85	41.87	87.11	40.09	"Copper Temp (°C)"
20.84	41.72	86.65	39.95	"Core Temp (°C)"

The elevation drive performance matrix is shown in Table 17.

7.5.2 Azimuth Drive

A preliminary azimuth drive design has been performed by Phase USA based on the mechanical configuration and loading scenarios provided by NRC, [RD04]. Loads, based on the NRC wind tunnel data scaled for the reflector size and wind speeds of the ngVLA, are shown in Table 18.

Table 18 Azimuth Drive Loads

Max Azimuth Drive Loads [kNm]			
Precision	Normal	Limit	Survival
0.6	1.2	9.9	61.7

Two drive concepts are under consideration for the azimuth drive, Figure 23; direct drive (left) and direct pinion and gear drive (right).

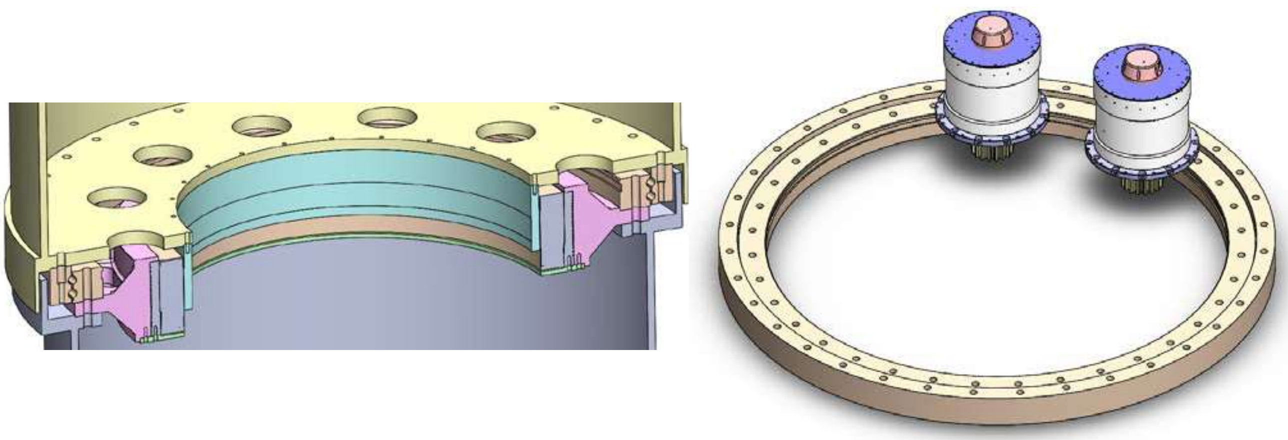


Figure 23 Azimuth Drive Options

7.5.2.1 Azimuth Direct Drive

The proposed Direct Drive Azimuth system is a Three-Phase, sinusoidal, Single Air Gap design, Figure 24 featuring;

- Distributed Drives, embedded in motor sectors or near by
- 1.34m diameter, 120mm stack, 4mm air gap
- Traditional Direct Drive Configuration
- Based on TK13440-120-1000

Figure 24 Example direct drive configuration

7.5.2.2 Azimuth Direct Pinion/Gear Drive

The direct pinion drive is similar to conventional gear and pinion azimuth drives except that the need for gearboxes is eliminated. Two motors (to remove backlash) mounted inside the yoke centre with pinions directly mounted to their output shafts, Figure 25, drive a ring gear that is integral with the azimuth bearing.

Figure 25 Example Direct Pinion Drive

The direct pinion/gear drive should offer a lower cost solution but may require more maintenance.

There are pros and cons to all configuration, at this time only very preliminary analysis has been performed. During the next phase a detailed trade study will be performed to determine the best solution from an overall cost/performance/operations perspective.

8 PRODUCTION LOGISTICS

Production of the proposed design would take place both on and off-site similar to that of the 18m, the details of which can be found in [RD05].

8.1 Primary Reflector Transport

As the 6m antennas are all located at the centre of the array core and near to the proposed production facility location, transport of the assembled primary reflector will be straight forward only requiring a standard flatbed trailer and a support fixture.

9 FUTURE WORK

9.1 Design and Analysis

Moving forward with the 6m design will require considerable effort in all aspects of the design due to the minimal effort applied thus far. Having said that much of the design will parallel that of the 18m and so it should be a matter of modelling and analysis with a minimal design iterations. Most of the future work outlined for the 18m in [AD03] will apply to the 6m. Particular aspects that differ from the 18m and will require more effort are listed here

9.1.1 iBUS Design

The proposed iBUS for the 6m is a plate steel structure as opposed to the structural steel space frame of the 18m. Design, analysis and optimization will be required for this component.

9.1.2 Feed/Secondary Support Structure

Due to the relative sizes of the primary and secondary reflectors the Feed/Secondary Support Structure will also differ significantly from that of the 18m and will require detailed analysis to ensure adequate performance and further design detailing for volume manufacture.

9.1.3 Mount Design

The mount used for the design presented here will need to be further optimized for the ngVLA 6m application.

9.1.4 Integrated FEA Model

An integrated FEA model will be developed to allow analysis of system level performance including;

- Pointing Analysis
- Aperture Efficiency Analysis
- Survivability

Front End Technical Requirements

020.30.03.01.00-0001-REQ-A-FRONT_END_TECH_REQS

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
W. Grammer	Electronics Div., NRAO	2018-07-23
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-07-23

APPROVALS	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer 2019.07.24 09:34:52 -06'00'	Electronics Division, NRAO	2019-07-24
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.28 15:22:48 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.28 15:23:03 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-07-13	W. Grammer	1–4	Initial draft version
02	2018-09-24	W. Grammer	All	Incorporate corrections from R. Selina, add additional content
03	2018-09-27	S. Durand	All	Small Edits
04	2018-10-17	W. Grammer, R. Selina	4.3, 4.4, 8.1	Added req #s in tables 4.41, 4.42; other minor edits.
05	2018-10-24	W. Grammer, R. Selina, J. Jackson	5.3, 6.5	Added gain slope and ripple requirements to tables, with explanation in text. Corrected M&C system module designations.
06	2018-10-25	W. Grammer, R. Selina	5.4	Added a new section on dynamic range requirements.
07	2018-11-02	W. Grammer	4.2, All	Deleted section on ngVLA project background, as directed. General cleanup and reformatting done.
08	2019-07-23	W. Grammer	All	Incorporated review comments and corrections. Added subsections on feed horns.
A	2019-07-24	A. Lear	All	Prepared document for approvals and release.

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
3 Overview of the Front End Technical Requirements 7
3.1 Document Outline 7
3.2 General Front End Description 7
3.3 Summary of Front End Requirements 7
3.3.1 General Functional Specifications 8
3.3.2 Other General Requirements 8
4 Front End Functional and Performance Requirements 9
4.1 RF Frequency Ranges 9
4.2 Sensitivity Requirements 9
4.3 Feed Horn Performance Requirements 9
4.4 Gain Requirements 10
4.5 Dynamic Range Requirements 10
4.6 Cryogenic Cooling Requirements 10
4.7 Spurious Signals/Radio Frequency Interference Generation 10
4.8 Environmental Conditions 11
4.8.1 Normal Operating Conditions 11
4.8.2 Specific Environmental Requirements 11
4.9 Maintenance and Reliability Requirements 11
4.10 Monitor and Control Requirements 12
4.11 Lifecycle Requirements 12
5 Interface Requirements 13
5.1 Interface to the Power Supply Subsystem 13
5.2 Interface to the Cryogenic Subsystem 13
5.3 Interface to the Integrated Receivers and Downconverters (IRD) Subsystem 14
5.4 Interface to the Antenna Subsystem 14
5.5 Interface to the Monitor and Control Subsystem 15
6 Subsystem Requirements 16
7 Safety 16
7.1 General 16
7.2 Safety Design Requirements 16
7.2.1 Fire Safety 16
7.2.2 Vacuum Safety 16
7.2.3 Mechanical Safety 16
7.2.4 Electrical Safety 16
7.2.5 Handling, Transport, and Storage Safety 16
8 Requirements for Design 17
8.1 Analyses and Design Requirements 17
8.1.1 Reliability Availability Maintainability Analysis 17
8.2 Electromagnetic Compatibility Requirements 17

8.3 Materials, Parts, and Processes ... 17
8.3.1 Fasteners ... 17
8.3.2 Paints ... 17
8.3.3 Surface Treatment ... 17
8.3.4 Name Plates and Product Marking ... 17
8.3.5 Labels ... 18
9 Documentation Requirements ... 18
9.1 Technical Documentation ... 18
9.2 Software and Software Documentation ... 18
10 Verification and Quality Assurance ... 19
11 Key Performance Parameters ... 20
11.1 Maintenance Definitions ... 20
11.1.1 Maintenance Approach ... 20
11.1.2 Periodic Preventive Maintenance ... 20
12 Appendix ... 21
12.1 Abbreviations and Acronyms ... 21
12.2 MTBF Estimation for ngVLA Front End ... 22

1 Introduction

1.1 Purpose

This document aims to present a set of preliminary technical requirements for the initial design of the ngVLA Front End subsystem.

Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn are derived from the preliminary ngVLA Science Requirements [AD01].

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

1.2 Scope

The scope of this document is the ngVLA Front End work package. This consists of the cryogenically cooled receiver assemblies and their associated support electronics, mounted on the ngVLA antenna. It includes interface requirements that must be defined in detail.

It should be noted that the physical extent of the Front End work package extends into other subsystems in some cases: one example is that it includes the displacer cylinder from the cryocooler as part of the cryostat assembly, but not the displacer and motor subassemblies. Other examples of this are detailed later in this document.

This requirements document establishes the performance, functional, design, and test requirements applicable to the ngVLA Front End work package.

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 this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Environmental Specifications	020.10.15.10.00-0001-SPE
AD04	Operations Concept	020.10.05.00.00-0002-PLA
AD05	Protection Against Electric Shock – Common Aspects for Installation and Equipment	IEC 61140:2016
AD06	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD07	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
AD08	Military Handbook, Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
AD09	Non-Electronic Parts Reliability Data	NPRD-95
AD10	Electromagnetic Compatibility	IEC 61000-3-5
AD11	Subsystem Reference Design Description for Monitor & Control Hardware Interface Layer	020.30.45.00.00-0004-DSN
AD12	DC Power Supply Reference Design Description	020.30.50.00.00-0002-DSN
AD13	EMC & RFI Mitigation Requirements	020.10.15.10.00-0002-REQ

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	Front End Reference Design Description	020.30.05.00.00-0003-DSN
RD02	D. Gajewski et. al., “Reliability of GaN/AlGaN HEMT MMIC Technology on 100-mm 4H-SiC”, 26th Annual JEDEC ROCS Workshop, Indian Wells, CA, May 2011	
RD03	“Multiple Uses of Model 22C/350C Cryodyne Refrigerators: Installation, Operation and Servicing Instuctions”, Helix Technology Corporation, July 2002, page G-3	Doc. # 8040272, Rev. 100 Dwg. # 3695576, Rev. C
RD04	L. Baker, “Analysis of ngVLA Design #6 with Ideal and Actual Feed”, 8 January 2018	020.25.01.00.00-0001-REP

3 Overview of the Front End Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA Front End work package. These parameters determine the overall form and performance of the Front End work package.

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 Front End 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 Front End 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, 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 General Front End Description

The ngVLA will provide near-continuous frequency coverage from 1.2–116 GHz in multiple bands, with a gap at the atmospheric absorption band between ~50–70 GHz. The primary design goals are maximizing sensitivity for each band while also minimizing the overall operating cost. Therefore, receivers and feeds will be cryogenically cooled, with multiple bands integrated into a common cryostat to the greatest extent possible. Using feed designs that yield broad bandwidths and high aperture efficiencies are key to meeting these goals.

The proposed receiver configuration [RD01] will be implemented as six independent bands, each with its own feed. The upper five bands will be integrated into a single compact cryostat, while the lowest-frequency band occupies a second cryostat of similar volume and mass. Components within the cryostats are cryogenically cooled for optimum noise performance.

3.3 Summary of Front End Requirements

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

3.3.1 General Functional Specifications

Parameter	Req. #	Summary of Requirement	Traceability
Frequency Coverage	FE0001	1.2–116 GHz continuous, with a gap between 50.5–70 GHz	SYS0801
Frequency Band Overlap	FE0002	1% minimum, at band edges	SYS0806
Output Polarization Type	FE0003	Dual orthogonal	SYS0102
Number of Pixels/Receiver Band	FE0004	One	(TBD)
Number of Receiver Bands	FE0005	Maximum of 6	(TBD)
Number of Cryostats/Cryocoolers	FE0006	Maximum of 2	(TBD)

3.3.2 Other General Requirements

Parameter		Summary of Requirement	Traceability
Mass, Cryostat A	FE0007	74 kg max., including cryocooler	(TBD)
Mass, Cryostat B	FE0008	89 kg max., including cryocooler	(TBD)
Total Mass (Service Limit)	FE0009	163 kg, max.	(TBD)

4 Front End Functional and Performance Requirements

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

4.1 RF Frequency Ranges

The specified frequency range is the minimum over which the sensitivity and gain requirements defined for that band are met. Bandpass shape and precisely defined band edges are not critical for the Front End; bands may overlap.

Parameter	Req. #	Value	Traceability
Band 1 Frequency Range	FE0101	1.2–3.5 GHz	IRD0711
Band 2 Frequency Range	FE0102	3.5–12.3 GHz	SYS0801–0806
Band 3 Frequency Range	FE0103	12.3–20.5 GHz	SYS0801–0806
Band 4 Frequency Range	FE0104	20.5–34 GHz	SYS0801–0806
Band 5 Frequency Range	FE0105	30.5–50.5 GHz	SYS0801–0806
Band 6 Frequency Range	FE0106	70–116 GHz	SYS0801–0806

4.2 Sensitivity Requirements

Receiver noise temperatures shall be measured using the Y-factor method, taken at the frequency intervals specified in the table for each band. The average given is an overall unweighted average of all values, across the full band. Maximum limit is typically at the band edges, over a single interval.

Parameter	Req. #	Value	Traceability
Band 1 Noise Temperatures	FE0201	10.9 K average, 13.8 K maximum, 25 MHz meas. interval	SYS1011
Band 2 Noise Temperatures	FE0202	14.2 K, average, 15.5 K maximum, 100 MHz meas. interval	SYS1011–1012
Band 3 Noise Temperatures	FE0203	15.8 K, average, 18.6 K maximum 100 MHz meas. interval	SYS1012
Band 4 Noise Temperatures	FE0204	16.6 K, average, 19.5 K maximum 100 MHz meas. interval	SYS1012
Band 5 Noise Temperatures	FE0205	22.4 K, average, 26.5 K maximum 200 MHz meas. interval	SYS1012
Band 6 Noise Temperatures	FE0206	52.4 K, average, 72.6 K maximum 500 MHz meas. interval	SYS1013

4.3 Feed Horn Performance Requirements

Feed horn specifications are derived from electromagnetic and physical optics simulations. For calculation of overall aperture efficiency, the antenna optics are included in the simulation [RD04]. The Band 1 and 2 feeds are wideband ridged types, while the Band 3–6 feeds are axially corrugated types.

Parameter	Req. #	Value	Traceability
Beam Subtended Angle, Bands 1–6	FE0301	55 degrees, nom., @ –16 dB edge taper, all planes	ANT0204
Band 1–2 Aperture Efficiency	FE0311	0.80 avg. total, excluding Ruze (surface)	(TBD)
Band 1–2 Side Lobe Levels	FE0312	–20 dB max., all planes	(TBD)

Parameter	Req. #	Value	Traceability
Band 1–2 Cross Polarization	FE0313	–20 dB max., all planes	(TBD)
Band 1–2 Return Loss	FE0314	–15 dB max.	(TBD)
Band 3–6 Aperture Efficiency	FE0321	0.85 avg. total, excluding Ruze (surface)	(TBD)
Band 3–6 Side Lobe Levels	FE0322	–30 dB max., all planes	(TBD)
Band 3–6 Cross Polarization	FE0323	–30 dB max., all planes	(TBD)
Band 3–6 Return Loss	FE0324	–20 dB max.	(TBD)

4.4 Gain Requirements

The minimum Front End gain requirement stems from a need to reduce noise contributions from subsequent signal amplification and down-conversion stages to <1K of total system noise temperature.

Gain is specified as between the input of the feed horn and the output connector on the cryostat bulkhead. The gain ripple and slope requirements are derived from the system-level requirement of 3 dB for each. The system requirement includes contributions from both the Front End and IRD subsystems, but no budget for sharing this allowance across them has been established.

Tentatively, therefore, 20% of the overall budget (0.6 dB) has been allocated to the Front End. The remaining 80% (2.4 dB) is allocated to the IRD subsystem, given it has twice as much analog gain and several added lossy signal-conditioning components in its cascade.

Parameter	Req. #	Value	Traceability
Gain, Bands 1–6	FE0401	30 dB, minimum	SYS1011–1013
Gain Stability, Bands 1–6	FE0402	Maximum change < 0.01 dB, over 1 hour	SYS1701, SYS4901–4902
Gain Ripple, Bands 1–6	FE0403	<0.6 dB peak-to-peak (TBC)	SYS1702
Gain Slope, Bands 1–6	FE0404	<0.6 dB, over 80% BW (TBC)	SYS1703

4.5 Dynamic Range Requirements

Parameter	Req. #	Value	Traceability
Input Dynamic Range	FE0501	30 dB min., 50 dB goal	SYS1201
Gain Calibrator Dynamic Range	FE0502	30 dB	SYS1202
Input Power Damage Threshold	FE0503	+10 dBm, avg. (TBC)	SYS1204

4.6 Cryogenic Cooling Requirements

Parameter	Req. #	Value	Traceability
Cryostat A 1st Stage Loading	FE0601	20W max., 80 K stage temp	
Cryostat A 2st Stage Loading	FE0602	5W max., 20 K stage temp	
Cryostat B 1st Stage Loading	FE0611	20W max., 80 K stage temp	
Cryostat B 2nd Stage Loading	FE0612	5W max., 20 K stage temp	

4.7 Spurious Signals/Radio Frequency Interference Generation

The Front End subsystem shall conform to the system EMC and RFI requirements outlined in [AD13].

4.8 Environmental Conditions

4.8.1 Normal Operating Conditions

Parameter	Req. #	Value	Traceability
Temperature (outside)	FE0801	–15 C ≤ T ≤ +35 C	ENV0323
Temperature Rate of Change	FE0802	< 3.6 °C per hour	ENV0324
Altitude	FE0803	Max. 2500 meters	ENV0351

4.8.2 Specific Environmental Requirements

Except for the exposed radome/vacuum window on Cryostat A, the Front End subsystem components will be located entirely within a weather-tight enclosure with temperature regulation. Other than the requirements below, details about this enclosure are beyond the scope of this document.

Parameter	Req. #	Value	Traceability
Temperature (inside)	FE0811	+20 C ≤ T ≤ +30 C	
Temperature Rate of Change	FE0812	< 1 °C per hour	

4.9 Maintenance and Reliability Requirements

The maintenance and reliability requirements support high-level requirements that limit the array's total operating cost. For the antenna electronics system as a whole, approximately half of the MTBF budget for the antenna itself (~17,500 hrs.) is assumed.

The dominant maintenance driver for the antenna electronics is likely to be the cryocooler, as on the VLA. It is estimated to have an MTBF of ~six years, assuming a continuous, average running speed of 40 Hz. Given there will be two basically identical cryocoolers per antenna, the net MTBF is therefore three years, which is actually less than what is currently specified for the entire antenna electronic system. However, the actual MTBF in practice will depend on how often the cryocoolers are exchanged during scheduled periodic maintenance. If this is less than three years, the effective MTBF will be longer. This in turn will determine what fraction of the overall antenna electronic system MTBF can be allocated for the Front End and other antenna electronic subsystems.

The intrinsic reliability of the Front End is difficult to estimate due to a lack of reliability data for the cryogenic LNAs under controlled conditions. Life tests of comparable MMIC technology [RD02] indicate the MTBF should be well into the tens of millions of hours. Given the low power and low temperatures inherent in our receivers, intrinsic device reliability would likely be even higher. However, overall LNA reliability will be drastically reduced due to the temperature cycling they are subject to, when a cryocooler needs to be exchanged, or due to a power failure or vacuum loss that causes a warmup. The failure mechanism here is mechanical, usually a broken or loosened bond wire to the MMIC chip. Reliability is again hard to predict, but from the observed failure rate of VLA LNAs, and accounting for a ~3.5-fold reduction in the number of bonds for an equivalent MMIC, the MTBF of the ngVLA Front End with 14 MMIC LNAs works out to roughly 100,000 hours. See the Appendix for details of this analysis.

Monitor points or 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.

"Failure" will be defined as a condition that places the system outside of its performance specifications or into an unsafe state, requiring repair.

Parameter	Req. #	Value	Traceability
Antenna Electronics MTBF	(TBD)	≥35,000 hrs. (4 years)	SYS2402
Front End Subsystem MTBF	FE0901	≥100,000 hrs. (~12 years)	

4.10 Monitor and Control Requirements

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

Other features of the M&C interface are to be specified in the Monitor and Control ICD.

Parameter	Req. #	Value	Traceability
Self-Monitoring	FE1001	The Front End 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

4.11 Lifecycle Requirements

Lifecycle costs include manufacturing, transportation, construction/assembly, operation and decommissioning.

Parameter	Req. #	Value	Traceability
Design Life	FE1101	The Front End shall be designed to be operated and supported for a period of 20 years.	SYS2801
Lifecycle Optimization	FE1102	The Front End design shall minimize its lifecycle cost for 20 years of operation.	SYS2802

5 Interface Requirements

This section describes Front End interfaces. Interface Control Documents (ICDs) are required between the Front End and all connecting systems. In many cases, specifications for the interfaces are not yet available, but the broad scope of the ICDs can be defined.

These interfaces shall be developed and documented by the Front End Designer and approved by ngVLA as part of the Front End reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Power Supply Subsystem

The Power Supply Subsystem provides DC voltages required by the Front End electronics, packaged in modules F512 and F522 [AD05]. Voltages and currents supplied are: +32.5V @0.5A, +17.5V @6A, +7.5V @0.5A, and –7.5V @0.1A, from the P501 power supply module [AD12].

The electromechanical interface details are presently undefined. However, it will likely consist of a single multi-pin round, twist-lock, or threaded connector interface, like those widely used by the US military (e.g., MIL-DTL-26482, MIL-DTL-38999, MIL-DTL-22992). These are highly rugged, weather-tight, and reliable, with a multitude of pin sizes and counts available at moderate cost. Location is likely to be on the rear panel of the F521 and F522 electronics modules.

5.2 Interface to the Cryogenic Subsystem

The cryocooler unit consists of two parts: a drive motor/valve/displacer assembly, and a polished steel cylinder that slides over the displacers. The cylinder is the mechanical interface for both cold stages, and is an integral part of the cryostat assembly. The displacer assembly is external to the cryostat and removable, and is considered part of the cryogenic subsystem. The interface between these parts is an interface plate or flange pattern that allows a gas-tight seal and properly aligns the two parts. Figure 1 presents a mechanical drawing of this interface pattern [RD03].

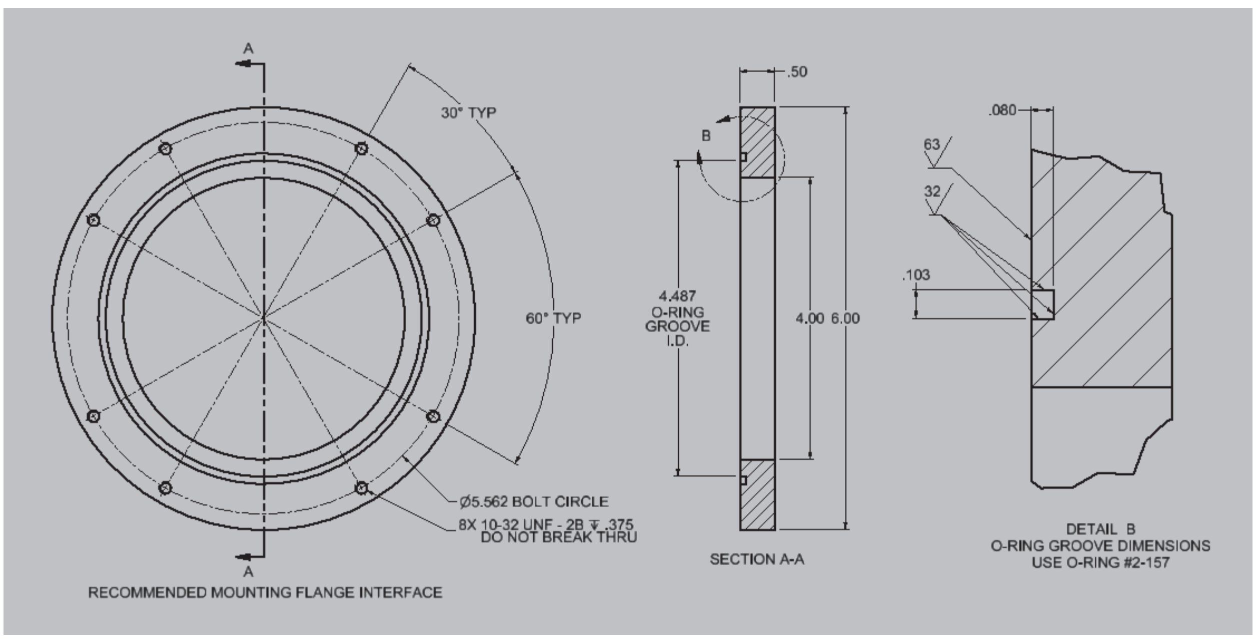


Figure 1 - Cryocooler displacer mechanical interface.

5.3 Interface to the Integrated Receivers and Downconverters (IRD) Subsystem

The IRD subsystem module will be mounted in close proximity to Cryostat B to keep the RF interconnects to it as short as possible. It might even be feasible to bolt them directly together, using blind-mate connectors instead of cables/waveguides, but this will be decided later on. Longer armored cables will be used to connect the Band 1RF outputs of the Cryostat A to the IRD module.

The table below shows the type and number of RF interconnects with the Front End subsystem. The physical locations and outlines of the connectors are still TBD.

Signal at Interface	Type	Parameter	Value
Band 1 RF	Output	Connector	SMA (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 2 RF	Output	Connector	SMA (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 3 RF	Output	Connector	2.92 mm (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 4 RF	Output	Connector	2.92 mm (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 5 RF	Output	Waveguide size	WR-22 (UG599)
		Number	2 (one per pol.)
Band 6 RF	Output	Waveguide size	WR-10 (UG387)
		Number	2 (one per pol.)

5.4 Interface to the Antenna Subsystem

A dual offset-Gregorian optical configuration for the antenna is assumed. The key interface specification is the subtended angle of the subreflector at the secondary focal point, which drives the design of all feed horns, and the physical size of the cryostats as well.

The Front End cryostat assemblies will be mounted at the secondary focus of the antenna, on a platform attached to the feed arm structure. The platform will include an X-Y axis motorized positioner for focusing and band selection and the temperature-controlled enclosure.

Figure 2 shows a rendering of the mounting concept, which will be the same for both the 18-meter and 6-meter antennas. Detailed mechanical interface drawings are pending completion of the antenna design.

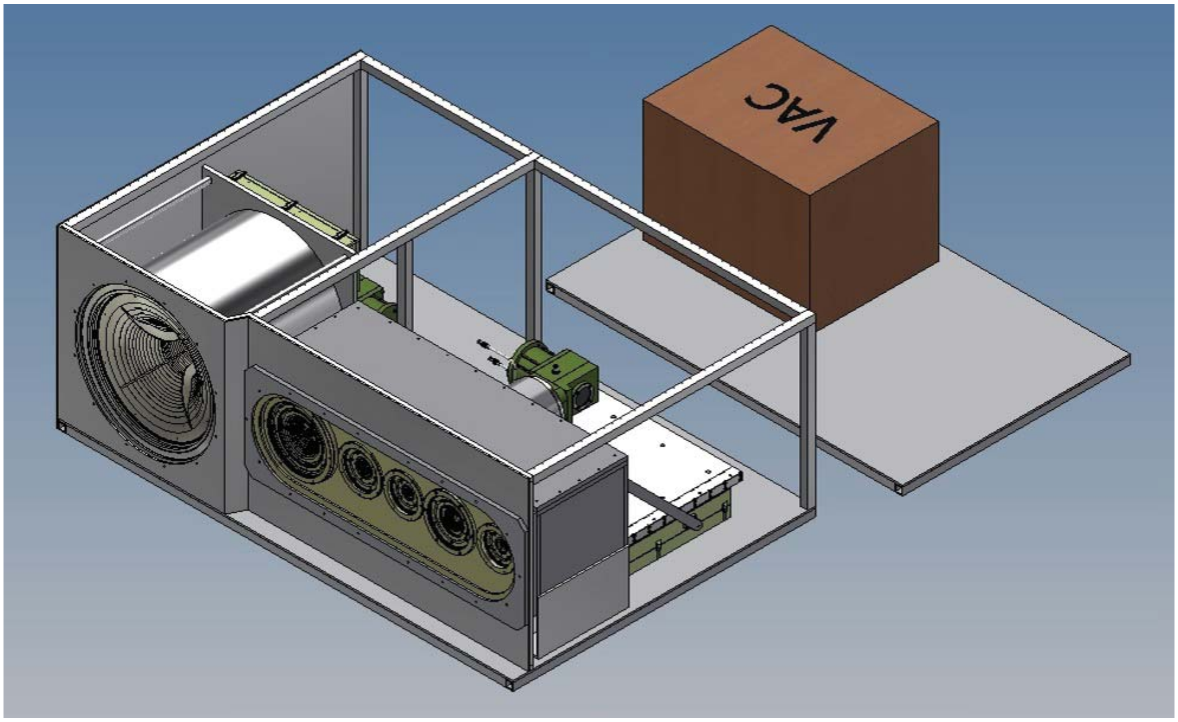


Figure 2 - Front End subsystem enclosure, opened to show cryostats and IRD assembly.

Parameter	Req. #	Value	Traceability
Feed Subtended Half Angle	FE0301	55° between the optical axis and edge of the subreflector, at the secondary focus	ANT0204

5.5 Interface to the Monitor and Control Subsystem

The two Front End cryostat assemblies presently contain only RF electronics. All the analog support electronics for Cryostats A and B are packaged within two external modules, referred to as F521A and F521B, respectively. These will be located inside the platform enclosure on the antenna feed arm, in close proximity to the cryostats. The support electronics provide the following functions:

- DC bias/driver circuitry for LNAs, noise calibrator sources, and other active components,
- RF output control/leveling for the noise calibrator sources,
- Input signal conditioning from the cryostat vacuum and temperature sensors, and
- Driver circuitry and current monitoring for the cryostat vacuum solenoid valve.

Electrical connection to the cryostats is assumed to be via multi-conductor shielded cables, with a bulkhead receptacle/cable plug pair at each end. Specific details are undefined at present; however, these will likely consist of single, multi-pin round, twist-locking connector interfaces, with a hermetic glass seal for contacts on the cryostat receptacle side, to maintain vacuum integrity.

It may be feasible, and even desirable, to integrate some or all of the support electronics into their respective cryostats, but for now are they are assumed to be separate assemblies.

The Cryo and LNA Monitor and Control (M&C) module (designated F520) contains the MIB, or Monitor and Control Interface Board, which provides the communications link to the monitor and control subsystem. The F522 is similar to the F521A/B but also provides control electronics for the vacuum pump common to both cryostats [AD11].

6 Subsystem Requirements

Derivation of any subsystem requirements shall be included as part of the Front End reference and conceptual design efforts and updated throughout the design. Post CDR/FDR, the subsystem requirements shall only be updated through formal project change control processes, which will include the designer, manufacturer, and NRAO.

7 Safety

7.1 General

In general, the Front End subsystem is fairly benign from a safety standpoint, posing a low risk of injury to personnel or damage to other equipment.

7.2 Safety Design Requirements

7.2.1 Fire Safety

There are no combustibles, flammable liquids or gases in the Front End subsystem.

7.2.2 Vacuum Safety

Because the cryostats will usually be under vacuum while in storage or transport, there is a potential implosion hazard if one of the large cryostat windows or radomes is breached. The chance of this is low, and will be minimized by proper design, and handling protocols during shipment or installation.

7.2.3 Mechanical Safety

There are no external exposed moving parts, or known pinch points that could cause injury.

7.2.4 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard. 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 [AD06] while taking into account the altitude of up to 2500 m above sea level.

7.2.5 Handling, Transport, and Storage Safety

The design of the Front End shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation. These cryostat radomes and windows are fairly robust, but nevertheless must be protected from any impact or abrasion, to minimize the chance of breakage and possible injury to personnel from flying debris.

Moderate care must be exercised when removing or installing the Front End cryostat assemblies, as they are heavy, and can be damaged if dropped more than a few centimeters. A lifting device or small hoist is recommended for installation and removal of the cryostats. As needed, lift points shall be designed into the equipment, and clearly labeled.

8 Requirements for Design

8.1 Analyses and Design Requirements

8.1.1 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. To this end, the Parts Count Method for predicting reliability of the system can be applied, as described in the MIL-HDBK-217F [AD08], but the designer may propose to use other methods. For non-electronic parts, the values of NPRD-95 [AD09] or data from manufacturers or other databases may be used.

Another, more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in [AD08]. This may be used if the result of the Parts Count Method does not comply with the Maintenance and Reliability requirements.

The ngVLA equipment will typically 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 [AD08]. The analysis shall result in estimates of the Mean Time Between Failures (MTBF), the Mean Time To Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

8.2 Electromagnetic Compatibility Requirements

The ngVLA Front End element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).

8.3 Materials, Parts, and Processes

8.3.1 Fasteners

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

8.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

8.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

8.3.4 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 the like may be used upon approval by ngVLA.

For Line Replaceable Units (LRUs), it is highly desirable that the serial number of the unit be ascertainable over the monitor and control interface.

8.3.5 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled.

9 Documentation Requirements

9.1 Technical Documentation

All documentation related to the Front End 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 CAD system used is AutoDesk Inventor and/or AutoCAD.

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

9.2 Software and Software Documentation

The Front End 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 on-line, 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, or 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.

The following table summarizes the expected verification method for each requirement.

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
FE0101-0106	Frequency Range, Bands 1–6				X	
FE0201-0206	Noise Temperatures, Bands 1–6				X	
FE0311, 0321	Overall Aperture Efficiency	X	X			
FE0312-0313 FE0322-0323	Feed Horn Radiation Pattern	X	X			
FE0314,0324	Feed Horn Return Loss				X	
FE0401	Gain, Bands 1–6				X	
FE0402	Gain Stability, Bands 1–6				X	
FE0601-0612	Cryocooler Thermal Loading	X	X			
FE0901	Front End Subsystem MTBF	X	X			
FE1101	Design Life	X				

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 are parameters that 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 discussed in the narrative in Section 4.

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 Front End (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 the table below. 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.
Receiver Noise Temperature	FE0201-0206
Overall Aperture Efficiency	FE0311, 0321
Feed Horn Performance (side lobes, cross polarization, return loss)	FE0312-0314 FE0322-0324
Cryostat Masses	FE0007-0009
Cryocooler Thermal Loading	FE0601-0612
Mean Time Between Failures	FE0901

11.1 Maintenance Definitions

11.1.1 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 two trained people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the Front End. A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

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

11.1.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals to keep the Front End operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CAD	Computer Aided Design
CDR	Critical Design Review
CoDR	Conceptual Design Review
EMC	Electro-Magnetic Compatibility
FAT	Factory Acceptance Test
FDR	Final Design Review
ICD	Interface Control Document
IRD	Integrated Receiver Downconverter/Digitizer
KPP	Key Performance Parameters
LNA	Low Noise Amplifier
LRU	Line Replaceable Unit
MIB	Monitor/Control Interface Board
MMIC	Monolithic Microwave Integrated Circuit
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
M&C, M/C	Monitor and Control
ngVLA	Next Generation VLA
RD	Reference Document
RFI	Radio Frequency Interference
SAT	Site Acceptance Test
TBD	To Be Determined
VLA	Jansky Very Large Array

12.2 MTBF Estimation for ngVLA Front End

1. EVLA LNA Failure Rate, from March 2013 to September 2018 (5.5 years)

Year	# repairs*
2013	10
2014	6
2015	17
2016	6
2017	10
2018	5
TOTAL:	**54**

* Excludes LED failures, upgrades

Active Antennas:	**27**
Cryo LNAs per antenna:	**16**
Total LNAs:	**432**
Duration (yrs):	**5.5**
Duration (hrs):	**48,213**

Failure Rate (/hr-LNA):	**2.593E-06**
MTBF (hrs):	**3.857E+05**

2. Predicted ngVLA MMIC LNA MTBF (1 antenna):

Failure reduction factor:	**3.6**	(relative wire bond count)
MMIC LNAs per antenna:	**14**	(2 ea, Bands 1–5; 4 on Band 6)

Failure Rate (/hr-Ant):	**1.008E-05**
MTBF (hr-Ant):	**9.918E+04**

Front End Reference Design Description

020.30.03.00.00-0002-DSN-A-FRONT_END_REF_DESIGN

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
W. Grammer	Electronics Div., NRAO	2019-05-21
S. Durand, Antenna Electronics IPT Lead	Antenna Electronics	2019-04-01

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.24 16:22:59 -06'00'	Electronics Div., NRAO	2019-07-24
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 16:51:42 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 16:51:58 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
1	2018-07-13	W. Grammer	All	Initial draft
2	2018-07-13	D. Urbain	6.3	Location of IR filter was corrected
3	2018-07-20	W. Grammer	6.1, Appendix A and B	Updated T_{LNA}, T_{RX} values for updated cascade analysis.
4	2018-08-27	W. Grammer	All	Update performance tables and plots, insert block diagram, add content for interfaces, and other minor changes.
5	2018-09-11	W. Grammer	5.1, 6.4, Table 2	Updated SEFD numbers and text to reflect increase in array to 263 antennas. Completed the interface section. Modified document number for consistency with present product tree.
6	2018-09-28	S. Durand, W. Grammer	All	Small edits and formatting changes.
7	2018-10-10	W. Grammer	All	Corrected the document number on title page, headers.
8	2018-10-17	W. Grammer R. Selina	5.2	Minor wording changes.
9	2018-10-24	W. Grammer R. Selina J. Jackson	Table 2, Figs. 6-7, 6.4.5	Added 1K contribution from IRD to Tsys. Corrected M&C module references.
10	2018-10-30	W. Grammer R. Selina	Fig. 9	Added calibrator path components to Front End subsystem block diagram.
11	2018-11-02	W. Grammer	All	Small edits and formatting changes.
12	2019-03-15	W. Grammer	All	Updated content from ASU, JPL, and EMSS; many formatting changes.
13	2019-03-29	W. Grammer	4.2, 6.2	Remove sentence about funding; removed TBD reference in item #11.
14	2019-05-21	W. Grammer	All	Small corrections, formatting changes.
A	2019-07-24	A. Lear	All	Prepare PDF for approvals & release.

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 4
3 Subsystem Overview 6
4 Background and Concept Evolution 6
4.1 General Design Constraints 6
4.2 Wideband Receiver/Feed Concepts 7
4.2.1 Caltech Prototype Receiver 8
4.2.2 JPL Prototype Receiver 8
4.3 The "Baseline" Design Concept 8
4.4 Toward a Reference Design 12
5 Reference Design Description 14
5.1 Configuration Description and Performance 14
5.2 Front End Subsystem Block Diagram 20
5.3 Front End Packaging Concept 20
5.4 Front End Interfaces to Other Subsystems 22
5.4.1 Interface to the Cryogenic Subsystem 22
5.4.2 Interface to the Integrated Receivers and Downconverters (IRD) Subsystem 22
5.4.3 Interface to the Antenna Subsystem 23
5.4.4 Interface to the Monitor and Control Subsystem 24
5.4.5 Interface to the Power Supply Subsystem 24
6 Appendix 25
6.1 Abbreviations and Acronyms 25
6.2 Caltech 4-Band Front End Concept 26
6.3 NASA/JPL Ultra-Wideband Receiver (8-48 GHz) 30
6.4 ngVLA Reference Front End Receiver Cascade, LNA Noise Tables 32

1 Introduction

1.1 Purpose

This document provides a description for the Front End subsystem reference design. It covers the design approach, functions, key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

This document covers the entire design of the Front End subsystem as part of the ngVLA Reference Design. It includes the subsystem design, how it functions, and its interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev./Doc. No.
AD01	Front End Technical Requirements	020.30.03.01.00-0001-REQ
AD02	System Reference Design	020.10.20.00.00-0001-REP
AD03	Cryogenic Subsystem Reference Design Description	020.30.10.00.00-0002-DSN
AD04	Integrated Downconverters & Digitizers Design Description	020.30.15.00.00-0002-DSN
AD05	Subsystem Reference Design Description for Monitor and Control Hardware Interface Layer	020.30.45.00.00-0004-DSN
AD06	DC Power Supply Reference Design Description	020.30.50.00.00-0002-DSN

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev/Doc. No.
RD01	C. Langley & K. Baker (NRAO), Private Communication	N/A
RD02	L. D'Addario, "Advanced Cryocoolers For Next Generation VLA," ngVLA Memo No. 24, 2017-09-19	http://library.nrao.edu/public/memos/ngvla/NGVLA_24.pdf
RD03	S. Weinreb, "Future of the VLA and Other Topics," NRAO Socorro Colloquium, 2014-09-26	N/A
RD04	S. Weinreb, "Receiver Overview," ngVLA Technical Workshop, Pasadena CA, 2015-04-09	https://safe.nrao.edu/wiki/pub/NGVLA/TechnicalWorkingGroup/WeinrebReceiverOverviewApr9_2015.pdf
RD05	S. Weinreb, A. Soliman, & H. Mani, "Single Cryocooler 1.2 to 116 GHz Receiver for ngVLA," Kavli II Workshop, Baltimore MD, 2016-08-3–5	N/A

RD06	S. Weinreb & H. Mani, "Low Cost 1.2 to 116 GHz Receiver System: A Benchmark for ngVLA," ngVLA Science Meeting, Socorro NM, 2017-06-26–29	https://science.nrao.edu/science/meetings/2017/ngvla-science-program/presentations/monday/WeinrebManiJun24Receiver.pdf
RD07	H. Mani, "Wideband Receiver Prototype for ngVLA: Development Report," NRAO Socorro Colloquium, 2019-01-25	N/A
RD08	J. Velazco et al., "Development of an Ultra-Wideband Receiver Package for the Next Generation Very Large Array," IEEE Aerosp. Conf., Big Sky MT, 2019-03-07	N/A
RD09	J. Shi et al., "Quadruple-Ridged Flared Horn Operating from 8 to 50 GHz," *IEEE Trans. Antennas Propag.*, 2017-10-06	https://ieeexplore.ieee.org/document/8060581
RD10	M. Pospieszalski, "Low Noise InP HFET Receivers," ngVLA Technical Workshop, Pasadena CA, 2015-04-08–9	https://safe.nrao.edu/wiki/pub/NGVLA/TechnicalWorkingGroup/PospiesLNAApr9_2015.pdf
RD11	A. Akgiray, PhD Thesis, Caltech, 2013	https://thesis.library.caltech.edu/7644/1/Akgiray_PhDThesis_FinalVersion.pdf
RD12	C. Granet et al., "A Wide-Band 4–12.25 GHz Feed System for the Australia Telescope 22m Diameter Antenna," 2016	Private communication; publish date is still TBD
RD13	D. Hoppe & E. Long, "Technology Development for the North America Array: Feed Update," 2016-05-06	Private communication; internal NASA/JPL presentation
RD14	L. Baker & B. Veidt, "DVA-1 Performance with an Octave Horn from CST & GRASP Simulations," 2014	Private communication; unpublished internal memo
RD15	L. Baker, "Analysis of ngVLA Design #6 With Ideal and Actual Feed," 2018-01-08	020.25.01.00.00-0001-REP
RD16	S. Weinreb et al., "Cryogenic 1.2 to 116 GHz Receiver for Large Arrays," EuCAP, London UK, 2018-04-12.	N/A
RD17	L. Locke et al., "Q-band single pixel receiver development for the ngVLA and NRC," *Proc. SPIE*, Vol. 10708, 2018-11-14	http://library.nrao.edu/public/memos/ngvla/NGVLA_32.pdf
RD18	L. Locke (NRC), Private Communication	N/A
RD19	R. Lehmensiek, "Final Report: ngVLA Project PO No. 362812," EMSS Antennas (Pty) Ltd, 2019-02-07	EMSS Doc#: EA-NGV-DR-01 Rev. 1
RD20	D. deVilliers & R. Lehmensiek, "SKA Reflector and Feed Design," Caltech ngVLA Optics Workshop, 2018-06-19	N/A
RD21	B. Butler (NRAO), Private Communication	N/A
RD22	R. Selina, "System-Level Cost Comparison of Offset and Symmetric Optics," ngVLA Antenna Memo No. 1, 2019-04-26	http://library.nrao.edu/public/memos/ngvla/NGVLA_24.pdf
RD23	L. Locke & S. Srikanth, (title TBD), NRAO, 2019	Internal memo in preparation

3 Subsystem Overview

The basic purpose of the ngVLA Front End subsystem is the reception and amplification of incoming signals from astronomical sources collected by the antenna optics, over a broad frequency range. Given the extremely low input levels, very high gain is required, with the lowest possible added instrumental noise for maximum sensitivity. The receivers must also have a good temporal gain and phase stability, and high linearity. Weight is an important concern given that the antenna optics places the Front End package on a movable platform within the feed arm, rather than at a fixed location under the main reflector as on the VLA antennas.

The ngVLA science goals require continuous frequency coverage from 1.2–116 GHz in multiple receiver bands, with a gap at the atmospheric absorption band between ~50–70 GHz. Maximizing overall sensitivity in each receiver band, while minimizing the total operating cost are the primary design goals. Therefore, receivers will be cryogenically cooled, with multiple bands integrated into a common cryostat where feasible. Use of feed horn designs that have broad bandwidth and high aperture efficiency are also key to meeting these goals. Compact feed designs are also preferred, as they can be integrated into the receiver cryostat and cooled, further reducing the system noise.

Section 4 describes evolution of the concept, but it can be skipped without loss of continuity, if desired.

4 Background and Concept Evolution

The ngVLA Front End concept went through a considerable amount of evolution over several years, including a period where there were three different concepts under development by separate organizations. However, as the science requirements, technical specifications, and costing for the ngVLA were all taking shape over the same period, alternative design concepts were a natural and expected part of the process.

4.1 General Design Constraints

One key factor that drove the Front End system design from the start was the need to reduce overall operating cost, particularly in the cryogenic system. The ngVLA as currently envisioned will have 263 antennas, more than nine times that of the current array, but with an operations budget constrained to just three times that of the VLA and VLBA. It was immediately apparent that a system with separately cooled receiver bands and multiple helium compressors on each antenna (as implemented on the VLA and VLBA) would be inordinately expensive to build, operate and maintain, if directly scaled for the ngVLA. To attain the desired reduction in overall cost, the following design guidelines or constraints were gradually recognized:

- **Maximize the fractional bandwidth of individual bands to the extent possible to reduce the total band count.** This is critical for bands at the low end of the frequency range: for example, an octave of bandwidth at the low end is 1.2 GHz, compared to 58 GHz at the high end. Low-frequency receivers (and feeds) also tend to be large and heavy, so reducing their number is critical to controlling the total cost and mass of the Front End package. However, the trade-off with wider bandwidth is degraded performance of the LNA and feed horn; i.e., a higher receiver noise temperature (T_{RX}) and a lower aperture efficiency (η_A). Taken too far, the additional antennas needed to offset this loss in sensitivity would effectively negate any cost savings with fewer bands.
- **Minimize the number of cryocoolers and cryostats required per antenna.** This is accomplished by packaging multiple receiver bands into a common cryostat. Benefits are a reduction

in the total cryogenic load, and improvement of overall reliability by having fewer displacers, motors and seals to wear out or fail. While relatively easy to accomplish for the compact high-frequency bands, it becomes less practical at lower frequencies, where the size of the feed horn equals or exceeds the associated receiver package. With large high-gain feeds like those in the VLA antennas, receiver consolidation is not practical, with the possible exception of the Q- and Ka-bands. Conversely, low-gain feeds are advantageous in this regard given that they are much smaller than high-gain feeds, provided their RF performance is acceptable. This will obviously influence the optical and mechanical design of the antenna as well.

- **Use a single helium compressor per antenna.** The VLA has three helium compressors per antenna (81 total, running continuously). Together, they consume 57% of the total electrical power supplied to the VLA antennas, or 46% if the VLA correlator is also included [RD01]. They also require frequent maintenance. Going to a single, larger compressor designed for longer life and lower maintenance will result in significant savings, even if the overall helium flow requirement is the same. One downside is the compressor becomes a single point of failure for the antenna: this risk could be mitigated with a dual-redundant compressor configuration. However, given the large number of antennas, loss of a single antenna has less of an impact than in the VLA, so the extra cost may not be justified.
- **Improve the overall efficiency and reliability of the cryogenic system.** The VLA cryogenic system gets the job done, but its design is more than 40 years old. A modern system using variable-speed scroll-type compressors, cryocoolers with variable-speed drives, and intelligent control will yield much higher overall efficiency than the fixed-speed systems of the VLA. Advanced cryocooler designs (Stirling, pulse-tube) are also more efficient and reliable than the traditional Gifford-McMahon (G-M) type [RD02], and will be considered for the ngVLA if they are cost effective and can handle the cooling requirements.

The broader objective is to obtain the optimum array sensitivity while remaining within the overall array construction and operating cost constraints. Low system temperatures are obviously important, driven largely by the Front End electronics, but the other major factor is the aperture efficiency for the antenna/feed combination. A complex interdependence drives the choice of antenna optics, feed type, and the number of individual receiver cryostats required.

For example, a symmetric Cassegrain antenna like that of the VLA or VLBA permits using traditional high-gain corrugated feed horns with near-optimum beam characteristics, for high illumination efficiency. On the other hand, blockage and scattering losses can be quite significant, especially for the smaller primary aperture sizes favored by ngVLA, requiring more antennas to recover the lost collecting area. This has a cost penalty [RD22]. An unblocked design like a dual offset Gregorian antenna will have higher efficiency, though this comes with a higher construction cost and a requirement for compact feeds (possibly with lower illumination efficiency) lightweight enough to be moved onto the focal point.

4.2 Wideband Receiver/Feed Concepts

Discussions on possible receiver/feed configurations for a next-generation VLA began in late 2014, shortly after an invited talk at NRAO in Socorro given by Dr. Sander ("Sandy") Weinreb of Caltech [RD03]. His initial concept used an ultra-wideband (UWB) Quad-Ridge Feed Horn (QRFH) and Low-Noise Amplifier (LNA) to cover a 10–100 GHz frequency range with a single receiver. By the first ngVLA technical workshop in April 2015, this initial concept had evolved into a design with two separate 7:1 bandwidth QRFHs covering 1.2–8.4 GHz and 8–55 GHz, and a conventional corrugated feed with waveguide output for the 70–116 GHz band [RD04]. Coverage between 55–70 GHz is unnecessary because of the high atmospheric attenuation in this band.

By early 2016, funded projects at Caltech and at NASA/JPL were ongoing, with the objective to design and prototype wideband receivers. Both were largely concluded in 2018, and are described below.

4.2.1 Caltech Prototype Receiver

Sandy Weinreb led a team of graduate students at Caltech to design and build a prototype ngVLA receiver with their own LNA and QRFH technology. The primary aim was to cover the full 1.2–116 GHz in a single cryostat that was relatively compact and low in cost.

Initially it was a three-band system (1.2–7.2/8–48/70–116 GHz) using a pair of 6:1 bandwidth QRFHs. In July 2016, the concept was revised to a four-band configuration with re-optimized 3.5:1 bandwidth QRFHs [RD05]. By mid-2017 the QRFH profile had been re-optimized for better overall illumination efficiency, but at the expense of higher spillover noise [RD06].

Detailed performance estimates for the Caltech four-band concept and QRFH are given in Section 6.2, along with renderings and photos of the cryostat concept. Construction of a demonstration cryostat including a Band 1 receiver was recently completed, and was cooled successfully to below 100K and 20K, on the QRFH and LNAs respectively [RD07]. Measurement of the receiver noise temperature is pending.

4.2.2 JPL Prototype Receiver

Melissa Soriano and Jose Velazco led a team of engineers at JPL, to design and prototype an 8–48 GHz UWB receiver under a three-year NASA grant. This ambitious project consisted of three parallel efforts:

- Design, fabrication and testing of an 8–48 GHz cryogenic MMIC LNA. This built on earlier work at Caltech, using foundries at OMMIC and NGC.
- Design and optimization of a dielectric-loaded QRFH, in collaboration with Caltech. The goal was improved and flatter efficiency over frequency, with minimal added loss.
- Design, fabrication and testing of a prototype 8–48 GHz receiver cryostat, incorporating the new LNA and QRFH designs.

Noise and gain measurements of the redesigned LNAs and completed receiver are given in Section 6.3, along with a rendering and photo of the receiver cryostat [RD08]. The redesigned OMMIC LNA (Figure 18) had a T_N ~20K from about 4 to 30 GHz, but rose steadily to ~50K by 48 GHz. However the NGC LNA (Figure 19) achieved a nearly flat 20K to 47 GHz, with gain > 20 dB. Overall, the receiver achieved an average T_{RX} of ~30K, and less than 40K across the band (Figure 21).

Development of the dielectric-loaded feed was deferred in favor of an all-metal type based on a Caltech design [RD09], but fabricated at JPL.

4.3 The "Baseline" Design Concept

From almost the beginning, much discussion and debate focused on Caltech's wideband LNA and feed performance relative to those used in the VLA and GBT. In these instruments, the "cryo3" InP LNAs designed and built at the NRAO CDL perform near their theoretical noise limit, over about a waveguide (~1.66:1) fractional bandwidth. Beyond that, the noise performance can be optimized only over a portion of the band (typically the high end) but will suffer at the low end, by a factor of two or more relative to narrow-band LNAs [RD10].

Similarly, the average illumination efficiency (η_I) of a low-gain QRFH with 6:1 bandwidth is only around 60% [RD11], quite a bit lower than a conventional waveguide-bandwidth corrugated feed horn (~82%). Both these factors contribute to a significant loss in antenna sensitivity for spectral line detection. For continuum detection, the large instantaneous bandwidth of an UWB receiver will yield a ~90% relative *gain* in sensitivity, somewhat offsetting the performance penalty from the UWB LNA and QRFH. Nevertheless, it seemed clear the overall negative impact on telescope sensitivity could be substantial.

On the other hand, it was recognized that wideband receivers would likely be required to cover the lowest decade of bandwidth (~1–10 GHz), in order to stay within the operating cost cap for ngVLA. While a single QRFH-based design like that proposed in [RD03] is theoretically possible, a pair of receivers with ~3:1 bandwidth would have far better overall performance. By comparison, at least four receivers with octave and/or waveguide bandwidth are necessary, as implemented in the VLA: this approach was deemed a non-starter for the ngVLA, due to its cost. *Therefore, it was taken that fractional bandwidths > 3:1 would be required in the receiver bands below ~10 GHz, with a reasonable performance degradation accepted as a necessary compromise*. Whether this approach could be extended to higher frequencies was still debated.

To help quantify the performance tradeoffs with the wideband configurations described in the previous section, a so-called “Baseline” configuration was formulated as a basis for comparison. An initial 4-band configuration was proposed by Srikanth at NRAO in early 2016, with two low frequency bands added soon after. The approach was deliberately conservative: only existing LNA, feed horn, and receiver technologies with known performance would be included.

On the receiver bands above ~10 GHz, fractional bandwidth was limited to 1.67:1 for optimum LNA performance in low-loss, all-waveguide receivers, and the use of traditional corrugated feed horns. Below 10 GHz, the bandwidth restriction was relaxed to ~3:1 to reduce to two the number of receivers required for coverage down to 1.2 GHz. Broadband, smooth-wall conical feed horns coupled to matching quad-ridge OMTs were proposed for use on these bands, like those described in [RD12]. A small opening angle (~15°) was prescribed for all the feeds in the Baseline configuration to remain within their design limits.

Table 1 shows a summary of the Baseline configuration definition and estimated performance numbers (aperture efficiency, system temperature, etc.). The assumptions made were:

- Unblocked primary aperture (i.e. dual offset Gregorian or Cassegrain optics)
- No antenna shaping; all reflectors are pure conics
- Secondary mirror electrically large at 1.2 GHz, for negligible diffraction losses
- Surface accuracy of **160 μm** RMS, primary and secondary combined
- Sky temperature (T_{SKY}) based on a PWV of **6 mm**, with an elevation angle of **45** degrees

Band #	Dewar #	f_L GHz	f_M GHz	f_H GHz	$f_H:f_L$	BW GHZ	Feed Horn Properties			OMT	Aperture Eff., η_A			Spillover, K		
							Temp	L, mm	D, mm		@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	A	**1.2**	**2.1**	**3.6**	3.00	2.4	300	2711	1127	QR	0.62	0.72	0.78	3	3	3
2	B	**3.6**	**6.2**	**10.8**	3.00	7.2	300	904	376	QR	0.62	0.72	0.78	3	3	3
3	C	**11**	**14.1**	**18**	1.64	7	300	410	241	WG	0.74	0.74	0.74	3	3	3
4	C	**18**	**23.2**	**30**	1.67	12	300	251	147	WG	0.74	0.73	0.72	3	3	3
5	C	**30**	**38.7**	**50**	1.67	20	20	150	88.4	WG	0.72	0.70	0.67	3	3	3
6	C	**70**	**90**	**116**	1.66	46	20	64.4	37.9	WG	0.56	0.49	0.38	3	3	3

Band #	Dewar #	T_{LNA}, K			T_{RX}, K			T_{SKY}, K			T_{SYS}, K			(T_{SYS}/η_A), K		
		@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H	@ f_L	@ f_M	@ f_H
1	A	2.5	2.8	5.2	8	6	9	4.4	4.5	4.6	**15**	**14**	**17**	**25**	**19**	**21**
2	B	8	6.5	7.5	12	10	12	4.6	4.7	5.1	**20**	**18**	**20**	**32**	**25**	**26**
3	C	5	6	7	10	11	12	5.1	5.7	7.8	**18**	**20**	**23**	**24**	**27**	**31**
4	C	7	8	10	12	14	18	7.8	20.9	11.1	**23**	**38**	**32**	**31**	**52**	**45**
5	C	10	12	14	18	22	28	11.1	16.3	62.5	**32**	**41**	**94**	**45**	**59**	**140**
6	C	29	26	40	39	41	60	75	27	123	**117**	**71**	**186**	**207**	**146**	**484**

Table 1 - Parameters and performance estimates for baseline receiver/feed configuration.

To allow a fair performance comparison of all three configurations, corresponding estimates were compiled for the wideband and UWB cases, with the same assumptions for the antenna optics and sky temperature as above. The different opening angles of the Baseline and wideband/UWB feeds are not a factor, as they only affect the design of the optics. Given the overall sensitivity of the antenna is proportional to its aperture efficiency η_A, and inversely proportional to system temperature T_{SYS}, the quantity (T_{SYS}/η_A) was defined as the metric for comparison, with lower values implying greater sensitivity over a fixed (narrow) bandwidth.

Figure 1 shows a comparison plot of (T_{SYS}/η_A) over frequency between the Baseline configuration (in green) and two wideband configurations described earlier, for all but the highest band (essentially the same receiver in all three). The UWB configuration assumes a Caltech-designed QRFH with Teflon dielectric rod loading; estimated aperture efficiency is taken from [RD13]. Looking at the curves, the following observations can be drawn:

1. The Baseline case has significantly better sensitivity at virtually all frequencies, especially against the UWB case. This is primarily due to the much better overall aperture efficiency of its feed horns. The wideband configuration fares a little better, particularly between 4–10 GHz: the QRFH is cooled to 20K on this band, giving it a slight advantage.
2. The 3:1 conical feed suffers from a large drop in aperture efficiency at the lower band edge, compared to the other feed types. It is also sitting at ambient (~300K), which will contribute an extra 1–2K over a cooled QRFH.
3. The step change between band boundaries in the wideband/UWB curves are indicative of their less-than-optimal LNA noise temperature at the lower band edge, an effect mentioned earlier in this section. It is particularly noticeable at 15 GHz, the Band 2–3 transition for the wideband configuration.

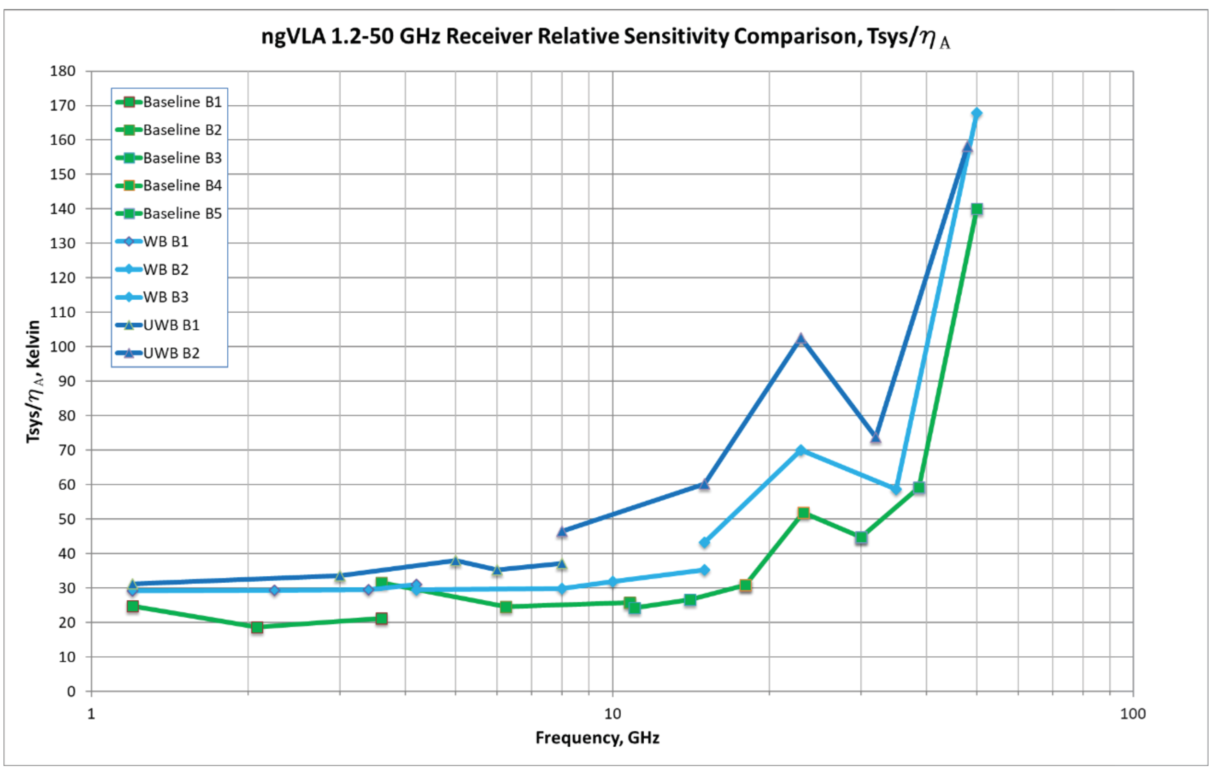


Figure 1 - Relative sensitivity of baseline, wideband, and UWB receiver configurations.

One serious downside of the Baseline configuration are the feed sizes, particularly on Band 1, which is ***very*** large: over 2.7 meters in length and 1.1 meters in diameter at the aperture. This is a direct consequence of the small opening angle required with these types of feeds. The large feeds on Bands 1–4 were impractical to cool and hence are external to the receivers, like those on the VLA. Another consequence of the feed size was the need for three separate cryostats (Band 1, Band 2, and Bands 3–6). This obviously will have a negative cost impact on both construction and operations compared to the single-cryostat wideband configurations.

To visualize all this, Figure 2 shows how the Baseline feeds and cryostats might be arranged for band selection on a rotating platform, as on a dual-offset antenna. The EVLA L-band and C-band receivers are used to represent the approximate size of the Band 1 and 2 Baseline receivers, and are both roughly a meter in length. Clearly, the size and mass of the Band 1 package likely exceeds all the others combined, and could make it impractical for anything other than a static location, as on the VLA or VLBA antennas.

In summary, the Baseline configuration offered much better overall sensitivity than either wideband configuration, achieving the same total effective collecting area with fewer antennas. However, frequency coverage below 4 GHz in a dual-offset antenna would likely not be feasible, given the size of the feed. The wide opening angle of the Caltech QRFH offered a distinct advantage in this regard, but had relatively poor efficiency compared to the corrugated feed.

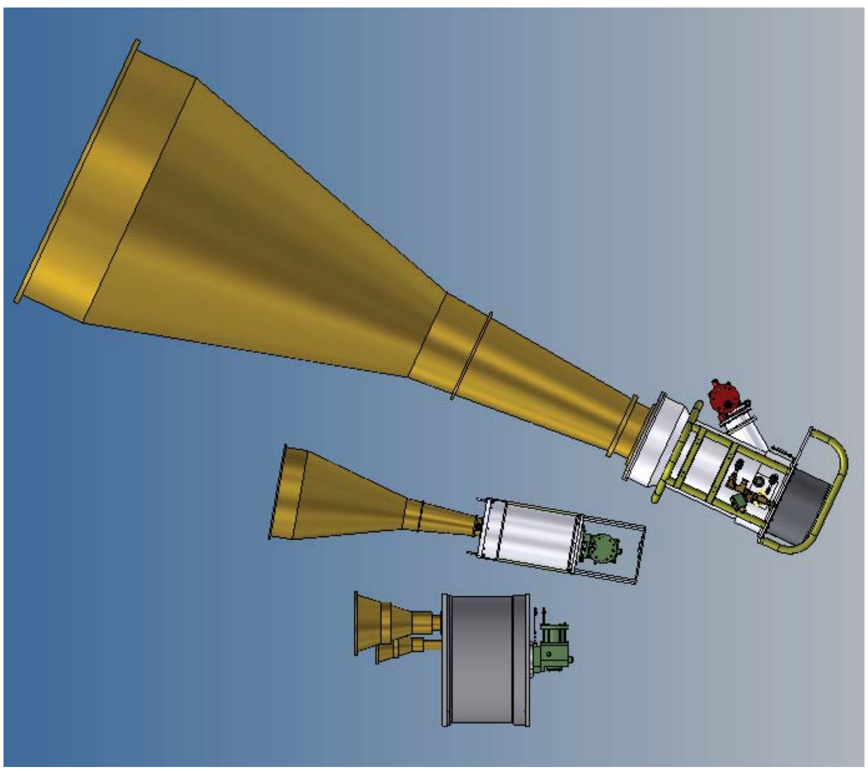


Figure 2 - Baseline cryostats and feeds, aligned for rotation.

4.4 Toward a Reference Design

At the start of 2017, there were basically two somewhat viable Front End configurations, neither of which was entirely satisfactory, and they were unable to coexist on the same antenna because of incompatible opening angles. However, in the absence of well-defined science cases to drive technical requirements, it was still unclear whether low frequency coverage was really a priority, or if it was acceptable to give up some sensitivity in exchange for added frequency coverage or receiver bandwidth.

The situation changed after the ngVLA Science Meeting in June 2017, where concrete science cases were agreed upon and priorities set. From these, the following became clear:

- Maximizing sensitivity was a priority for most of the science cases. This implies receivers with optimum low noise, feeds with uniformly high aperture efficiency, and shaped antenna optics.
- Frequency coverage down to L-band became a firm requirement, though sensitivity for this band could be less than optimum, if necessary.

Given the mandate for L-band coverage, the choices seemed to be:

- Revert to a VLA-style symmetric Cassegrain antenna that could accommodate the large low-frequency feeds of the Baseline configuration, accepting the unavoidable blockage and scattering losses, or
- Adopt the wideband configuration, accept the hit to sensitivity at high frequencies as unavoidable, and hope for future performance improvements in the QRFH.

Fortunately, a possible solution to the feed conundrum had been proposed a few months earlier by Lynn Baker at Cornell University. While under contract by NRC in Canada a few years earlier, he and German Cortes had designed an octave-band corrugated feed horn with a wide (55°) opening angle for use on the Canadian SKA prototype antenna, DVA-1. Unlike the traditional type, the corrugations on the DVA-1 feed were radially concentric and oriented along the axial direction. Performance results shown in a report [RD14] indicated it had excellent match, acceptably low cross-polarization, and good aperture efficiency, relatively flat over frequency. Figure 3 shows a graphic of the feed horn, along with a plot of the DVA-1 aperture efficiency over normalized frequency.

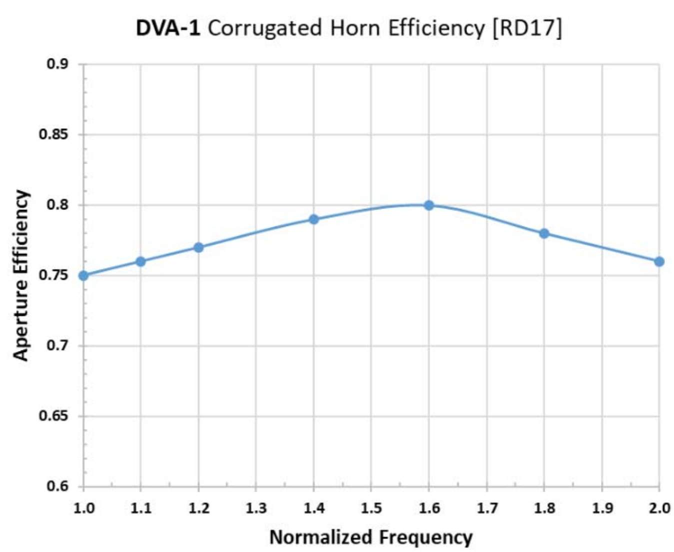


Figure 3 - DVA-1 corrugated feed horn, 3D rendering and aperture efficiency.

Compared to the QRFH, the axially corrugated DVA-1 feed has slightly higher overall aperture efficiency and a flatter response, but over a narrower (2:1) bandwidth. It is also highly compact compared to the

Baseline's corrugated feeds, though not as small as the QRFH with an equivalent opening angle. While the aperture efficiency is not quite as high as a traditional corrugated horn, it is a viable alternative on Bands 3–6 of the Baseline configuration, and small enough when scaled to be integrated into the cryostat. A more recent analysis by Baker [RD15] has confirmed the loss in overall efficiency over an ideal Gaussian feed for an ngVLA antenna at 5 GHz is only about 2%. The backlobe and spillover are also very low, compared to the QRFH.

Best of all, the similar opening angles for the axially corrugated feed horn and QRFH allow them to coexist on the same antenna or be mixed within a cryostat. The QRFH is well-suited for the bands below about 10 GHz, as it is highly compact, transitions directly to coax (no polarizer needed), and covers the wide bandwidths needed in this range to reduce cost and weight. The axially corrugated feed is preferred above 10 GHz, with its compact size, uniformly high aperture efficiency, low spillover and waveguide output. It is also relatively simple to fabricate, making it suitable for mass production.

Selecting these two feeds was a key decision in moving toward the final reference design. Other changes were made but were relatively minor and are described in the next section.

5 Reference Design Description

The term "reference design" in the context of the ngVLA refers to a technically viable design concept that can meet the subsystem requirements with low attendant risks, and is sufficiently detailed and mature to permit accurate costing. While the level of detail is still short of an actual preliminary design, progression to that stage would be technically straightforward, with minimal development required, and yielding the expected performance.

5.1 Configuration Description and Performance

The proposed ngVLA reference Front End configuration is implemented as six independent receiver bands, each with its own feed. The upper five bands will be integrated into a single, moderately sized cryostat (B), while the lowest (Band 1) occupies a second cryostat (A) of comparable volume and mass. All feeds are sufficiently compact to be cryogenically cooled, reducing losses ahead of the low-noise amplifiers (LNAs). Due to its size, the Band 1 feed will be cooled to 80 K, while all other feeds are cooled to 20 K. A variable-speed Gifford-McMahon cryocooler with ~5W of cooling capacity on the 20K stage (equivalent to a CTI Model 350) is used on each cryostat.

Table 2 shows the reference Front End band frequencies, approximate feed dimensions, and estimated performance data (aperture efficiency, noise temperatures) at three frequencies: midband, lower, and upper band edge. Frequency coverage is continuous except for the expected break in the atmospheric absorption band at ~50–70 GHz. The frequency overlap at the boundary between Bands 4 and 5 was deliberate: it allows observations at ~30 GHz with higher sensitivity, away from a band boundary. Output polarization on all receivers is linear, rather than circular as on the VLA: this simplified the receiver design, reducing receiver noise and allowing greater fractional bandwidth for the all-waveguide receivers on Bands 3–6.

For continuous coverage between 1.2–12.6 GHz, waveguide or even octave-bandwidth receivers are not cost-effective, given the ~10:1 frequency range. On Bands 1 and 2, wideband (up to 3.5:1) receivers mated to a Quad-Ridge Feed Horn (QRFH) are proposed. The QRFH is a very broadband feed, which can be designed for large opening angles (45–60°), making it highly compact even at low frequencies [RD11]. It has dual coaxial outputs for both orthogonal linear polarizations, eliminating the need for a separate polarizer or OMT, with additional savings in space and cost. Aperture efficiency, spillover and loss are less than optimum with this feed, and LNA performance will be somewhat compromised over the lower part of the band [RD10]. However, significant cost savings are realized by effectively halving the number of receivers and cryostats required per antenna.

Band #	Dewar #	f_L GHz	f_M GHz	f_H GHz	$f_H:f_L$	BW GHz	Feed Horn Properties Temp	ϑ, deg	L, mm	D, mm	OMT	Pol. Out
1	A	**1.2**	**2.0**	**3.5**	2.92	2.3	80	58.0	330.2	360.0	QR	Lin.
2	B	**3.5**	**6.6**	**12.3**	3.51	8.8	20	58.0	113.2	123.4	QR	Lin.
3	B	**12.3**	**15.9**	**20.5**	1.67	8.2	20	55.0	28.90	53.00	WG	Lin.
4	B	**20.5**	**26.4**	**34**	1.66	13.5	20	55.0	17.34	31.80	WG	Lin.
5	B	**30.5**	**39.2**	**50.5**	1.66	20	20	55.0	11.65	21.37	WG	Lin.
6	B	**70**	**90**	**116**	1.66	46	20	55.0	5.078	9.313	WG	Lin.

Band #	Dewar #	Aperture Eff., η_A @ f_L	@ f_M	@ f_H	Spillover, K @ f_L	@ f_M	@ f_H	T_{LNA}, K @ f_L	@ f_M	@ f_H	T_{RX}, K @ f_L	@ f_M	@ f_H
1	A	0.80	0.79	0.74	12.8	10.1	4.0	2.6	2.8	5	9.9	10.3	13.8
2	B	0.80	0.78	0.76	12.8	7.0	3.9	6.7	7.2	5	13.4	15.4	14.4
3	B	0.84	0.87	0.86	4.1	4.1	4.1	5	8	8.7	13.9	16.9	18.6
4	B	0.83	0.86	0.83	4.1	4.1	4.1	5.7	6	7.8	15.4	16.2	19.5
5	B	0.81	0.82	0.78	4.1	4.1	4.1	7.8	8.4	14.1	19.1	20.4	26.5
6	B	0.68	0.61	0.48	4.1	4.1	4.1	25	26	42	50.6	49	72.6

Band #	Dewar #	T_{SKY}, K @ f_L	@ f_M	@ f_H	**T_{SYS}, K** @ f_L	@ f_M	@ f_H	**(T_{SYS}/η_A), K** @ f_L	@ f_M	@ f_H	**Array SEFD, Jy** @ f_L	@ f_M	@ f_H
1	A	4.4	4.5	4.6	**28.1**	**25.9**	**23.4**	**35**	**33**	**32**	**1.55**	**1.44**	**1.39**
2	B	4.6	4.7	5.3	**31.8**	**28.1**	**24.6**	**40**	**36**	**32**	**1.75**	**1.59**	**1.42**
3	B	5.3	6.3	13.6	**24.3**	**28.3**	**37.3**	**29**	**32**	**43**	**1.27**	**1.43**	**1.91**
4	B	13.6	12.1	12.4	**34.1**	**33.4**	**37.0**	**41**	**39**	**44**	**1.80**	**1.72**	**1.95**
5	B	11.1	16.9	70.3	**35**	**42**	**102**	**43**	**51**	**130**	**1.91**	**2.27**	**5.73**
6	B	68.3	15.4	112.3	**124**	**69**	**190**	**182**	**113**	**396**	**8.02**	**4.99**	**17.45**

Table 2 - Performance estimates, 6-band reference design configuration.

Explanatory Notes for Table 2:

I. Sensitivity (SEFD) calculation is for an array of 244 x 18-meter and 19 x 6-meter diameter antennas. The optical performance of both antenna types is assumed identical.
   1. The aperture efficiency is for the feed with the antenna, and assumes an unblocked primary aperture, an offset feed (low) Gregorian design, a secondary (subreflector) of 3.5m aperture, shaped optics, and a ground shield for spillover noise reduction.
   2. Antenna surface (Ruze) efficiency is included in the aperture efficiencies shown. Surface accuracy assumed is for precision conditions (160 µm RMS, uniformly distributed).
   3. Estimates for sky temperature (TSKY) were provided by B. Butler (NRAO), modeling opacity at VLA site. An elevation angle of 45 degrees was assumed for all bands. The precipitable water vapor (PWV) was assumed to be 6 mm for Bands 1–5, and 1 mm for Band 6.
   4. Outputs on all bands are linearly-polarized.
   5. Band 1 feed is cooled to ~80K. Band 2–6 feeds are cooled to ~20K.

6. Opening angle (θ) is defined here as the angle subtended between the central optical axis and the edge of the subreflector, at the secondary focus of the antenna.
7. Bands 1–2 use a wideband (~3.5:1) QRFH, designed for an opening angle of 58 degrees. The most recent version uses a revised spline feed profile on the QRFH to maximize overall aperture efficiency over the band (H. Mani and W. Zhong, 2017).
8. Bands 3–6 use axially-corrugated feeds, directly scaled from a design by G. Cortes and L. Baker for the NRC DVA-1 antenna [RD14]. Feed opening angle is 55°.
9. Band 6 LNA and receiver noise temperature estimates shown are courtesy of D. Cuadrado (U. of Manchester) and S. Weinreb.
10. For Bands 1–2, the illumination efficiency component assumes the mapping (shape) function used on the SKA antenna; analysis with the ngVLA antenna shaping is TBD.
11. For Bands 3–6, a high-efficiency mapping function for the ngVLA reference optical design was used; illumination efficiency and spillover noise are taken from [RD15].
12. Bands 1–2 TRX includes contributions from: radome/window, IR filter(s), feed, cal coupler, LNA and coax cables.
13. Bands 3–6 TRX includes contributions from radome, window, IR filter, feed, OMT, cal coupler, LNA and waveguides.
14. The TSYS for all bands includes an extra 1 K noise contribution from the IRD subsystem.
15. A detailed breakdown of the cascaded TRX for each band is shown in Section 6.3.
16. LNA noise values are taken from the table at the end of Section 6.3.

Figure 4 shows a photo of a QRFH for Band 1, fabricated by Caltech/ASU in February 2018 for installation into their test cryostat. The feed was machined from aluminum, then gold plated to lower the infrared emissivity for reduced loading on the cold stage. A ruler next to feed gives an idea of scale, though it is still remarkably small for an L-band horn. Next to the photo is the measured input return loss on both ports, which is >10 dB from 1.2 to 5 GHz, and in close agreement with the modeled results [RD16].

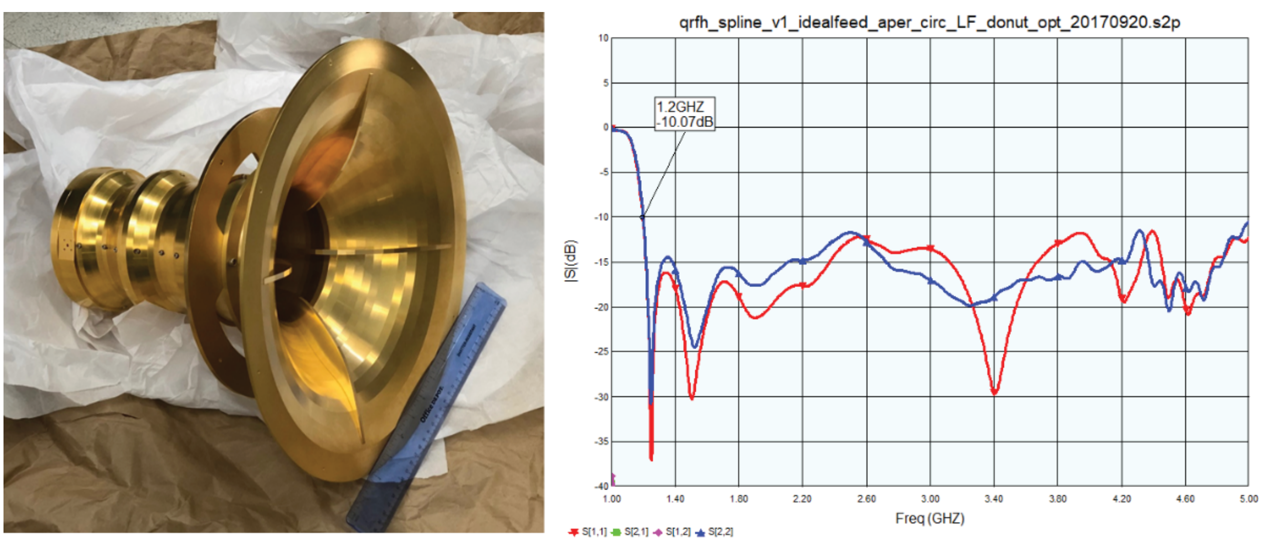


Figure 4 - Band 1 quad-ridge feed horn prototype (photos courtesy S. Weinreb).

For optimum performance at the higher frequencies, waveguide-bandwidth (~1.66:1) receivers are proposed to cover 12.3–50.5 GHz and 70–116 GHz, in four separate bands (3–6). Excellent low-noise amplifier (LNA) performance is readily achievable, and use of waveguide in the signal path up to the LNA input minimizes the loss and its associated noise contribution, without adding undue size or weight. An axially corrugated conical feed horn with a wide opening angle (~55° subtended beam, from center to edge of the subreflector) has been selected as the reference feed design for these receivers. Based directly on a design by Cortes and Baker [RD14] for the Canadian DVA-1 antenna, it yields aperture efficiency and cross-polarization performance comparable to a traditional corrugated horn but in a compact size.

Figure 5 shows a photo of this same feed design, scaled to Q-band (35-50 GHz) as a test piece for a future ngVLA Band 5 receiver [RD17]. Note that the feed is actually smaller than the mating waveguide flange to the OMT. Despite its size, conventional machining was sufficiently accurate for fabrication. Also included is a plot of the simulated and measured return loss, which shows excellent input match over the specified frequency range [RD18].

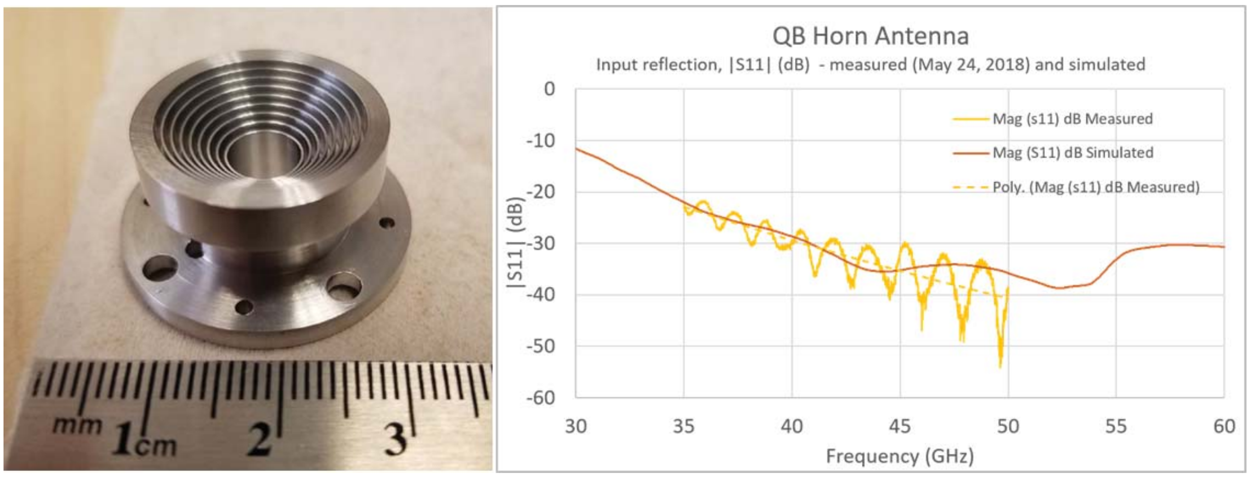


Figure 5 - Prototype Q-band axially corrugated feed horn.

Scaling this feed a factor of two smaller for W-band (70–116 GHz) seemed a daunting prospect, given the very small feature sizes and high depth/width (aspect) of the corrugation ring spacings. Therefore, a study was contracted to a consulting firm, EMSS, who had experience with a similar feed design from the SKA project. EMSS performed a detailed analysis on sensitivity of electromagnetic performance to dimensional variations in the corrugations, and did trial machining and precision metrology of test pieces from various metals and alloys [RD19]. Their conclusion was that a wide-angle corrugated horn is feasible at W-band, and is manufacturable by conventional subtractive machining. As a further confirmation, the NRAO CDL successfully machined the Baker corrugated feed design scaled to W-band, for actual RF testing. Both W-band feeds are shown in Figure 6 below. Pattern measurement and RF testing of the feeds were conducted at the Green Bank Observatory, and the results appear to show good agreement with simulations [RD23].

Figure 6 - Prototype W-band axially corrugated feed horns (left - Baker, right - EMSS).

The relative sensitivity metric (T_{SYS}/η_A) for ngVLA Reference Bands 1–5 is plotted against the eight VLA receivers in Figure 7. Data from Caltech's optimized wideband configuration (WB) in Section 6.2 is also included in the plot for comparison. Lower numbers indicate greater sensitivity per unit of collecting area. For the VLA antenna, the high spillover and drop in efficiency are very evident at L-band on the VLA antenna, due to tradeoffs made in the feed design; above Ku-band, the steady drop in surface (Ruze) efficiency is evident.

The Reference and WB configurations for Bands 1 and 2 track closely, not surprising as they use the same feed and antenna optics. Improvement here is possible by using direct noise cal injection into the QRFH [RD20], and revising the feed illumination efficiency for the ngVLA mapping function. At Ku-band and above, the Reference configuration outperforms both the VLA and WB configuration by a wide margin.

In the VLA case, the surface is the main reason, while for the WB case it is the combination of high LNA and spillover noise, and the lower illumination efficiency of the QRFH.

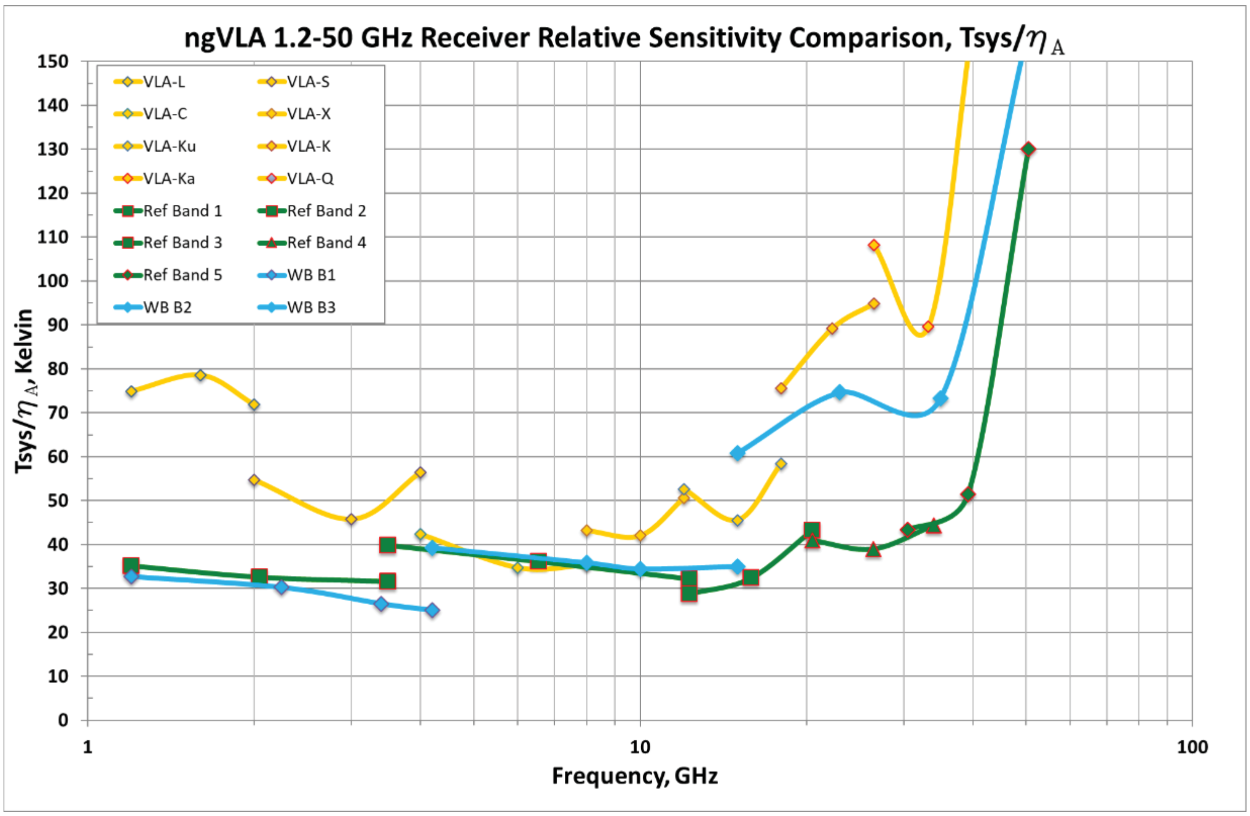


Figure 7 - Relative sensitivity of ngVLA reference Bands 1–5, versus a single VLA antenna.

The estimated relative sensitivity (T_{SYS}/η_A) for the ngVLA Reference Band 6 is shown in Figure 8. Note that the PWV assumed for this band is 1mm, not 6mm as with the other bands. The sharp rate of increase above 113 GHz is primarily due to sky opacity, and to a lesser degree, degradation of the receiver noise performance.

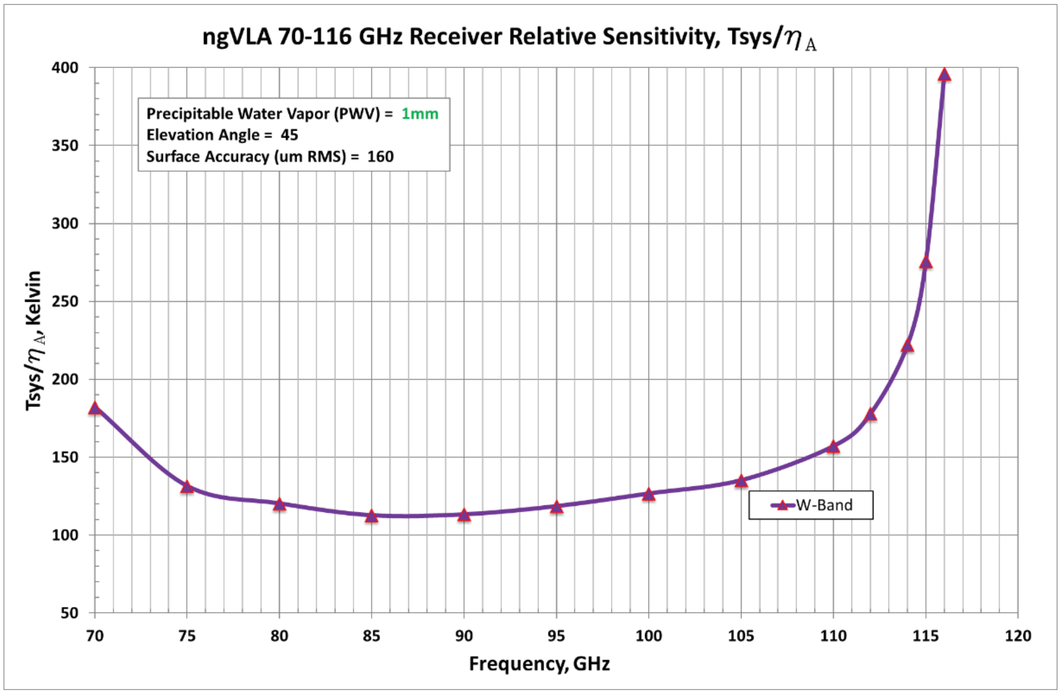


Figure 8 - Relative sensitivity of ngVLA reference Band 6.

Finally, for completeness, a plot of sky temperatures at the VLA site is shown in Figure 9. The sky opacity at the VLA site was modeled for three different values of PWV (13 mm, 6 mm, and 1 mm), representing various operating conditions [RD21]. A 45 degree antenna elevation angle was assumed.

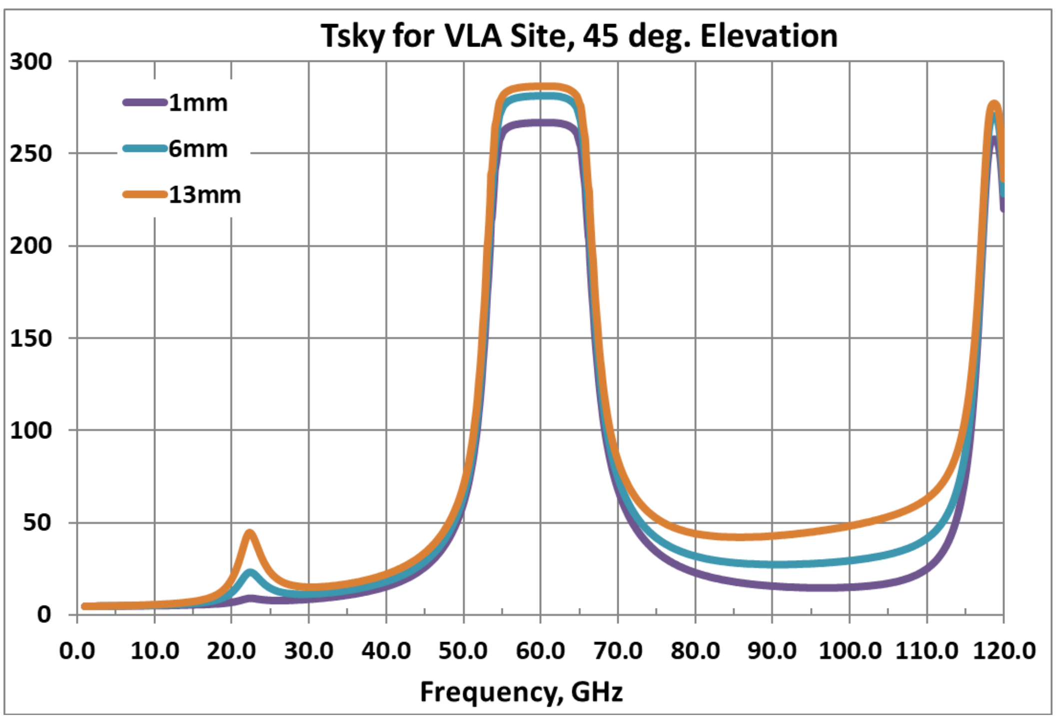


Figure 9 - Modeled Tsky data, VLA site.

5.2 Front End Subsystem Block Diagram

Figure 10 below shows the block diagram of the reference Front End subsystem. Each receiver has two orthogonal linearly polarized outputs, which feed the Integrated Receiver Downconverter/Digitizer (IRD) modules [AD04]. No frequency conversion is performed on any of the bands in the Front End portion of the system. There will be at least one multi-stage LNA per channel, though the high frequency bands may require a cascade of a second amplifier to produce sufficient overall gain to be within the input dynamic range of the IRDs.

Each receiver contains a calibrated noise injection path for self-calibration during observing. This is shown with a splitter and pair of directional couplers. The noise source driving this path has an adjustable output level (~30 dB dynamic range), and will be located outside the cryostat, possibly within the IRD module.

As mentioned before, it may be possible to eliminate the lossy coaxial couplers on Bands 1 and 2 by directly injecting the noise into the QRFH itself. But the concept will have to be proven first.

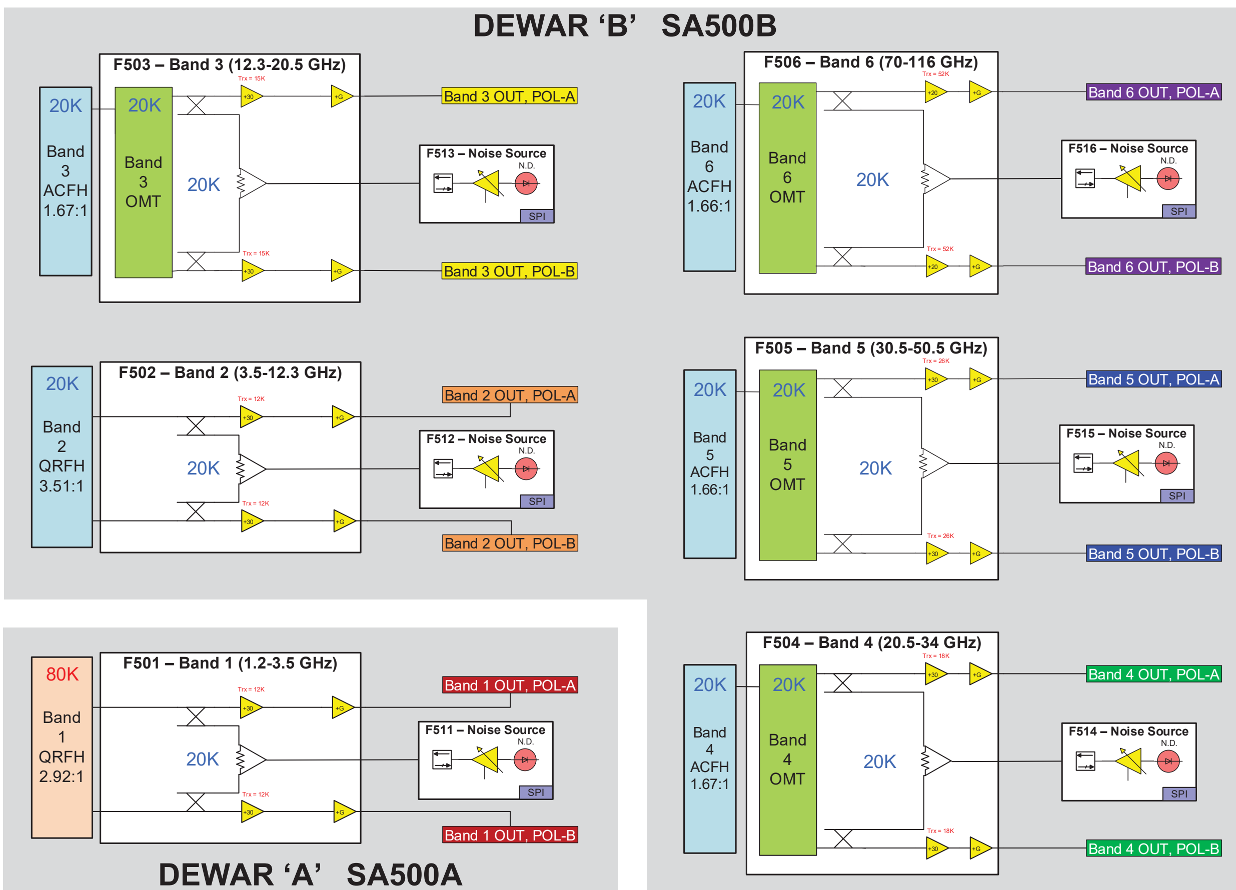


Figure 10 - Block diagram of Front End subsystem.

5.3 Front End Packaging Concept

The size and shape of Cryostat A are largely driven by the Band 1 feed, which is by far the largest component; the LNAs and other RF components are not shown, but take up very little space by comparison. One challenge with Band 1 will be reducing the infrared loading through the feed window, to allow cooling all the way to 80K, particularly in the center of feed structure. This will be important in reducing the contribution to system noise from RF loss in the feed.

The five receiver bands in Cryostat B are arranged in a line, to allow band selection with linear movement along a single axis. The relative offsets of the feed apertures from the top plate are adjusted to align the phase centers of all feeds on a same axis. In practice, a fine focal adjustment will likely be necessary when tuning across the bandpass on some of the high-frequency receivers, so the positioner for the Front End platform will probably have two axes of motion.

Cryostat B is envisioned to be a modular assembly, to allow separate production and testing of individual receiver bands. Each receiver subassembly is a mechanical integration of the feed horn, IR filter, thermal gap interface, LNAs and other cooled RF components. The feed windows, output coax and waveguide connections, bias and sensor wiring harnesses, and vacuum and temperature sensors will be part of the cryostat shell.

Figure 11 and Figure 12 show renderings of packaging concepts for Cryostat A and B, respectively.

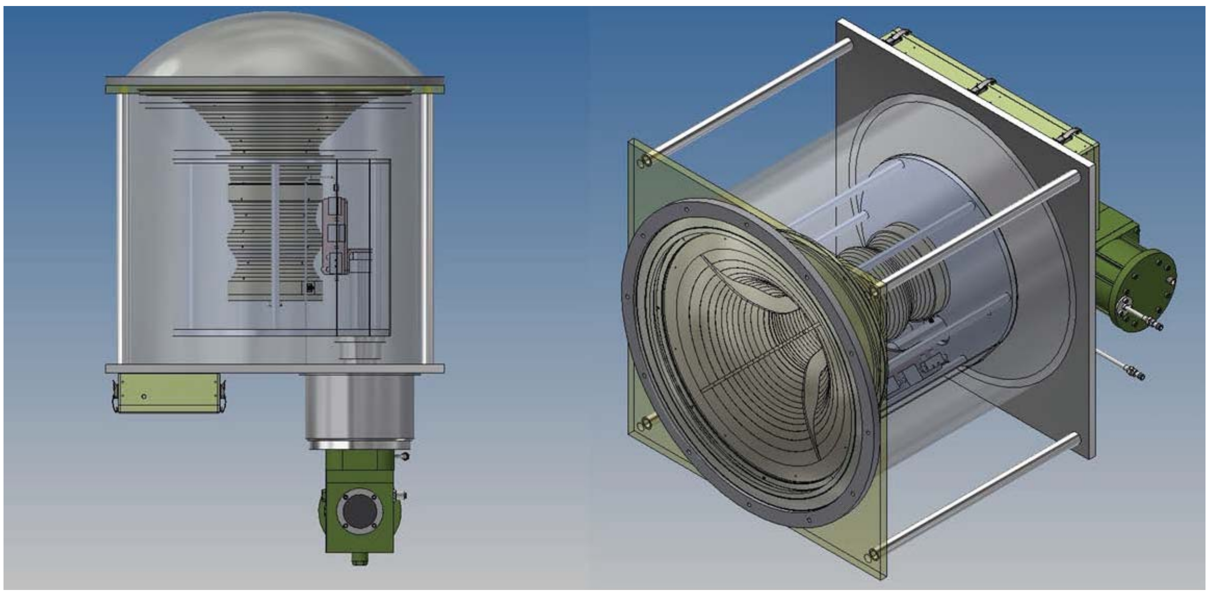


Figure 11 - ngVLA reference receiver Band 1 (cryostat A).

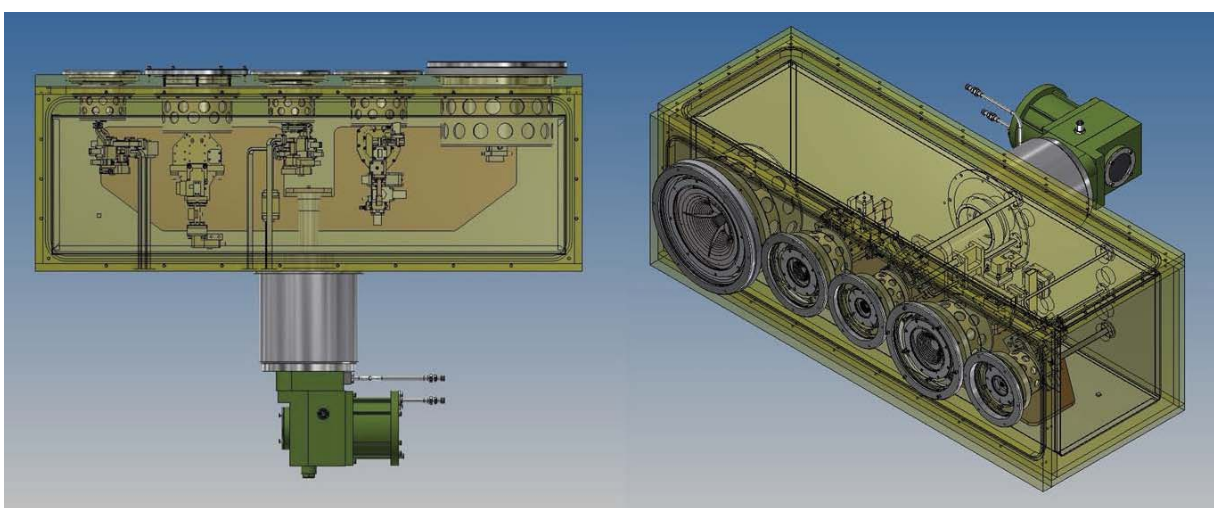


Figure 12 - ngVLA reference receiver Bands 2–6 (cryostat B).

Approximate dimensions and masses for both cryostats are:

- Cryostat A (Band 1): **458 x 406 mm** (Dia. x H); total mass ~ **74 kg**
- Cryostat B (Bands 2–6): **725 x 260 x 300** mm (L x W x H); total mass ~ **89 kg**

5.4 Front End Interfaces to Other Subsystems

This section provides information about the mechanical and electrical interfaces to the Front End cryostat assemblies. In many cases, detailed specifications for the interfaces are not yet fully defined, but the general scope of the interfaces are described here. These will eventually be documented in detail with Interface Control Documents (ICDs), generated jointly by designers from both sides. During the formal design and development phase of the project, the ICDs will be updated through formal change control processes.

Descriptions given of electrical/RF connectors, waveguide ports and mechanical flanges or attachment points reference the Front End side of the interface. Cables, waveguide and fiber routing between the cryostats and other electronic subsystems are beyond the scope of this document.

5.4.1 Interface to the Cryogenic Subsystem

The cryocooler unit consists of two separate parts: a drive motor/valve/displacer assembly, and a polished steel cylinder that slides over the displacers. The cylinder is the mechanical interface for both cold stages, and is an integral part of the cryostat assembly. The displacer assembly is external to the cryostat and removable, and is considered part of the Cryogenic subsystem. The interface between these parts is an interface plate or flange pattern that allows a gas-tight seal and properly aligns the two parts. A mechanical drawing of this interface pattern is shown in Figure 13 [AD03].

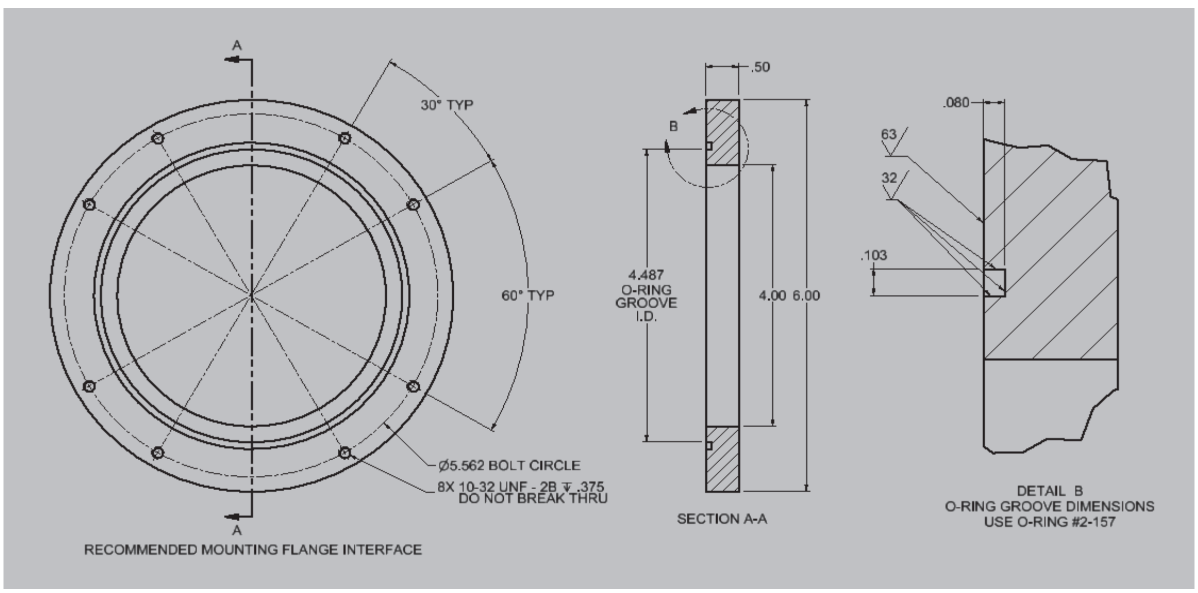


Figure 13 - Cryocooler displacer mechanical interface.

5.4.2 Interface to the Integrated Receivers and Downconverters (IRD) Subsystem

The IRD subsystem module will be mounted in close proximity to Cryostat B, to keep the RF interconnects to it as short as possible. It might even be feasible to bolt them directly together, using blind-mate connectors instead of cables/waveguides, but this will be decided later on. Longer armored cables will be used to connect the Band 1 RF outputs of Cryostat A to the IRD module.

Table 3 shows the type and number of RF interconnects with the Front End subsystem [AD04]. The physical locations and outlines of the connectors are still TBD.

Signal at Interface	Type	Parameter	Value
Band 1 RF	Output	Connector	SMA (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 2 RF	Output	Connector	SMA (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 3 RF	Output	Connector	2.92 mm (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 4 RF	Output	Connector	2.92 mm (F)
		Impedance	50 Ω
		Number	2 (one per pol.)
Band 5 RF	Output	Waveguide size	WR-22 (UG599)
		Number	2 (one per pol.)
Band 6 RF	Output	Waveguide size	WR-10 (UG387)
		Number	2 (one per pol.)

Table 3 - Interconnects between the Front End cryostats and IRD module.

5.4.3 Interface to the Antenna Subsystem

The Front End cryostat assemblies will be mounted at the secondary focus of the antenna, on a platform attached to the feed arm structure. A dual offset Gregorian optical configuration for the antenna is assumed. The platform will include an X-Y axis motorized positioner for focusing and band selection and the temperature-controlled enclosure. Figure 14 shows a rendering of the mounting concept, which will be the same for both the 18-meter and 6-meter antennas. Detailed mechanical interface drawings are pending completion of the antenna design.

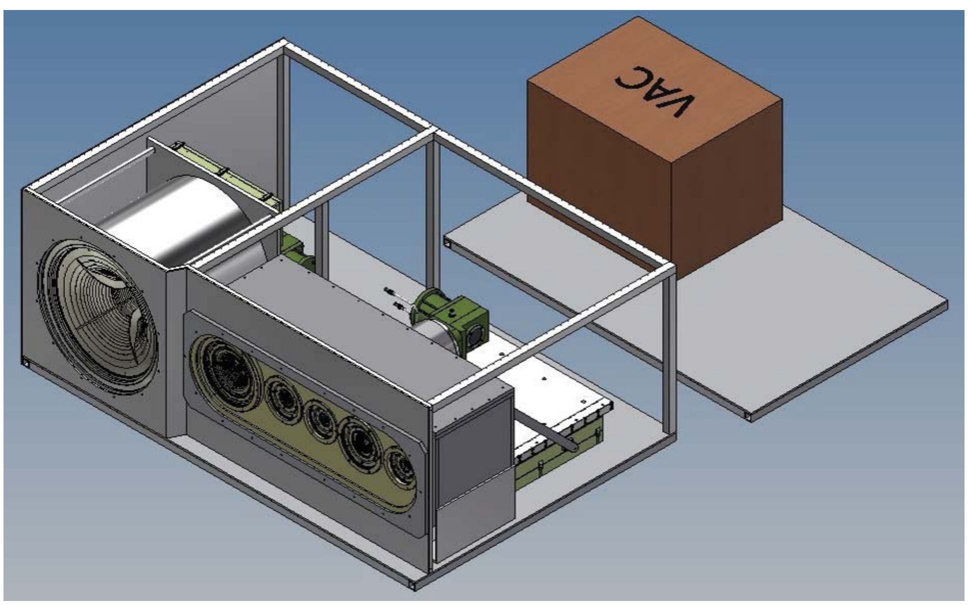


Figure 14 - Front End subsystem enclosure, opened to show cryostats and IRD assembly.

5.4.4 Interface to the Monitor and Control Subsystem

The two Front End cryostat assemblies presently contain only RF electronics. All the analog support electronics for Cryostats A and B are packaged within two external modules, referred to as F521A and F521B, respectively. These will be located inside the platform enclosure on the antenna feed arm, in close proximity to the cryostats. The support electronics provides the following functions:

- DC bias/driver circuitry for LNAs, noise calibrator sources, and other active components
- RF output control/leveling for the noise calibrator sources
- Input signal conditioning from the cryostat vacuum and temperature sensors
- Driver circuitry and current monitoring for the cryostat vacuum solenoid valve

Electrical connection to the cryostats is assumed to be via multi-conductor shielded cables, with a bulkhead receptacle/cable plug pair at each end. Specific details are undefined at present; however, these will likely consist of single, multi-pin round, twist-locking connector interfaces, with a hermetic glass seal for contacts on the cryostat receptacle side, to maintain vacuum integrity.

It may be feasible, and even desirable, to integrate some or all of the support electronics into their respective cryostats, but for now are they are assumed to be separate assemblies.

The Cryo and LNA M&C module (designated F520) contains the MIB, or Monitor and Control Interface Board, which provides the communications link to the monitor and control subsystem. The F522 is similar to the F521A/B but also provides control electronics for the vacuum pump common to both cryostats [AD05].

5.4.5 Interface to the Power Supply Subsystem

The Power Supply Subsystem provides DC voltages required by the Front End electronics, packaged in modules F521 and F522 [AD05]. Voltages and currents supplied are: +32.5V @ 0.5A, +17.5V @ 6A, +7.5V @ 0.5A and –7.5V @ 0.1A, from the P501 power supply module [AD06].

The electromechanical interface details are presently undefined. However, it will likely consist of a single multi-pin round, twist-lock, or threaded connector interface, like those widely used by the US military (e.g., MIL-DTL-26482, MIL-DTL-38999, MIL-DTL-22992). These are highly rugged, weather-tight, and reliable, with a multitude of pin sizes and counts available at a moderate cost. Location is likely to be on the rear panel of the F521 and F522 electronics modules.

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDL	Central Development Laboratory
GBT	Green Bank Telescope
IF	Intermediate Frequency
IRD	Integrated Receiver Downconverter/Digitizer (Subsystem)
LNA	Low Noise Amplifier
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
MMIC	Monolithic Microwave Integrated Circuit
NGC	Northrop Grumman Corporation
ngVLA	Next Generation VLA
NRC	National Research Council (Canada)
OMT	Ortho Mode Transducer
QRFH	Quad-Ridged Feed Horn
RD	Reference Document
RF	Radio Frequency
SEFD	System Equivalent Flux Density
SKA	Square Kilometer Array (telescope)
TBD	To Be Determined
UWB	Ultra Wide Band
VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array

6.2 Caltech 4-Band Front End Concept

Band #	Dewar #	f_L GHz	f_{M1} GHz	f_{M2} GHz	f_H GHz	$f_H : f_L$	BW GHZ	Feed Horn Properties Temp	L, in.	ID, in.	OMT
1	A	**1.2**	**2.2**	**3.4**	**4.2**	3.50	3	80	13.0	14.2	none
2	A	**4.2**	**8**	**10**	**15**	3.57	10.8	20	3.71	4.05	none
3	A	**15**	**23**	**35**	**50**	3.33	35	20	1.04	1.13	none
4	A	**70**	**90**	**105**	**116**	1.66	46	20	2.54	1.49	WG

Band #	Dewar #	Aperture Eff., η_A				Spillover, K				~T_{RAD} (K)
		@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	
1	A	0.80	0.79	0.72	0.78	12.8	9.4	4.6	3.9	0.0
2	A	0.80	0.79	0.72	0.77	12.8	9.4	4.8	4.0	0.0
3	A	0.79	0.77	0.69	0.70	10.7	4.0	4.8	4.0	3.5
4	A	0.68	0.61	0.54	0.48	4.1	4.1	4.1	4.1	0.0

Band #	Dewar #	T_{LNA}, K				T_{RX}, K				T_{SKY}, K			
		@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	@ f_L	@ f_{M1}	@ f_{M2}	@ f_H
1	A	3	3	3	4	9	10	10	11	4.4	4.5	4.6	4.6
2	A	6	6	7	8	14	14	15	17	4.6	4.8	5	6
3	A	12	12	12	20	28	28	29	38	6	22.1	13	62.5
4	A	25	26	26.5	42	50.6	48.8	51	72.6	68.3	15.4	16.9	112.3

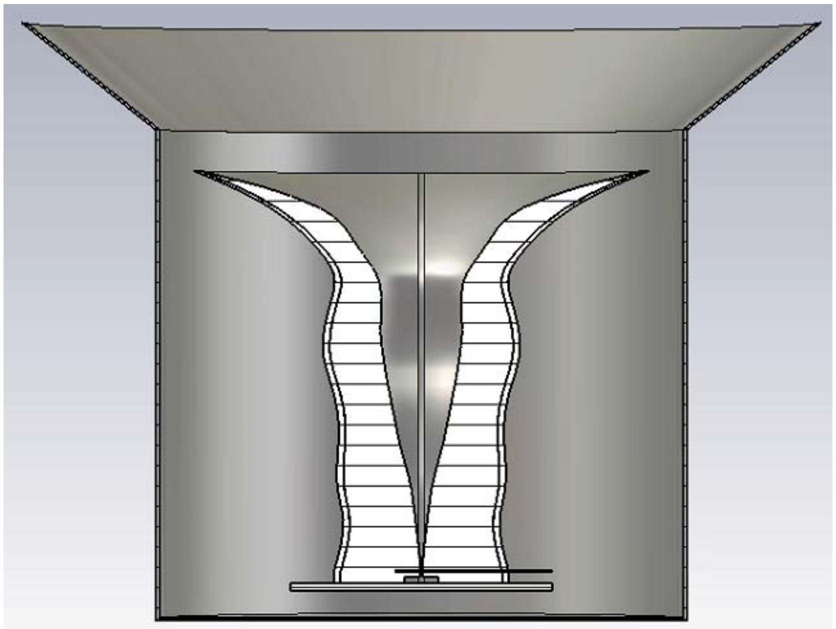
Band #	Dewar #	**T_{SYS}, K**				**(T_{SYS}/η_A), K**				**Array SEFD, Jy**			
		@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	@ f_L	@ f_{M1}	@ f_{M2}	@ f_H	@ f_L	@ f_{M1}	@ f_{M2}	@ f_H
1	A	**26**	**24**	**19**	**20**	**33**	**30**	**26**	**25**	**1.44**	**1.33**	**1.17**	**1.10**
2	A	**31**	**28**	**25**	**27**	**39**	**36**	**34**	**35**	**1.73**	**1.58**	**1.51**	**1.54**
3	A	**48**	**58**	**50**	**108**	**61**	**75**	**73**	**155**	**2.68**	**3.29**	**3.23**	**6.83**
4	A	**123**	**68**	**72**	**189**	**181**	**111**	**134**	**394**	**7.96**	**4.91**	**5.89**	**17.36**

Table 4 - Performance estimates, Caltech 4-band configuration.

<u>Explanatory Notes for Table 4</u>:

1. This band configuration was originally proposed by Dr. Sandy Weinreb, Caltech, August 2016. Recently, there have been discussions to possibly split Band 3 into two narrower bands for improved sensitivity, but no formal decision on this has been communicated.
2. Sensitivity (SEFD) calculation is for an array of 244 x 18-meter and 19 x 6-meter diameter antennas. The optical performance of both antenna types is assumed identical.
3. The aperture efficiency is for the feed with the antenna, and assumes an unblocked primary aperture, an offset feed (low) Gregorian design, a secondary (subreflector) of 3.5m aperture, shaped optics, and a ground shield for spillover noise reduction.
4. Antenna surface (Ruze) efficiency is included in the aperture efficiencies shown. Surface accuracy assumed is for precision conditions (160 µm RMS, uniformly distributed).

5. Estimates for sky temperature (T_{SKY}) were provided by B. Butler (NRAO), modeling opacity at VLA site. An elevation angle of 45 degrees was assumed for all bands. The precipitable water vapor (PWV) was assumed to be 6 mm for Bands 1–3, and 1 mm for Band 4.
6. Outputs on all bands are linearly-polarized.
7. Band 1 feed is cooled to ~80K. Band 2–4 feeds are cooled to ~20K.
8. Opening angle (ϑ) is defined here as the angle subtended between the central optical axis and the edge of the subreflector, at the secondary focus of the antenna.
9. Bands 1–3 use a wideband (~3.5:1) QRFH and Caltech LNAs. The feed is designed for an opening angle of 58 degrees, and uses a revised spline feed profile to maximize overall aperture efficiency over the band (H. Mani and W. Zhong, 2017).
10. Band 4 uses a wide-angle corrugated feed, based on a design by G. Cortes and L. Baker in the NRC DVA-1 SKA prototype antenna (2014). Band 4 LNA and receiver noise temperature estimates shown are courtesy of D. Cuadrado (U. of Manchester) and S. Weinreb.
11. For Bands 1–3, the illumination efficiency component assumes the mapping (shape) function used on the SKA antenna.
12. For Band 4, a high-efficiency mapping function for the ngVLA reference optical design was used; illumination efficiency and spillover noise are taken from [RD15].
13. Bands 1–3 T_{RX} includes contribution from window+IR filter, feed, coax losses (4-8K) and also the calibration injection coupler and post-amplifier (1.5+0.5K, 2.5+0.5K and 9+1K, on Bands 1, 2 and 3, respectively). The cal coupler contributes a significant amount of extra noise, but recent tests by the SKA project on a probe injection system in the feedhorn [RD20] are promising, and may allow the coupler to be eliminated entirely.
14. T_{RAD} is the approximate noise contribution from a weather radome. It is shown in a separate column for Band 3, but already included in T_{RX} for Bands 1, 2, and 4.



Feed cone is external to Dewar. Main effect is on the back lobe

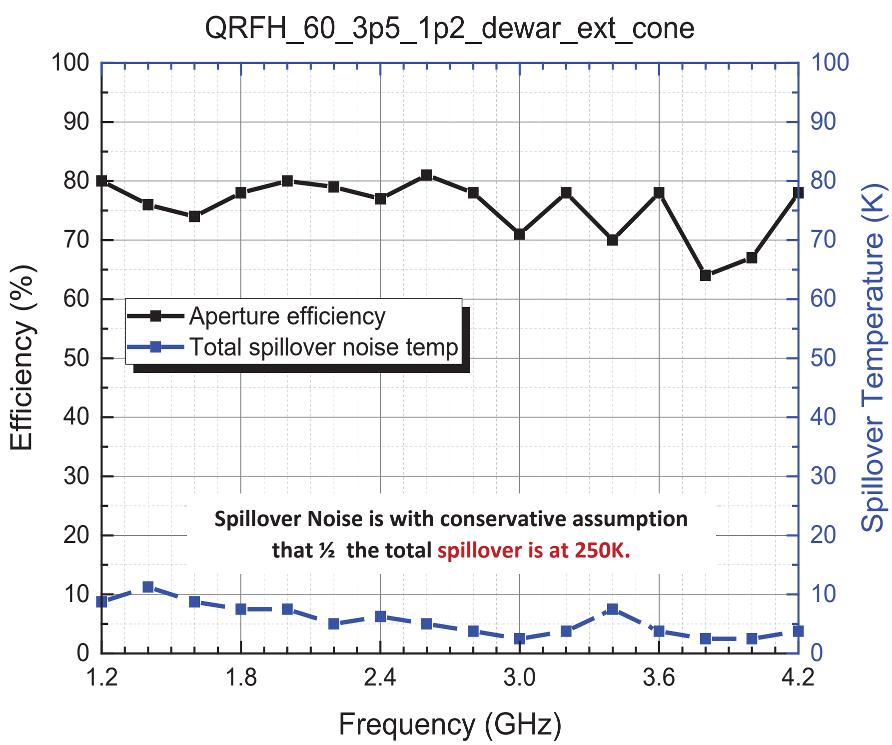


Figure 15 - QRFH cross section and shield cone, with simulated illumination efficiency and spillover noise.

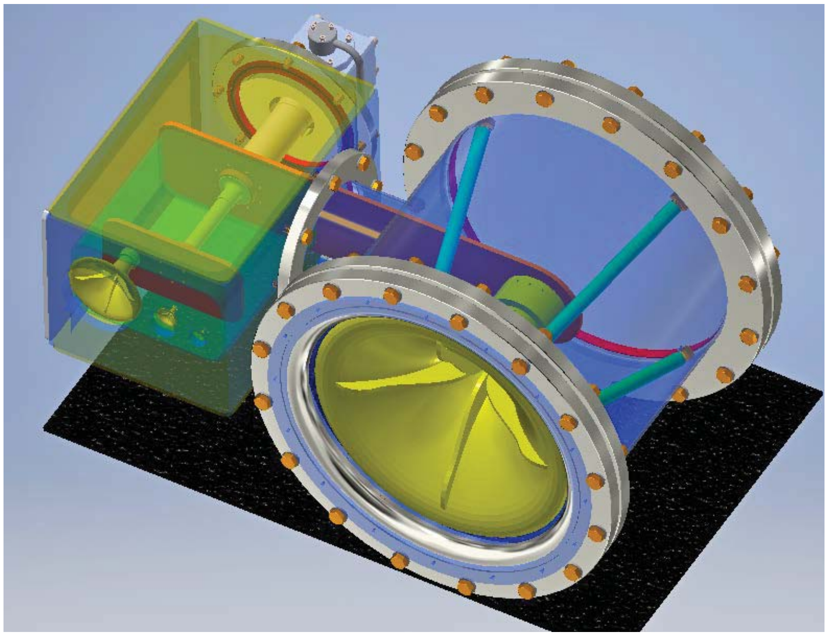


Figure 16 - 3D rendering of Caltech 4-band, single-cryostat Front End concept.

Figure 17 - Caltech/ASU Band 1 cryostat, open and fully assembled (cryocooler is below tabletop).

6.3 NASA/JPL Ultra-Wideband Receiver (8-48 GHz)

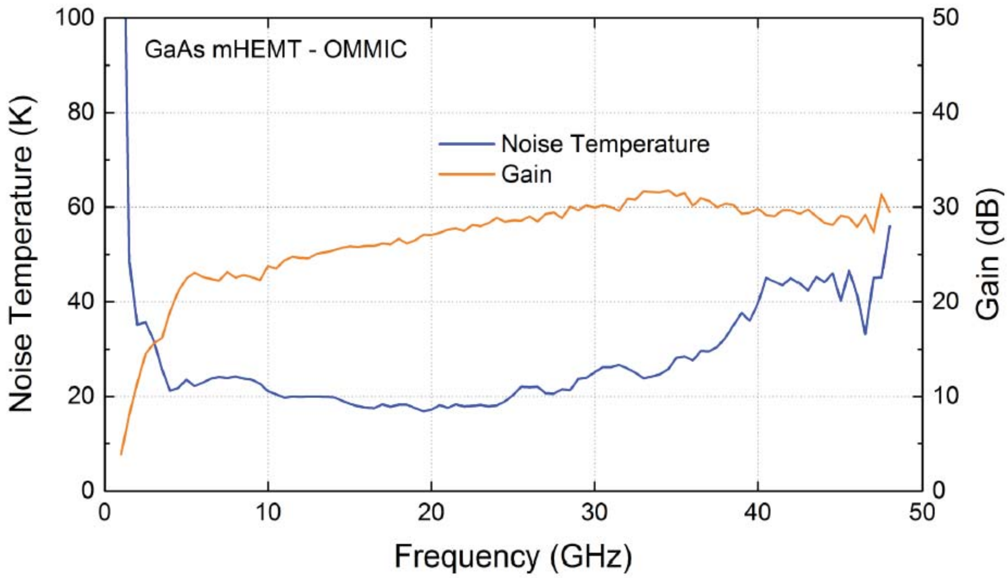


Figure 18 - OMMIC 70 nm GaAs m-HEMT LNA: gain and noise temperature.

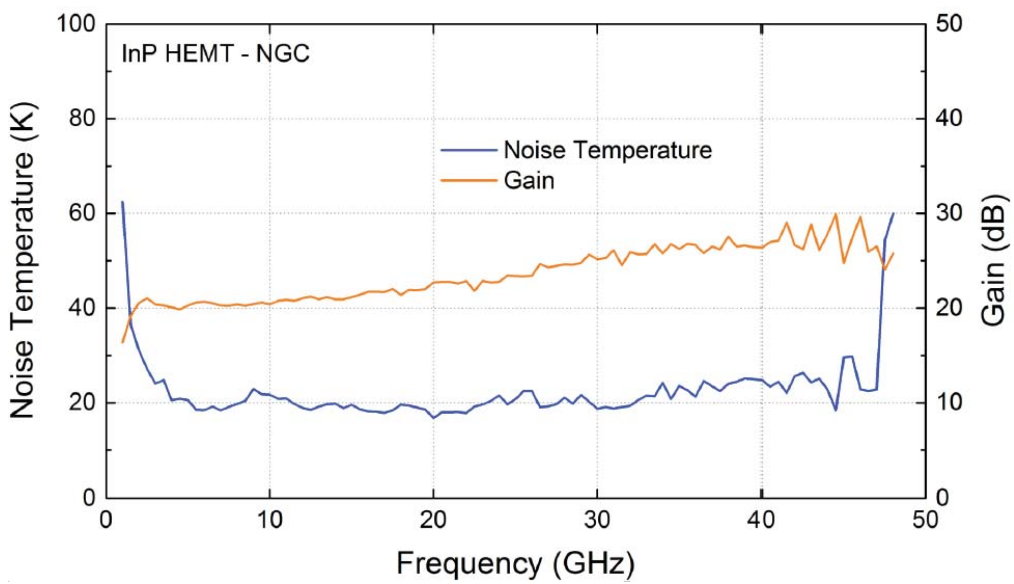


Figure 19 - NGC 35 nm InP HEMT LNA: gain and noise temperature.

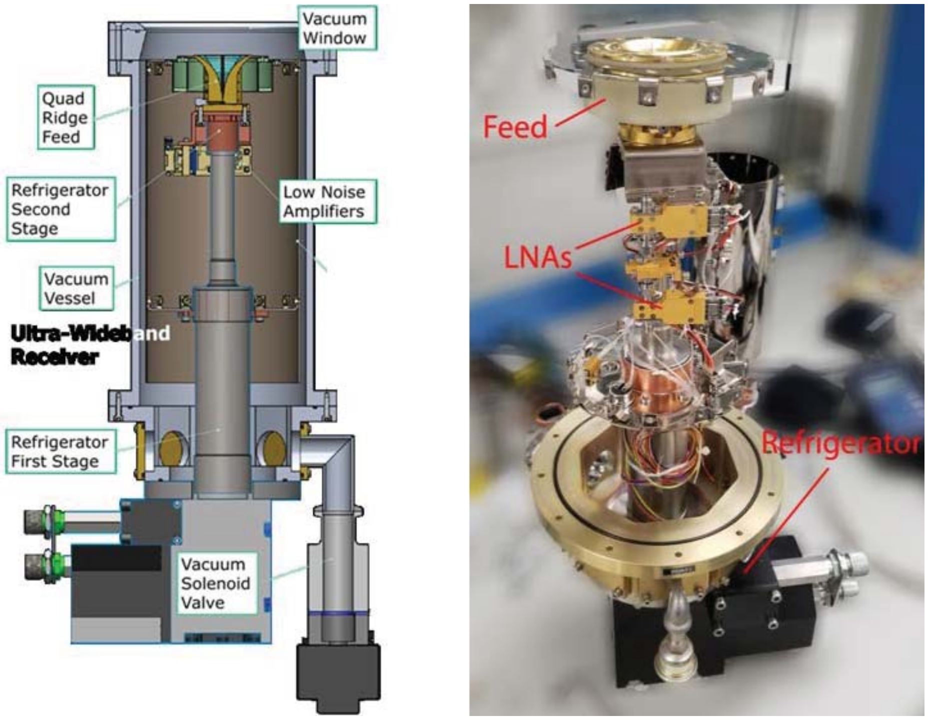


Figure 20 - JPL ultra-wideband receiver cryostat, side rendering and inside view.

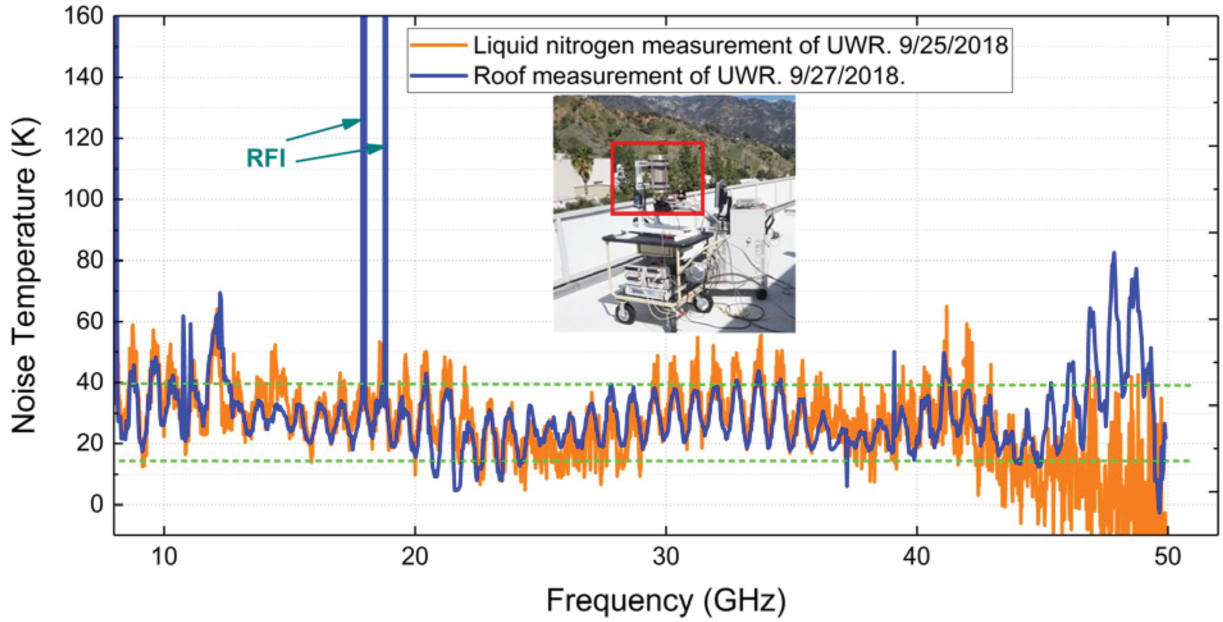


Figure 21 - JPL UWB receiver noise temperature, measured both with an LN2 load and on cold sky.

6.4 ngVLA Reference Front End Receiver Cascade, LNA Noise Tables

Band #:	Phys. Temp.	T-Line Len.	1											
Frequency:			1.2				2.0				3.5			
Component Type	K	m	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vacuum_Window	300		-0.02	1.38	-0.02	1.38	-0.02	1.38	-0.02	1.38	-0.02	1.38	-0.02	1.38
IR_Filter	190		-0.02	0.88	-0.04	2.27	-0.02	0.88	-0.04	2.27	-0.02	0.88	-0.04	2.27
Feed_Horn	80		-0.10	1.86	-0.14	4.15	-0.10	1.86	-0.14	4.15	-0.13	2.43	-0.17	4.72
OMT	50		0.00	0.00	-0.14	4.15	0.00	0.00	-0.14	4.15	0.00	0.00	-0.17	4.72
Coax_141Cu	50	0.1	-0.04	0.47	-0.18	4.64	-0.05	0.63	-0.19	4.80	-0.07	0.86	-0.24	5.62
Cal_Coupler	20		-0.45	2.18	-0.63	6.91	-0.45	2.18	-0.64	7.08	-0.45	2.18	-0.69	7.93
LNA_Band1	20		**36.50**	**2.60**	35.87	9.92	**36.80**	**2.80**	36.16	10.33	**36.87**	**4.98**	36.17	13.77
Coax_086SS	190	0.4	-0.62	29.09	35.25	9.93	-0.81	38.86	35.35	10.34	-1.06	52.80	35.11	13.78
Cascaded Values:					**35.3**	**9.9**			**35.3**	**10.3**			**35.1**	**13.8**

Band #:	Phys. Temp.	T-Line Len.	2											
Frequency:			3.5				6.6				12.3			
Component Type	K	m	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vacuum_Window	300		-0.02	1.38	-0.02	1.38	-0.03	1.84	-0.03	1.84	-0.03	2.08	-0.03	2.08
IR_Filter	190		-0.02	0.88	-0.04	2.27	-0.03	1.16	-0.05	3.01	-0.03	1.32	-0.06	3.41
Feed_Horn	20		-0.13	0.61	-0.17	2.88	-0.18	0.86	-0.24	3.88	-0.30	1.43	-0.36	4.86
OMT	20		0.00	0.00	-0.17	2.88	0.00	0.00	-0.24	3.88	0.00	0.00	-0.36	4.86
Coax_141Cu	20	0.1	-0.07	0.35	-0.24	3.24	-0.11	0.50	-0.34	4.40	-0.16	0.73	-0.52	5.65
Cal_Coupler	20		-0.45	2.18	-0.69	5.55	-0.45	2.18	-0.79	6.77	-0.45	2.18	-0.97	8.11
LNA_Band2	20		**35.98**	**6.69**	35.29	13.40	**34.76**	**7.16**	33.97	15.36	**34.91**	**5.00**	33.95	14.35
Coax_086SS	190	0.4	-1.07	52.97	34.22	13.41	-1.47	76.23	32.50	15.39	-2.00	111.32	31.94	14.40
Cascaded Values:					**34.2**	**13.4**			**32.5**	**15.4**			**31.9**	**14.4**

Band #:	Phys. Temp.	TLine Len.	3											
Frequency:			12.3				15.9				20.5			
Component Type	K	m	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas	G, dB	Te, K	Gcas	Tcas
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		-0.03	2.08	-0.03	2.08	-0.03	2.08	-0.03	2.08	-0.04	2.82	-0.04	2.82
Vacuum_Window	300		-0.03	2.08	-0.06	4.17	-0.03	2.08	-0.06	4.17	-0.03	2.08	-0.07	4.92
IR_Filter	190		-0.03	1.32	-0.09	5.51	-0.03	1.32	-0.09	5.51	-0.03	1.32	-0.10	6.26
Feed_Horn	20		-0.05	0.23	-0.14	5.75	-0.05	0.23	-0.14	5.75	-0.05	0.23	-0.15	6.49
OMT	20		-0.20	0.94	-0.34	6.72	-0.20	0.94	-0.34	6.72	-0.20	0.94	-0.35	7.47
Cal_Coupler	20		-0.20	0.94	-0.54	7.74	-0.20	0.94	-0.54	7.74	-0.20	0.94	-0.55	8.49
WG_WR51	20	0.1	-0.07	0.33	-0.61	8.11	-0.03	0.14	-0.57	7.90	-0.03	0.12	-0.58	8.62
LNA_Band3	20		**35.08**	**5.00**	34.46	13.87	**34.64**	**7.90**	34.07	16.91	**34.30**	**8.75**	33.72	18.62
WG_WR51	190	0.3	-0.21	9.57	34.25	13.87	-0.09	4.13	33.98	16.91	-0.08	3.35	33.65	18.62
Cascaded Values:					**34.3**	**13.9**			**34.0**	**16.9**			**33.6**	**18.6**

Table 5 - Cascaded gain and noise, Bands 1–3.

Band #:	Phys. Temp.	T-Line Len.	**4**											
Frequency:			**20.5**				**26.4**				**34.0**			
Component Type	*K*	*m*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		-0.04	2.82	-0.04	2.82	-0.05	3.33	-0.05	3.33	-0.05	3.47	-0.05	3.47
Vacuum_Window	300		-0.03	2.08	-0.07	4.92	-0.03	2.08	-0.08	5.44	-0.03	2.08	-0.08	5.58
IR_Filter	190		-0.03	1.32	-0.10	6.26	-0.03	1.32	-0.11	6.78	-0.03	1.32	-0.11	6.92
Feed_Horn	20		-0.05	0.23	-0.15	6.49	-0.05	0.23	-0.16	7.02	-0.05	0.23	-0.16	7.16
OMT	20		-0.20	0.94	-0.35	7.47	-0.20	0.94	-0.36	7.99	-0.31	1.49	-0.47	8.70
Cal_Coupler	20		-0.20	0.94	-0.55	8.49	-0.20	0.94	-0.56	9.02	-0.24	1.12	-0.71	9.96
WG_Band4	20	0.1	-0.08	0.36	-0.63	8.90	-0.05	0.24	-0.61	9.29	-0.04	0.21	-0.75	10.20
LNA_Band4	20		**33.65**	**5.65**	33.02	15.43	**29.16**	**6.00**	28.55	16.19	**28.00**	**7.80**	27.25	19.48
WG_Band4	190	0.3	-0.23	10.42	32.79	15.43	-0.15	6.84	28.40	16.20	-0.13	5.97	27.11	19.49
Cascaded Values:					**32.8**	**15.4**			**28.4**	**16.2**			**27.1**	**19.5**

Band #:	Phys. Temp.	T-Line Len.	**5**											
Frequency:			**30.5**				**39.2**				**50.5**			
Component Type	*K*	*m*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		-0.05	3.47	-0.05	3.47	-0.05	3.47	-0.05	3.47	-0.05	3.47	-0.05	3.47
Vacuum_Window	300		-0.03	2.08	-0.08	5.58	-0.03	2.08	-0.08	5.58	-0.03	2.08	-0.08	5.58
IR_Filter	190		-0.03	1.32	-0.11	6.92	-0.03	1.32	-0.11	6.92	-0.03	1.32	-0.11	6.92
Feed_Horn	20		-0.05	0.23	-0.16	7.16	-0.05	0.23	-0.16	7.16	-0.05	0.23	-0.16	7.16
OMT	20		-0.25	1.17	-0.41	8.37	-0.34	1.62	-0.50	8.84	-0.30	1.45	-0.46	8.66
Cal_Coupler	20		-0.22	1.02	-0.62	9.49	-0.23	1.09	-0.73	10.06	-0.20	0.94	-0.66	9.71
WG_WR22	20	0.05	-0.08	0.36	-0.70	9.90	-0.05	0.23	-0.78	10.32	-0.04	0.20	-0.71	9.94
LNA_Band5	20		**33.25**	**7.80**	32.55	19.06	**34.12**	**8.44**	33.34	20.42	**33.13**	**14.10**	32.42	26.52
WG_WR22	190	0.3	-0.46	21.18	32.09	19.07	-0.29	13.29	33.05	20.42	-0.25	11.40	32.17	26.53
Cascaded Values:					**32.1**	**19.1**			**33.0**	**20.4**			**32.2**	**26.5**

Band #:	Phys. Temp.	T-Line Len.	**6**											
Frequency:			**70.0**				**90**				**116.0**			
Component Type	*K*	*m*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*	*G, dB*	*Te, K*	*Gcas*	*Tcas*
Lossless Input	20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weather_Radome	300		-0.05	3.56	-0.05	3.56	-0.06	4.44	-0.06	4.44	-0.08	5.58	-0.08	5.58
Vacuum_Window	300		-0.03	2.08	-0.08	5.67	-0.03	2.34	-0.10	6.81	-0.05	3.47	-0.13	9.12
IR_Filter	190		-0.03	1.32	-0.11	7.01	-0.03	1.48	-0.13	8.33	-0.05	2.20	-0.18	11.38
Feed_Horn	20		-0.05	0.24	-0.16	7.25	-0.06	0.30	-0.20	8.63	-0.08	0.37	-0.26	11.77
OMT	20		-0.49	2.38	-0.65	9.72	-0.38	1.84	-0.58	10.55	-0.35	1.68	-0.61	13.55
Cal_Coupler	20		-0.68	3.40	-1.33	13.66	-0.53	2.60	-1.11	13.52	-0.50	2.44	-1.11	16.36
WG_WR10	20	0.025	-0.12	0.55	-1.45	14.41	-0.08	0.37	-1.19	14.00	-0.07	0.33	-1.18	16.78
LNA_Band6	20		**19.00**	**25.00**	17.55	49.32	**19.00**	**26.00**	17.81	48.18	**19.00**	**42.00**	17.82	71.90
WG_WR10	190	0.3	-1.42	73.64	16.13	50.62	-0.96	47.10	16.85	48.96	-0.84	40.64	16.98	72.57
Cascaded Values:					**16.1**	**50.6**			**16.9**	**49.0**			**17.0**	**72.6**

Table 6 - Cascaded gain and noise, Bands 4–6.

Band #	Freq. GHz	Gain dB	Trx K
1	1.2	35.25	9.9
	2.0	35.35	10.3
	3.5	35.11	13.8
2	3.5	34.22	13.4
	6.6	32.50	15.4
	12.3	31.94	14.4
3	12.3	34.25	13.9
	15.9	33.98	16.9
	20.5	33.65	18.6
4	20.5	32.79	15.4
	26.4	28.40	16.2
	34.0	27.11	19.5
5	30.5	32.09	19.1
	39.2	33.05	20.4
	50.5	32.17	26.5
6	70	16.13	50.6
	90	16.85	49.0
	116	16.98	72.6

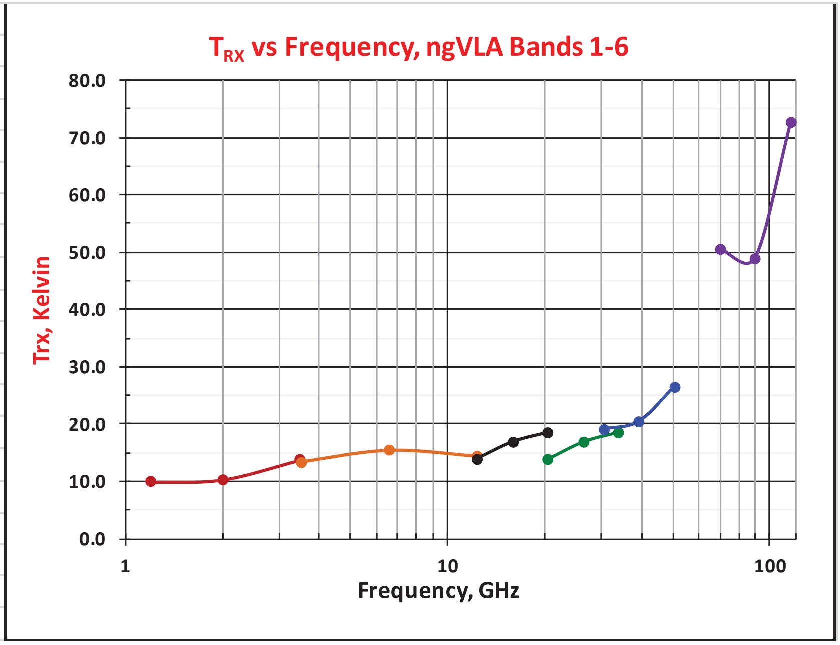


Figure 22 - Plot of receiver noise vs. frequency, Bands 1–6.

1 Freq. (GHz)	1 Ga [1] (dB)	1 Tn [1] (K)	2 Freq. (GHz)	2 Ga [2] (dB)	2 Tn [2] (K)	3 Freq. (GHz)	3 Ga [3] (dB)	3 Tn [3] (K)	4 Freq. (GHz)	4 Ga [4] (dB)	4 Tn [4] (K)	5 Freq. (GHz)	5 Ga [5] (dB)	5 Tn [5] (K)	6 Freq. (GHz)	6 Ga [6] (dB)	6 Tn [6] (K)
1.0	36.0	2.8	**3.0**	35.0	7.3	**12.0**	35.2	5.0	**20**	33.9	6.0	**30**	33.0	8.0	**70**	19.0	25.0
1.2	36.5	2.6	**3.5**	36.0	6.7	**12.5**	35.0	5.0	**21**	33.4	5.3	**31**	33.5	7.6	**72**	19.0	23.0
1.4	36.5	2.4	**4.0**	35.0	6.0	**13.0**	34.6	5.0	**22**	32.8	5.6	**32**	33.0	7.2	**74**	19.0	23.5
1.6	36.5	2.6	**4.5**	34.5	6.0	**13.5**	34.2	5.3	**23**	31.5	6.0	**33**	32.5	7.0	**76**	19.0	25.0
1.8	36.7	2.7	**5.0**	34.2	6.7	**14.0**	34.6	6.0	**24**	31.5	6.0	**34**	32.5	7.6	**78**	19.0	26.0
2.0	36.8	2.8	**5.5**	34.0	7.0	**14.5**	35.0	6.5	**25**	31.0	6.5	**35**	34.0	7.8	**80**	19.0	26.5
2.2	36.9	2.9	**6.0**	34.2	7.5	**15.0**	35.0	7.0	**26**	30.0	6.2	**36**	33.8	8.0	**84**	19.0	25.5
2.4	37.0	3.0	**6.5**	34.7	7.2	**16.0**	34.6	8.0	**27**	27.9	5.7	**37**	34.0	8.2	**88**	19.0	26.0
2.6	37.0	3.1	**7.0**	35.0	7.0	**17.0**	34.0	7.5	**28**	27.5	5.7	**38**	34.0	8.2	**92**	19.0	26.0
2.8	36.9	3.2	**7.5**	35.5	6.5	**18.0**	34.6	6.0	**29**	28.0	6.0	**40**	34.2	8.6	**96**	19.0	27.0
3.0	36.9	3.6	**8.0**	36.0	6.0	**19.0**	35.0	6.0	**30**	28.0	6.3	**42**	34.5	10.4	**100**	19.0	27.5
3.2	36.9	4.0	**9.0**	36.5	5.5	**20.0**	34.6	8.0	**31**	28.0	6.5	**44**	34.8	11.6	**104**	19.0	26.5
3.4	37.0	4.8	**10.0**	36.0	5.0	**21.0**	34.0	9.5	**32**	28.0	6.7	**46**	35.0	12.4	**108**	19.0	26.0
3.6	36.7	5.2	**11.0**	35.5	4.7	**22.0**	33.0	8.5	**33**	28.0	7.3	**48**	34.8	13.6	**112**	19.0	25.5
3.8	35.0	6.0	**12.0**	35.0	5.0	**23.0**	32.5	9.0	**34**	28.0	7.8	**50**	33.5	14.0	**114**	19.0	27.0
4.0	30.0	7.0	**13.0**	34.7	5.0	**24.0**	33.0	10.0	**35**	28.0	8.0	**52**	32.0	14.4	**115**	19.0	28.0
															116	19.0	42.0

NOTES:

[1] - Band 1 LNA data is a CSIRO 1-3 GHz InP LNA, w/100nm NGST devices (2003). CSIRO now has a newer MMIC; details unknown.

[2] - Band 2 LNA data is a Caltech 1-18 GHz GaAs MMIC LNA (p/n CIT-118), based on OMMIC WBA118B device, T=19K (August 2014)

[3] - Band 3 LNA data is a Caltech 1-18 GHz GaAs MMIC LNA (p/n CIT-118), based on OMMIC WBA118B device, T=19K (August 2014). A version with a waveguide input, or an NRAO or Low Noise Factory (LNF) amp would likely perform better, by ~0.5 - 2K.

[4] - Band 4 LNA is a combination of data from Low Noise Factory LNF-LNC16_28WB (20-26 GHz) and LNF-LNC23_42WB (27-35 GHz), assuming a custom WR-34 housing. A custom MMIC from LNF will be required for Band 4, but N. Wadefalk wrote (8/14/18) that there would be no added NRE or price change, as it's a simple design change, and the WR-34 launcher exists.

[5] - Band 5 LNA data is a Low Noise Factory LNF-LNC28_52WB, 28-52 GHz, in a WR-22 housing.

[6] - Band 6 LNA data is of a 35nm MMIC LNA based on 35nm NGIC devices, from David Quadrado-Calle, U. of Manchester.

[7] - Numbers highlighted in yellow are either undetermined or rough estimates.

Table 7 - LNA gain and noise temperature vs. Frequency, Bands 1–6.

Cryogenic Subsystem Requirements

020.30.10.00.00-0001-REQ-A-CRYOGENIC_SUBSYSTEM_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
D. Urbain	Electronics Div., NRAO	2018-10-24
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-18

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.24 10:25:47 -06'00'	Electronics Div., NRAO	2019-07-24
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:49:16 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:49:35 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
1	2018-07-27	D. Urbain	All	Initial draft
2	2018-09-13	D. Urbain	All	Revised draft
3	2018-09-27	S. Durand	All	Small edits
4	2018-10-19	D. Urbain	All	Answered RIDs
A	2019-07-24	A. Lear	All	Incorporated edits by M. McKinnon; prepared document for approvals and release

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
1.3 Assumptions Made Regarding the ngVLA Cryogenics 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
3 Overview of Subsystem Requirements 6
4 Functional Requirements 7
5 Operational Performance Requirements 7
5.1 Vacuum Pump Requirement 7
5.2 Cryocooler Requirements 7
5.3 Helium Compressor Requirements 8
6 Mechanical Interfaces 9
6.1 Receiver/Front End Mechanical Interface 9
6.2 Antenna Mechanical Interface 9
6.2.1 Available Space on the Antenna Platform 9
6.2.2 Mechanical Interface with the Antenna Platform 9
6.3 Elevation Wrap and Helium Lines 9
6.3.1 Flexible Helium Lines 9
6.3.2 Rigid Helium Lines 10
6.3.3 Helium Line Fittings 10
7 Electrical Interface 12
8 Environmental Conditions and Corresponding Operating Modes 12
8.1 Site Elevation 12
8.2 Limits of Operating Conditions 12
8.3 Survival Conditions 12
8.4 M&C Interfaces 13
8.5 Monitoring Interfaces (Multicast on Ethernet Bus) 13
8.5.1 Interface with Front End M&C 13
8.5.2 Interface with Nearest Weather Station 13
8.6 Command Interface (Star Configuration Ethernet Bus) 13
8.6.1 Interface with Antenna Master M&C Module 13
8.7 Serial RS232/485 Communications 13
8.7.1 Interface with the Vacuum Pump Controller 13
8.7.2 Interface with the Helium Compressor 13
8.8 SPI Communication with the Power Electronics 14
9 EMC/RFI Requirements 15
9.1 Shielding of Compressor Outdoor Unit 15
9.2 Shielding of Cryo M&C Enclosure 15
10 Maintenance 16
10.1 Scheduled Maintenance 16
10.2 Onsite Maintenance 16
10.3 Maintenance at the Service Center(s) 16

11 Shipping/Transport and Acceptance Test **16**
11.1 Shipping from Manufacturer to Integration Center *16*
11.2 Transport between Integration Center and Antenna *16*
11.3 Acceptance Test *16*
12 Appendix **17**
12.1 Enclosure *17*
12.2 Abbreviations and Acronyms *18*

1 Introduction

1.1 Purpose

This document aims to present a set of technical specifications for the ngVLA cryogenic subsystem. Requirements defined in this document are drawn from the ngVLA preliminary system requirements document [AD01], the ngVLA environment specification document [AD02] and the ngVLA EMC/RFI specification document [AD03].

1.2 Scope

The scope of this document includes requirements for the cryogenic subsystem, as delivered for ngVLA integration. The following requirements will be discussed in this document:

- Operational performance requirements
  - Vacuum pump
  - Refrigerator
  - Compressor
- Mechanical interfaces
  - With receiver
  - With antenna
- Electrical interfaces
- Environmental conditions
  - Site elevation
  - Normal operating conditions
  - Survival mode conditions
- Operating modes
  - Start-up
  - Cool down
  - Regular/observing mode
  - Warm-up
  - Recovery from survival mode
  - Stand-by mode
  - By-pass mode
- M&C interfaces
  - Multicast on Ethernet Bus
  - Command on Ethernet Bus
  - Serial interfaces
  - SPI communications
- EMC/RFI requirements
- Maintenance requirements
- Transport requirements

1.3 Assumptions Made Regarding the ngVLA Cryogenics

The ngVLA cryogenics subsystem is directly related to the ngVLA Front End. The [AD05] document decribes the reference design for the ngVLA Front End; based on this document, the cryogenics subsystem assumes two Dewars, each equipped with a two-stage Gifford McMahon (GM) refrigerator and a single helium compressor per antenna.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	System Level Environmental Specifications	020.10.15.10.00-0001-SPE
AD03	EMC-RFI Specifications	020.10.15.10.00-0002-REQ
AD04	ngVLA Monitor and Control Interface Layer: Preliminary Requirements & Design Description	020.50.25.00.00.0002-DSN
AD05	ngVLA Front End Design Description	020.30.03.01.00-0003-DSN
AD06	ngVLA Cryogenic Subsystem Reference Design Description	020.30.10.00.00-0002-DSN
AD07	Rick Perley, "Notes on RFI Emissions Levels," 12/21/2006	VLA-VLBA Interference Memo #34

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	R. Rayet et. al., "ngVLA Front-End Receivers Thermal Study Initial Analysis Report," Callisto France S.A.S., 7/11/2018	020.30.10.00.00-0004-REP
RD02	Measured performance data memo, FA-40 helium compressor with VFD, Sumitomo SHI, July 2018	020.30.10.00.00-0005-REP

3 Overview of Subsystem Requirements

This document presents the ngVLA cryogenic subsystem technical specifications. The cryogenics performance requirements are driven by the Front End concept described in [AD05] and by maintenance and power requirements established for the project. It has been emphasized that for the ngVLA project to be successful, the annual operation cost shall not exceed the current VLA and VLBA budgets by more than a factor of three. This is quite challenging considering that ngVLA aims for about 10 times the number of antennas.

To meet the operations budget goal, the number of receivers per antenna has been reduced to two, compared to eight on the VLA, and the cryocoolers and the compressor have been equipped with variable frequency drives (VFDs) for adjustable cooling capacity. Having the capability to adjust the cooling power allows the supply of pressurized helium to be matched to the demand, while minimizing power consumption.

4 Functional Requirements

The purpose of the cryogenic subsystem is to cool the sensitive receiver electronics to reduce intrinsic thermal noise and maximize sensitivity. The key functions include

- Establish Dewar vacuum.
- Cooling of feeds and receiver gain stages.
- Maintain Dewar vacuum through cryo-pumping.
- Adjust cooling capacity to meet the temperature requirements while minimizing the power consumption.

5 Operational Performance Requirements

5.1 Vacuum Pump Requirement

The vacuum pump removes air trapped inside the closed volume of the Front End cryostat. When the atmosphere is evacuated, heat transfer by convection between the outside walls and the inside components of the Dewar becomes negligible. In practice, a minimum vacuum is required before starting the refrigerator. If this threshold is not reached, the thermal loading is high enough to overcome its cooling power, preventing the electronics from reaching the desired temperature. It has been established that a Dewar pressure of 10^{-2} mbar is needed at the start for a successful cool down. Therefore, the vacuum pump selected must have a base pressure lower than this 10^{-2} mbar threshold (Table 1).

The ngVLA Front End concept has two cryostats, each with an approximate volume of 60–70 liters. It is desired to pump down both receivers in less than 15 minutes. The actual pump down time is difficult to estimate because it depends on many factors (pumping orifice size, presence of multi-layer insulation (MLI), cleanliness of the surfaces, etc.). Nevertheless, a quick calculation shows that an empty volume of 130 liters will require a 2 l/s pumping speed to reach 10^{-2} mbar in approximately 14 minutes. The minimum pumping speed is therefore specified at 2 l/s, but a larger capacity is recommended.

Vacuum pump minimum base pressure	10^{-2} mbar
Minimum pumping speed	2 l/s

Table 1 - Minimum requirements for the vacuum pump.

5.2 Cryocooler Requirements

The Front End design description [AD05] presents the ngVLA receiver concept. A new type of feed-horn selected for Bands 3–6 has allowed all six frequency bands to be fitted in two cryostats. A thermal analysis done by Callisto [RD01] (Table 2) gives us preliminary numbers for heat loads on both cryostats.

Cold-Head	Dewar A (Band 1)	Dewar B (Bands 2–6)
1st stage	9.88 W at 50 K	18.4 W at 50 K
2nd stage	3.08 W at 15 K	4.3 W at 15 K

Table 2 - Calculated thermal loads for the ngVLA cryostats (ambient temperature 20°C and vacuum pressure 10^{-6} mbar).

These calculated values are preliminary and some load reductions are possible by receiver design optimization. The sensitive electronics need not be cooled down to 15 K to give the desired sensitivity; 20 K is the temperature limit that needs to be achieved by the second stage of the cryocooler.

Based on this information, the following cooling capacities for the refrigerator have been selected (Table 3):

- **1st stage:** The cold-head shall have enough cooling capacity on the first stage when running at maximum speed to absorb 20W of heat and maintain the stage temperature at 80 K or below.
- **2nd stage:** The cold-head shall have enough capacity on the second stage when running at maximum speed to absorb 5W of heat and maintain the stage temperature at 20 K or below.

Cold-head	Cooling capacity	Temperature	Speed
1st stage	20 W	80 K	60 Hz
2nd stage	5 W	20 K	60 Hz

Table 3 - Cold-head specifications.

5.3 *Helium Compressor Requirements*

The helium compressor shall have enough flow capacity to run two medium-size refrigerators at nominal speed, each with a flow requirement that does not exceed 20 scfm for a supply pressure of 300psi. Because the energy cost is a major concern for ngVLA, the power consumption of the helium compressor shall not exceed 5 kW when operating at 60 Hz.

Table 4 lists the compressor performance requirements.

Electrical supply	3 phase 200V 60 Hz
Power consumption	Max 5kW at 60 Hz
Ambient temperature	–30°C to 45°C
Flow at 60 Hz and 300 psi supply pressure	40 scfm min
Weight	< 150 kg
Maintenance	30,000 hours

Table 4 - Helium compressor specifications.

6 Mechanical Interfaces

The various mechanical interfaces described below will be documented in greater detail in future ICDs.

6.1 Receiver/Front End Mechanical Interface

Each Front End assembly is equipped with one cold-head that can be removed for service. However, the cylinder housing the cold-head displacer shall be permanently attached to the cryostat because it has many hardware connections to the rest of the Dewar assembly.

6.2 Antenna Mechanical Interface

6.2.1 Available Space on the Antenna Platform

The antenna platform shall provide a volume of L(1.8m) x W(1.75m) x H(1.2m) for the compressor.

6.2.2 Mechanical Interface with the Antenna Platform

The helium compressor will be installed on an antenna platform above the azimuth bearing but below the elevation axis. The platform shall support the weight of the compressor and service personnel with the required safety factor (TBD). The mounting brackets that attach the compressor to the platform shall support the mechanical stresses induced by antenna rotation at full speed, followed by maximum deceleration, and the force applied by high winds on the compressor outdoor unit. Table 5 lists the most important parameters.

Inclination	Within 5 degrees of horizontal
Slew	180 deg/min
Wind	Max 50 m/s
Magnetic field	≤ 150 Gauss
Weight (compressor plus 2 people)	350 kg

Table 5 - Mechanical limits for the compressor mount on the antenna platform.

6.3 Elevation Wrap and Helium Lines

The compressor is located on a platform behind the dish and above the azimuth bearing, and the Front End cryostats are located on a platform supported by the subreflector feedarm. The helium lines (two lines: one supply, one return) are run from the compressor to the receiver platform, through the elevation axis cable wrap. On the receiver platform, the supply line connects to a two-way manifold that splits the flow between the two refrigerators. A second two-way manifold recombines the refrigerator output flows into the return line. The helium lines shall be built with a combination of rigid seamless stainless steel tubing that is securely attached to the antenna structure and some flexible sections; see details below. The helium lines are part of the cryogenic subsystem, and their exact location and mounting points shall be described in a future antenna ICD.

6.3.1 Flexible Helium Lines

The various sections of flexible lines are described below:

- Between compressor and antenna platform, the flex-lines will allow easy connection to the compressor using Aeroquip 5400 series refrigerant couplings.
- Through the elevation wrap, a set of armored flex-lines will join the rigid sections of lines from the compressor platform and the sub-reflector feed harm. The armored flexible shell (Figure 1) will help maintain a uniform bending radius on the line through the elevation wrap, and will guarantee the

minimum bend radius is not exceeded. The life expectancy of the flex-lines shall exceed 20 years of antenna operation (number of flex cycles is TBD).
  - Static bending radius 25 cm (10")
  - Dynamic bending radius 70 cm (28")
- Between the antenna feedarm and receiver platform, the flex-lines will allow free translation of the receiver platform for band selection, and easy connection to the refrigerators mounted to the cryostats.

Figure 1 - Armored flex-line cross section view.

6.3.2 Rigid Helium Lines

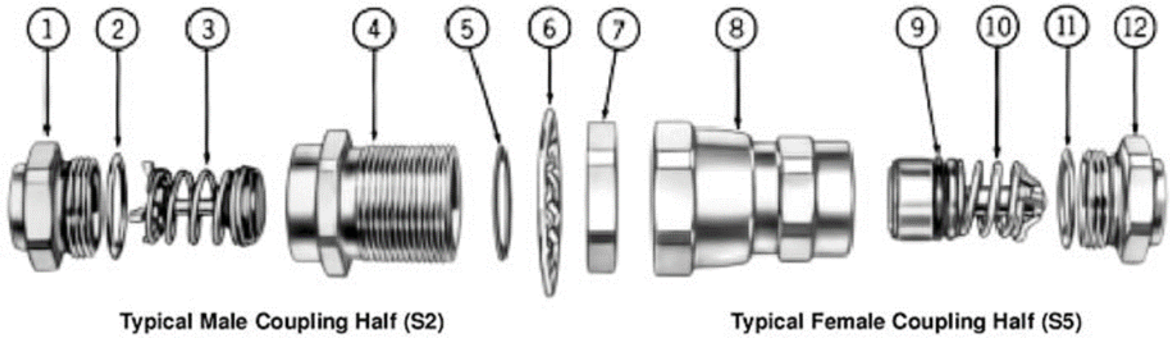
The rigid helium lines are made of seamless stainless steel ½" ID line, thoroughly cleaned inside to remove contaminants (oil and other chemical residues). The specified wall thickness is 0.065", with a working pressure of 4500 psig (e.g., Swagelok stainless steel seamless tubing).

6.3.3 Helium Line Fittings

The interconnection between two rigid lines will use Swagelok compression fittings (Figure 2).

Figure 2 - Swagelok fittings for rigid helium line connections.

The other connections will use Aeroquip 5400 series (or similar) self-sealing gas fittings (Figure 3), which are standard couplings for cryogenic equipment. The O-ring and gasket material shall be made out of butyl rubber, to meet the environmental requirement and avoid leaks in extremely cold weather conditions.



Component Part Numbers

Item No.	Dash Size ‣ / O.D. Tube Size ‣	–4 / 1/4"–3/8"	–8 / 1/4"–5/8"	–12 / 5/8"–7/8"	–16 / 7/8"–1 3/8"	Line Ref.
	Typical Male Half					1
1	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	2
2	O-Ring	22546–12	22546–17	22546–23	22546–28	3
3	Poppet Valve Assembly	5400–S20–4	5400–S20–8	5400–S20–12	5400–S20–16	4
4	Body	5400–17–4	5400–17–8	5400–17–12	5400–17–16	5
5	Gasket Seal	22008–4	22008–8	22008–12	22008–16	6
6	Lock Washer	5400–54–4S	5400–54–8S	5400–54–12S	5400–54–16S	7
7	Jam Nut	5400–53–4S	5400–53–8S	5400–53–12S	5400–53–16S	8
	Typical Female Half					9
8	Union Nut and Body Assembly	5400–S16–4	5400–S16–8	5400–S16–12	5400–S16–16	10
9	O-Ring	22546–10	22546–112	22546–116	22546–214	11
10	Valve and Sleeve Assembly	5400–S19–4	5400–S19–8	5400–S19–12	5400–S19–16	12
11	O-Ring	22546–12	22546–17	22546–23	22546–28	13
12	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	14

*Specify O.D. Tubing size of adapter required in 16th of an inch. Example: –4 coupling with 3/8" O.D. tubing is 6/16 or –6. Part number is then 202208–6–4.

Figure 3 - Aeroquip 5400 series couplings.

7 Electrical Interface

Table 6 shows the cryogenics subsystem electrical power requirements from the antenna. These requirements will be described in more detail in a future antenna ICD.

Description	Voltage	Current max breaker protection	Frequency	Power consumption
Single phase	120 (±5%) VAC	35 A	60 Hz	1 kW max
3 Phase Delta configuration, 5 wires Ph1, Ph2, Ph3 and Neutral plus GND	200 (±10%) VAC	25 A	60 Hz	5 kW max

Table 6 - Antenna power requirements.

8 Environmental Conditions and Corresponding Operating Modes

8.1 Site Elevation

The ngVLA core array will be located at the Very Large Array site, on the plains of San Agustin (elevation 2100 m). The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. The cryogenic subsystem shall be designed to operate at altitudes ranging from sea level up to 2500 m.

8.2 Limits of Operating Conditions

The cryogenic subsystem shall operate normally within the environmental limits listed in Table 7.

Parameter	Req. #	Value
Solar Thermal Load	ENV0321	Exposed to full Sun
Wind	ENV0331	W ≤ 15 m/s average over 10 min.; W ≤ 20 m/s gust
Temperature	ENV0332	–20 °C ≤ T ≤ 45 °C
Precipitation	ENV0333	5 cm/hr over 10 min
Ice	ENV0334	No ice accumulation on outdoor compressor unit

Table 7 - Operating conditions.

8.3 Survival Conditions

Outside of the operating condition limits (Table 8) some degradation in performance is acceptable.

Parameter	Req. #	Value
Wind	ENV0341	0 m/s ≤ W ≤ 50 m/s average
Temperature	ENV0342	–30°C ≤ T ≤ 50°C
Radial Ice	ENV0343	2.5 cm
Rain Rate	ENV0344	16 cm/hr. over 10 min
Snow load	ENV0346	100 kg/m^2 on horizontal surfaces
Hail stones	ENV0347	2.0 cm diameter

Table 8 - Survival conditions.

8.4 M&C Interfaces

The compressor M&C Module will be delivered with the Cryo M&C Enclosure. It shall control the helium compressor and both refrigerators as well as the vacuum pump. It will collect monitoring information from various sub assemblies but will only receive commands from the antenna M&C.

8.5 Monitoring Interfaces (Multicast on Ethernet Bus)

8.5.1 Interface with Front End M&C

The compressor M&C Module will use temperature and pressure information provided by the individual cryostat M&C Modules to adjust independently the speed of each cold-head. The temperature and pressure data will be multicast by the Cryostat M&C modules on the Ethernet bus.

8.5.2 Interface with Nearest Weather Station

The compressor M&C Module will use monitored information from the nearest ngVLA weather station to select or modify certain modes of operation. For example, the starting speed during the start-up procedure will be adjusted based on the ambient temperature. The weather station M&C module will multicast the data on the Ethernet bus, and the compressor M&C Module will subscribe to the data stream and collecting the information as needed.

8.6 Command Interface (Star Configuration Ethernet Bus)

8.6.1 Interface with Antenna Master M&C Module

The control messages to the compressor M&C Module will always come from the antenna master M&C module. Any other module that needs to send a control message to the compressor M&C Module will do so through the antenna master M&C module and reciprocally. The flow of control messages will use the Ethernet bus in star configuration with the antenna master M&C module as the central hub for the antenna.

8.7 Serial RS232/485 Communications

8.7.1 Interface with the Vacuum Pump Controller

For the reference design, the vacuum pump controller is located inside the cryo M&C enclosure. The compressor M&C module will communicate with the vacuum pump controller through a serial RS232/485 connection. A hardware interlock will prevent the pump from running if oil temperature is not within the manufacturer's recommended range.

8.7.2 Interface with the Helium Compressor

The compressor M&C module is located with the compressor power electronics (VFD) inside a shielded weather proof enclosure. The temperature and pressure sensors listed in Table 9 are placed in various locations inside the compressor outdoor unit. The compressor M&C module will communicate with the compressor outdoor unit and retrieve the information through a serial interface. The compressor information will be multicast by the compressor M&C module on the Ethernet bus to make it available to other modules.

Sensor type	Location
Temperature	
Ts	Scroll capsule
Tx	Oil heat exchanger input
Tr	Oil return line to Scroll capsule
Tg	Heat exchanger output gas
Tc	Coalescer input
Pressure	
Ps	Supply line
Pr	Return line
Frequency/speed	
Fc	Cooling fan speed
Current	
Is	Scroll capsule current
If	Fan current

Table 9 - Outdoor compressor monitor points.

8.8 SPI Communication with the Power Electronics

The cryo M&C enclosure will house the compressor M&C module and the power electronics (VFDs) and shelter them from the environment while also providing RFI shielding. The compressor M&C module will communicate with the power electronics that drives the compressor capsule and cold-heads via SPI Bus. Table 10, Table 11, and Table 12 show monitor points for compressor VFD and Dewars A and B.

Sensor type	Location
Frequency/speed	
F_{comp}	Speed scroll capsule
Current	
I_{comp1}	Compressor Scroll capsule current phase 1
I_{comp2}	Compressor Scroll capsule current phase 2
I_{comp3}	Compressor Scroll capsule current phase 3
Voltage	
V_{comp1}	Compressor Scroll capsule voltage phase 1
V_{comp2}	Compressor Scroll capsule voltage phase 2
V_{comp3}	Compressor Scroll capsule voltage phase 3

Table 10 - Compressor VFD monitor points.

Sensor type	Location
Frequency/speed	
F_{DWA}	Speed cold-head receiver Dewar A
Current	
I_{DWA-1}	Dewar A cold-head current phase 1
I_{DWA-2}	Dewar A cold-head current phase 2
Voltage	
V_{DWA-1}	Dewar A cold-head current voltage phase 1
V_{DWA-2}	Dewar A cold-head current voltage phase 2

Table 11 - Dewar A VFD monitor points.

Sensor type	Location
F_{DWB}	Speed cold-head receiver Dewar B
Current	
I_{DWB-1}	Dewar B cold-head current phase 1
I_{DWB-2}	Dewar B cold-head current phase 2
Voltage	
V_{DWB-1}	Dewar B cold-head current voltage phase 1
V_{DWB-2}	Dewar B cold-head current voltage phase 2

Table 12 - Dewar B VFD monitor points.

9 EMC/RFI Requirements

The digital electronics in the M&C modules and the high power switching electronics in the VFD drives require shielding from RFI emissions. The following sections describe the measures taken in this regard.

9.1 Shielding of Compressor Outdoor Unit

The compressor outdoor unit has a Scroll capsule that runs at variable speed due to a VFD located in the Cryo M&C Enclosure. The cable that carries the three-phase power between them will have to be shielded and have a ground connection at both ends.

9.2 Shielding of Cryo M&C Enclosure

The Cryo M&C Enclosure contains the compressor M&C interface LRU, the VFD LRUSs for the Scroll capsule, and the two cold-heads, as well as controllers for the cooling fan and vacuum pump. All the electronics listed above can generate RFI and must be contained within an RFI-tight enclosure(s). The connections to the M&C enclosure shall be done through special filtered connectors. The whole assembly must meet the VLA RFI requirements [AD07]. The validation of the shielded enclosure will be done in the VLA reverberation chamber with a specially designed test set.

10 Maintenance

10.1 Scheduled Maintenance

Scheduled maintenance will be performed on the cryogenics system when the antenna is being serviced (Table 13). Because of the large number of antennas, it is anticipated that one antenna will have a major overhaul every 35,000 hours.

Compressor Charcoal trap adsorber	≥ 35,000 hrs of operation
Compressor heat exchanger cleaning	≥ 35,000 hrs of operation
Compressor fan motor bearing replacement	≥ 35,000 hrs of operation
Cold-head replacement	≥ 35,000 hrs of operation
System static pressure recharge (He)	≥ 10,000 hrs (TBC)
Compressor oil refill	≥ 35,000 hrs of operation

Table 13 - Scheduled maintenance.

10.2 Onsite Maintenance

All scheduled maintenance (see Table 13) shall be performed at the site when the antenna is being serviced. Unscheduled repairs shall also be done at the site, unless it is a compressor failure that requires depressurization of the helium circuit to be fixed.

10.3 Maintenance at the Service Center(s)

All compressor repairs that require depressurization of the helium circuit shall be done at the service center(s). Cold-head overhaul shall also be done at the service center(s).

11 Shipping/Transport and Acceptance Test

11.1 Shipping from Manufacturer to Integration Center

The compressor shall be mounted on a wood pallet with tilt sensors and shock sensors to ensure safe delivery by truck and early detection of possible abuse.

11.2 Transport between Integration Center and Antenna

The compressor shall be transported from the integration center to the antenna in a truck equipped with a crane that will allow the compressor to be lifted up to the antenna platform.

11.3 Acceptance Test

The compressor shall be tested at the factory and delivered with a complete set of test data and a compliance report. The cold-heads shall also be tested at the factory and delivered with the load maps and the compliance reports.

The M&C enclosure will be tested in the reverberation chamber to ensure compliance with the VLA requirements. A recently-serviced compressor or cold-head will be tested at the integration center and will have to pass a series of acceptance tests prior to being released as a spare unit.

12 Appendix

12.1 Enclosure

For the reference design we are not considering an outside enclosure for the outdoor compressor unit; however, the possibility to add such an enclosure to the antenna platform will be evaluated during the design phase. Some parameters to consider for the enclosure include:

- Weather protection
  - Avoid snow/ice accumulation on compressor
  - Minimize exposure to rain water (corrosion)
  - Shield the cooling fan from high winds
  - Prevent damage from hailstorms
  - Reduce sun damage (UV)
- Impact on antenna design
  - Extra weight on platform
  - Extra volume on platform
  - Extra cost
  - Reduced accessibility
  - Increased maintenance time (enclosure must be removed to access compressor outdoor unit)

12.2 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ICD	Interface Control Document
LNA	Low Noise Amplifier
LRU	Line-Replaceable Unit
M&C	Monitor and Control
MLI	Multi Layer Insulation
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
RD	Reference Document
SPI	Serial Peripheral Interface
VFD	Variable Frequency Drive
VLA	Jansky Very Large Array

Cryogenic Subsystem Reference Design Description

020.30.10.00.00-0002-DSN-A-CRYOGENIC_SUBSYSTEM_REF_DESIGN

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
D. Urbain	Electronics Div., NRAO	2018-10-30
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-18

APPROVALS (Name and Signature)	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer — R. Selina 2019.07.24 12:12:18 -06'00'	Electronics Div., NRAO	2019-07-24
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:56:16 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:56:32 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	2018-04-17	D. Urbain	All	Initial Draft
0.2	2018-05-15	D. Urbain	All	Revision after Rob Selina review
2.0	2018-06-05	S. Durand	All	June Update
3.0	2018-06-07	D. Urbain	7,10,11	Revise mainly section 10 after conversation with W. Koski
4.0	2018-06-15	D. Urbain	All	Reorganize document; add vacuum pump requirements
5.0	2018-06-22	D. Urbain	10,11,12	Revise the communication sections
6.0	2018-07-18	D. Urbain	All	Change vacuum pump description
7.0	2018-07-23	D. Urbain	All	Update document after R. Selina review
8.0	2018-09-13	D. Urbain	All	Revise document
8.1	2018-09-13	S. Durand	All	Revise document
8.2	2018-10-05	D.Urbain	Number	Correct document number
8.3	2018-10-23	D. Urbain	All	Answer RIDs
8.4	2018-10-30	D. Urbain	6.2	Add information on vacuum pump
A	2019-07-24	A. Lear	All	Incorporate minor edits by M. McKinnon; prepare document for approvals and release

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
1.3 Assumptions Made Regarding the ngVLA Cryogenics 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
2.3 Vocabulary 6
3 Overview of Subsystem Requirements 7
4 Key Experiments that Led to the Reference Design 7
4.1 The Green Antenna VFD Experiment 7
4.2 The Variable-Speed Compressor Experiment 7
4.3 How Reliability is Linked to Operating Frequency 8
4.4 Comparison of VLA and ngVLA Reference Design 8
5 Monitor and Control Interfaces 10
5.1 Monitoring Interfaces (Multicast on Ethernet bus) 11
5.1.1 Interface with Front End M&C 11
5.1.2 Interface with the Nearest Weather Station 11
5.1.3 M504 Weather Station Module 12
5.2 Command Interface (Star Configuration Ethernet Bus) 12
5.2.1 Interface with Antenna Master M&C Module 12
5.3 Serial RS232/485 Communications 12
5.3.1 Interface with the Vacuum Pump Controller 12
5.3.2 Interface with the Helium Compressor 13
5.4 SPI Communication with the Power Electronics 13
6 Operational Performance Requirements 15
6.1 Vacuum Pump Requirement 15
6.2 Onboard Vacuum Pump 15
6.3 Vacuum Pump Equipment for the Integration Center and Service Vehicle 16
6.4 Cryocooler Requirements 16
6.5 Cold-Head Selection 17
6.6 Helium Compressor Requirements 18
6.7 Helium Compressor Selection 18
7 Mechanical Interfaces 21
7.1 Receiver/Front End Mechanical Interface 21
7.2 Antenna Mechanical Interface 22
7.2.1 Required Space on the Antenna Platform 22
7.2.2 Mechanical Interface with the Antenna Platform 22
7.2.3 Compressor M&C Enclosure Interface 23
7.3 Elevation Wrap and Helium Lines 23
7.3.1 Flexible Helium Lines 23
7.3.2 Rigid Helium Lines 24
7.3.3 Helium Line Fittings 24
8 Electrical Interface 25

9 Environmental Conditions and Corresponding Operating Modes 25
9.1 Site Elevation 25
9.2 Limits of Operating Conditions 25
9.3 Survival Conditions 25
9.3.1 Extreme Heat 26
9.3.2 Extreme Cold 26
9.3.3 Extreme Wind 26
10 Modes of Operation 27
10.1 Start-Up Mode 27
10.2 Cool-Down Mode 27
10.3 Observing Mode 27
10.4 Warm-Up Mode 27
10.5 Recovery Mode 27
10.6 Stand-By Mode 27
10.7 Bypass Mode 28
11 EMC/RFI Requirements 29
11.1 Shielding of Compressor Outdoor Unit 29
11.2 Shielding of Cryo M&C Enclosure 29
11.3 Cooling of Cryo M&C Enclosure 29
12 Maintenance 30
12.1 Scheduled Maintenance 30
12.2 Onsite Maintenance 30
12.3 Maintenance at the Service Center(s) 30
13 Shipping/Transport and Acceptance Test 30
13.1 Shipping from Manufacturer to Integration Center 30
13.2 Transport between Integration Center and Antenna 30
13.3 Acceptance Test 30
14 Appendix 31
14.1 Compressor Enclosure 31
14.2 Abbrevations and Acronyms 32

1 Introduction

1.1 Purpose

This document provides a description for the cryogenic subsystem reference design. The purpose of the cryogenic subsystem is to cool the sensitive receiver electronics to reduce intrinsic thermal noise and maximize sensitivity. During the selection process emphasis was placed on power consumption and reliability as well as maintenance cost in order to meet the operating budget target.

1.2 Scope

The scope of this document is to present the complete cryogenic equipment selected for the ngVLA Reference Design. It starts with a hardware description of the pump, the refrigerator, and the compressor and it follows with the antenna interfaces requirements. The environmental conditons and the various mode of operation are also presented. The M&C interface with the rest of the control electronics is described in detail, but no budgetary information is listed.

1.3 Assumptions Made Regarding the ngVLA Cryogenics

The ngVLA cryogenics is directly related to the ngVLA Frontends. [AD05] describes the reference design for the ngVLA Front End. Based on this information, the cryogenics subsystem assumes two Dewars per antenna, each equipped with a two-stage Gifford McMahon (GM) refrigerator, with both connected to a single Helium compressor.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev/Doc. No.
AD01	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	System Level Environmental Specifications	020.10.15.10.00-0001-SPE
AD03	EMC-RFI Specifications	020.10.15.10.00-0002-REQ
AD04	Monitor and Control Interface Layer: Preliminary Requirements & Design Description	020.30.45.00.00.0004-DSN
AD05	Front End Design Description	020.30.03.01.00-0003-DSN
AD06	Cryogenics Subsystem Requirements	020.30.10.00.00.0001-REQ
AD07	R. Perley, "Notes on RFI Emissions Levels" 12/21/2006	VLA-VLBA Interference Memo #34

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev / Doc. No.
RD01	R. Rayet et. al., "ngVLA Front-End Receivers Thermal Study Initial Analysis Report," Callisto France S.A.S., 7/11/2018	020.30.10.00.00-0004-REP
RD02	Measured performance data memo, FA-40 Helium compressor with VFD, Sumitomo SHI, July 2018	020.30.10.00.00-0005-REP
RD03	Wootten, D. Urbain, W. Grammer and S. Durand, "The ngVLA Cryogenics," 231th AAS meeting, January 8–12 2018 National Harbor, MD	Poster session
RD04	D. Urbain, "ngVLA Cryogenics Subsystem Concept," URSI meeting, January 4–7, 2017, Boulder, CO	n/a
RD05	D. Urbain, W. Grammer, et al., "Improved Power Efficiency for Cryogenics at the VLA," ICC19 June 20–23 2016, San Diego CA	Cryocoolers 19, Edited by S.D. Miller and R.G. Ross Jr, pp. 505–511
RD06	D. Urbain, W. Grammer, S. Sturgis, "ngVLA Cryogenics Reference Design," ngVLA Reference Design Workshop, Socorro NM, July 2018; private communication	n/a
RD07	James Gregg, "MTBF Report on EVLA Cryogenics," NRAO, Socorro NM, 3/29/2016, Private Communication	n/a
RD08	Adixen_SD Pump Service Manual	Alcatel Vacuum Technology pp. 54-98, 2011

2.3 Vocabulary

In the following document, refrigerator, cold-head, and cryocooler represent the same piece of equipment. Dewar and cryostat are also interchangeable.

3 Overview of Subsystem Requirements

This document presents the design discription of the ngVLA cryogenic subsystem. The performance requirements for the cryogenics are driven by the Front End concept and by maintenance and power requirements established for the project. It has been emphasized that for the ngVLA project to be successful, the annual operation cost shall not exceed the current VLA and VLBA budget by more than a factor of three. This is quite challenging considering that the project is aiming for about ten times the number of antennas.

In order to meet the operations budget goal, the number of receivers per antenna has been reduced to two, compared to eight on the VLA, and the cryocoolers and the compressor have been equipped with variable frequency drives (VFDs) for adjustable cooling capacity. Having the capability to adjust the cooling power allows the supply of pressurized Helium to be matched to the demand, while minimizing power consumption.

4 Key Experiments that Led to the Reference Design

4.1 *The Green Antenna VFD Experiment*

The Green Antenna initiative was initiated by the NRAO Socorro Electronics Division in 2015, with a goal of finding ways to reduce the power consumption and improve reliability of the VLA. The VFD experiment described in [RD05] demonstrated the speed of the refrigerators used to cool the Front Ends could be reduced, with limited impact on the temperature of the cooled electronics. Table 1 shows the temperature variations for six VLA Dewars as the refrigerator speed is reduced to 30 Hz in 5 Hz steps. This experiment was essential in showing that most of the VLA receivers do not require the full cooling capacity of their refrigerator after cooldown. In addition, a variable-speed refrigerator could reduce the total helium flow required from the associated compressor.

	C Band		X Band		Ku Band		K Band		Ka Band		Q Band	
Frequency	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K
50 Hz	0.0	0.1	0.0	0.2	0.0	0.6	1.2	0.1	1.3	0.1	2.6	0.4
45 Hz	1.3	0.2	1.3	0.6	1.3	0.8	2.5	0.2	3.9	0.6	7.7	0.7
40 Hz	**2.6**	**0.3**	**2.6**	**0.8**	**1.3**	**1.2**	**3.8**	**0.4**	**5.2**	**1.2**	**12.8**	**1.8**
35 Hz	5.2	1.2	5.1	2.0	2.6	3.1	5.1	0.6	3.9	4.4	17.9	2.6
30 Hz	7.8	1.3	9.0	2.5	3.9	5.6	9.0	1.1	7.8	6.0	33.0	7.7

Table 1 - Results of the VFD experiment at the VLA.

4.2 *The Variable-Speed Compressor Experiment*

This experiment used a Quantum Design HAC4500 helium compressor equipped with a commercial inverter, to show how the speed of the compressor could be adjusted to meet the flow requirement as the number of refrigerators connected to it increases. Figure 1 [RD03] shows the results of the experiment. As the number of refrigerators drops, the demand for pressurized helium from the compressor is reduced and the speed of the motor can be lowered. When the motor slows down, its power consumption drops, and the operating cost is reduced proportionally.

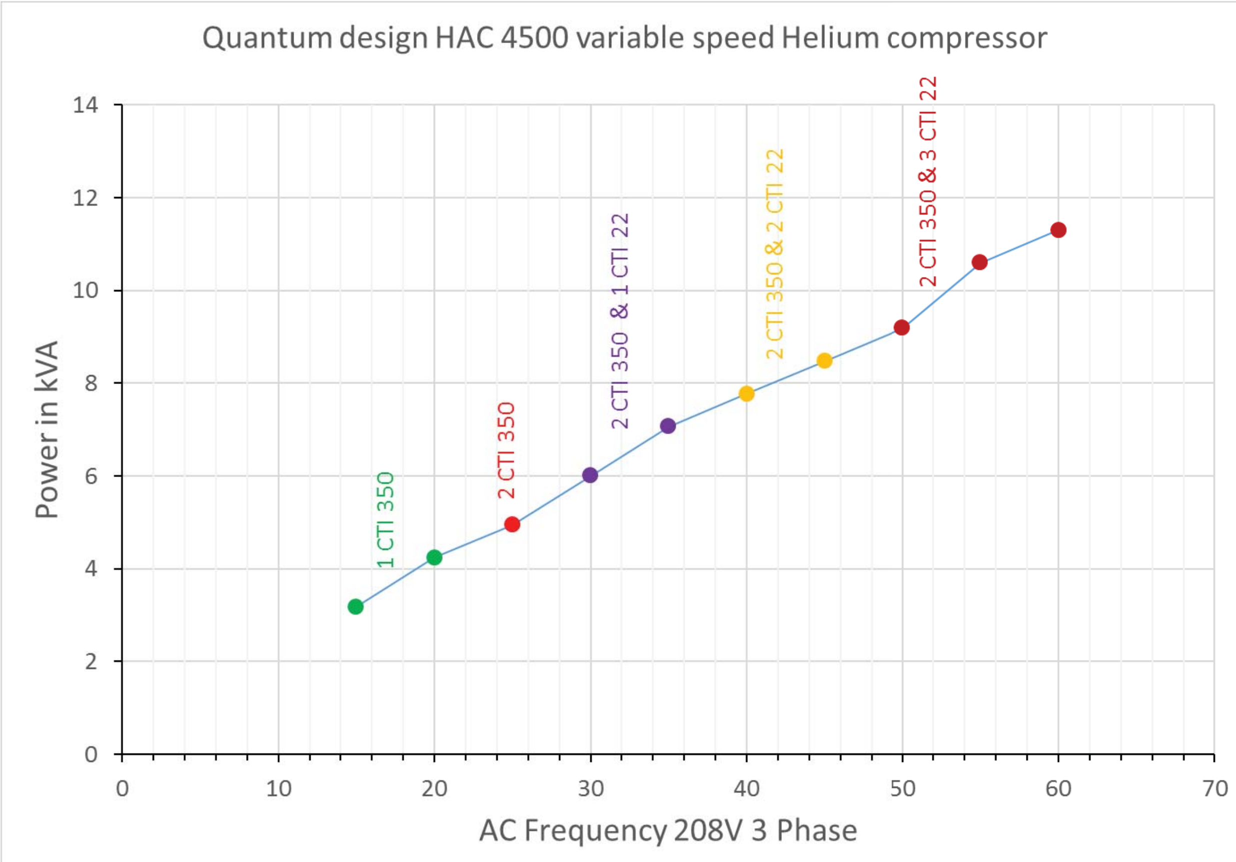


Figure 1 - Variable-speed compressor: capacity and power consumption vs. speed.

4.3 How Reliability is Linked to Operating Frequency

The two experiments described above were key to development of the ngVLA cryogenic reference design, and address how operations cost can be reduced by lowering power consumption. However, speed reduction has the added benefit of reducing mechical wear and improving associated reliability. This was clearly seen in the VLA maintenance data collected over several years [RD07]. The data did show a direct correlation between the refrigerator MTBF and their operating speed: a Model 22 refrigerator operates at 200 rpm, while a Model 350 runs at 72 rpm, and the maintenance interval for the Model 350 is on average three times longer than the Model 22.

4.4 Comparison of VLA and ngVLA Reference Design

Table 2 shows a direct comparision between the VLA and the ngVLA reference design. The data come from a VLA maintenance survey and from power measurements conducted on a prototype compressor and published in [RD02]. The maintenance index is a normalized reliability measure, based on VLA maintenance data, and scaling with total number of refrigerators. For instance, a single Model 350 refrigerator in the VLA run at full speed (60 Hz) has an index of 1, while a single Model 22 has an index of 3. The ngVLA reference design calls for running Model 350 refrigerators at 40 Hz, or 2/3 their nominal speed, so their associated index is 0.66. These indices are used to then estimate total maintenance effort based on number of refrigerators and their respective operating speeds, in both the VLA and ngVLA.

	VLA	ngVLA Reference Design	Ratio (ngVLA to VLA)
Number of Antennas	27 x 25m	214 x 18m + 19 x 6m + 30 18m	9.74
Helium Compressor	3 x 27 = 81	1 x 263 = 263	3.25
AC Power Consumption	81 x 6 = 486kW	263 x 3.75 = 986kW	2.03
Cryocoolers Per Antenna	1 x Model 22, 6 x Model 350, 1 x Model 1050	2 x Model 350	n/a
Total Number of Cryocoolers	27 x 8 = 216	263 x 2 = 526	2.43
Estimated Cryocooler Maintenance Index	27 x (1 x 3 +6 x 1+1 x 1) = 270	263 x (2 x 0.66) = 350	1.3

Table 2 - Comparison of VLA and ngVLA reference design.

The table shows that while the ngVLA has almost 10 times the number of antennas, the estimated energy cost from the cryogenic equipment should only double, and the maintenance required (and associated cost) is only 1.3 times that of the VLA. These numbers show that the reference design is well within the operating cost that was set initially for the ngVLA proposal.

5 Monitor and Control Interfaces

The cryogenic subsystem (Figure 2) is composed of the cryo M&C enclosure (compressor M&C [F525], compressor VFD, Dewar A VFD, Dewar B VFD and vacuum pump controller), the vacuum pump, the compressor outdoor unit, and the Dewar A and B cold-heads. The cryo M&C enclosure shall control the helium compressor and the vacuum pump, and drive both refrigerators. It will collect monitoring information from the weather station and the Front End M&C modules (F521 and F522), but will only accept commands from the antenna M&C module (M500).

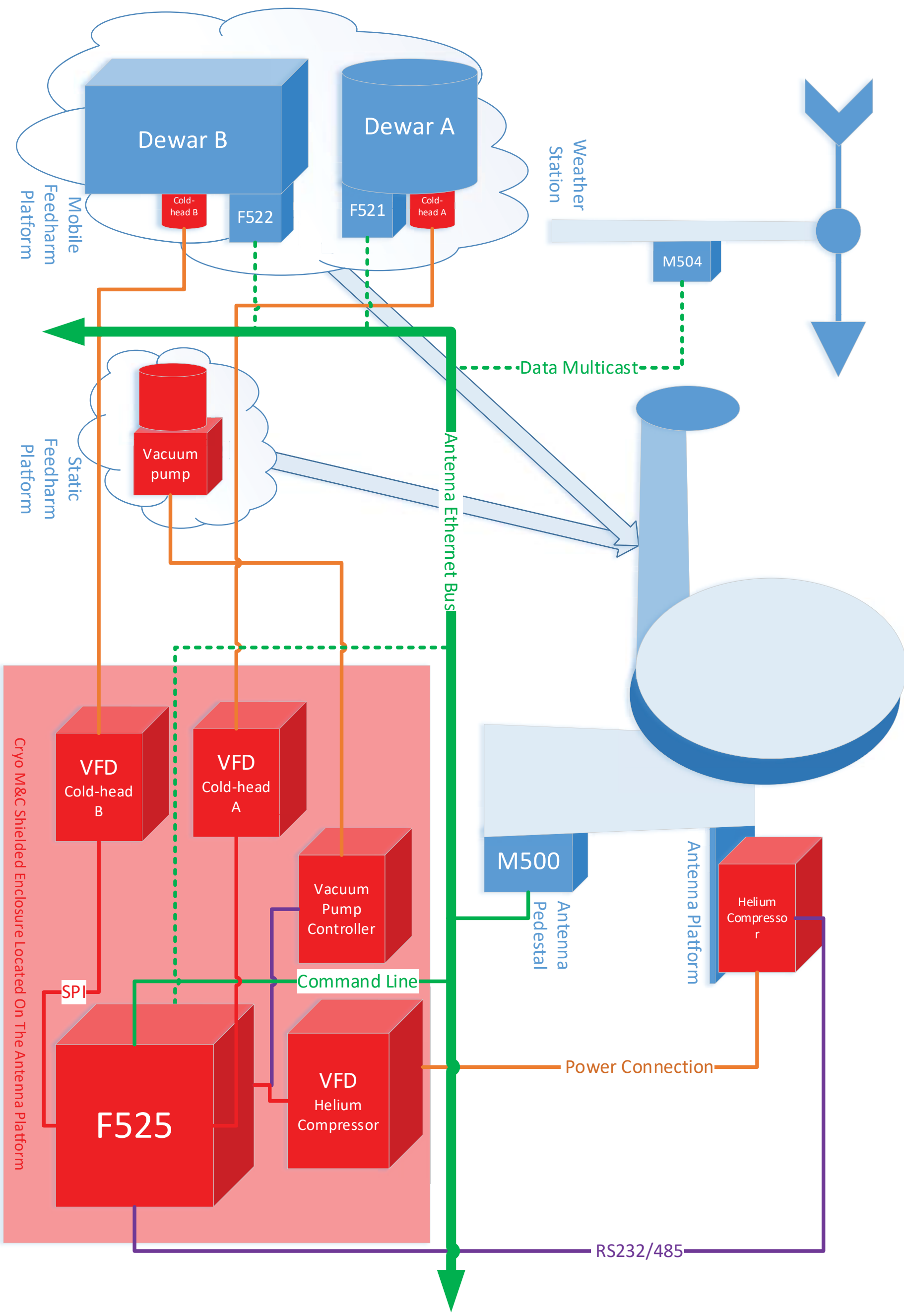


Figure 2 - Cryogenics Monitor and Control subsystem block diagram.

5.1 Monitoring Interfaces (Multicast on Ethernet bus)

5.1.1 Interface with Front End M&C

The compressor M&C (module F525) will use temperature and pressure information provided by individual cryostat M&C modules (F521, F522) to adjust independently the speed of each cold-head. Temperature and pressure data will be multicast by the F521 and F522 modules on the Ethernet bus and the F525 will collect the information stream directly.

5.1.1.1 F521 Dewar A Interface Module

The following values shall be monitored by the F521.

Dewar A	**Location**
Band 1	
$T_{b1\text{-}1}$ Temperature 1st stage	Feed
$T_{b1\text{-}2}$ Temperature 2nd stage	LNA
V_{d1} Vacuum pressure	Dewar A base plate
V_{p1} Vacuum pressure	Vaccuum manifold

Table 3 - F521 Dewar A monitor points.

5.1.1.2 F522 Dewar B Interface Module

The following values shall be monitored by the F522.

Dewar B	**Location**
Band 2	
$T_{b2\text{-}1}$ Temperature 1st stage	Radiation shield
$T_{b2\text{-}2}$ Temperature 2nd stage	LNA band 2
Band 3	
$T_{b3\text{-}2}$ Temperature 2nd stage	LNA band 3
Band 4	
$T_{b4\text{-}2}$ Temperature 2nd stage	LNA band 4
Band 5	
$T_{b5\text{-}2}$ Temperature 2nd stage	LNA band 5
Band 6	
$T_{b6\text{-}2}$ Temperature 2nd stage	LNA band 6
V_{d2} Vacuum Pressure	Dewar B base plate
V_{p2} Vacuum pressure	Vacuum manifold

Table 4 - F522 Dewar B monitor points.

5.1.2 Interface with the Nearest Weather Station

The compressor M&C will use monitored information from the nearest ngVLA weather station to select or modify certain modes of operation. For example, the starting speed during the start-up procedure will be adjusted based on the ambient temperature. The selected weather station M&C module (M504-xx, Table 5) will multicast the data on the Ethernet bus, and the F525 module will subscribe to the data stream and collect the information as needed.

5.1.3 M504 Weather Station Module

Environmental conditions	
T_{amb} Outside temperature	Weather station
W_{spd} Wind Speed	Weather station

Table 5 - M504 weather station monitor points.

5.2 Command Interface (Star Configuration Ethernet Bus)

5.2.1 Interface with Antenna Master M&C Module

The control messages to the compressor M&C will always come from the antenna master M&C module (M500). Any other module that needs to send a control message to the F525 will have to send it through the M500 and reciprocally. The flow of control messages (Table 6) will use the Ethernet bus in a star configuration with M500 as the central hub for the antenna.

Heat Dewar A	Turn on the heater inside Dewar A
Heat Dewar B	Turn on the heater inside Dewar B
Start Pump	Start the vacuum pump
Pump Dewar A	Open Dewar A solenoid vacuum valve
Pump Dewar B	Open Dewar B solenoid vacuum valve
Start Compressor	Start Helium compressor
Cool Dewar A	Start cold-head Dewar A
Cool Dewar B	Start cold-head Dewar B
Stop Pump	Stop vacuum pump
Stop Compressor	Stop Helium compressor
Standby Dewar A	Put the Dewar A in stanbby mode
Standby Dewar B	Put the Dewar B in standby mode
Close Solenoid Dewar A	Close Dewar A solenoid vacuum valve
Close Solenoid Dewar B	Close Dewar B solenoid vacuum valve

Table 6 - List of cryogenic commands from antenna master M&C module.

5.3 Serial RS232/485 Communications

5.3.1 Interface with the Vacuum Pump Controller

For the reference design, the vacuum pump controller (Table 7) is located inside the cryo M&C enclosure. The compressor M&C module will communicate with the vacuum pump controller through a serial RS232/485 connection. A hardware interlock will prevent the pump from running if the oil temperature is not within the manufacturer's recommended range (Table 8).

T_{pump} Temperature of vacuum pump	Physical temperature of the pump. Must be within range to start the pump.
P_{vl} Pressure vacuum line	Pressure between the pump and the receiver vacuum manifolds.

Table 7 - Vacuum pump monitor points.

Heat vacuum pump	Turn on heater backing pump to bring its temperature within operating range
Start pump	Turn on the pumps
Stop pump	Turn off the pumps

Table 8 - Vacuum pump list of commands.

5.3.2 Interface with the Helium Compressor

The compressor M&C module (F525) is located with the compressor power electronics (VFD) inside a shielded weather proof enclosure. The temperature and pressure sensors listed in Table 9 are placed in various locations inside the compressor outdoor unit. The F525 module will communicate with the compressor outdoor unit and retrieve the information through a serial interface. The compressor information will be multicast by the compressor M&C module on the Ethernet bus to make it available to other modules.

Sensor type	Location
Temperature	
T_s	Scroll capsule
T_x	Oil heat exchanger input
T_r	Oil return line to Scroll capsule
T_g	Heat exchanger output gas
T_c	Coalescer input
Pressure	
P_s	Supply line
P_r	Return line
Frequency/speed	
F_c	Cooling fan speed
Current	
I_s	Scroll capsule current
I_f	Fan current

Table 9 - F525 compressor M&C module monitor points.

5.4 SPI Communication with the Power Electronics

The cryo M&C enclosure will house the compressor M&C module (Table 10) and power electronics VFDs (Table 11, Table 12), and will shelter them from the environment while providing RFI shielding. The compressor M&C module will communicate with the power electronics that drive the compressor capsule and the two cold-heads via SPI Bus (Table 13, Table 14, Table 15).

Frequency/speed	
F_{comp}	Speed scroll capsule
Current	
I_{comp1}	Compressor scroll capsule current phase 1
I_{comp2}	Compressor scroll capsule current phase 2
I_{comp3}	Compressor scroll capsule current phase 3
Voltage	
V_{comp1}	Compressor scroll capsule voltage phase 1
V_{comp2}	Compressor scroll capsule voltage phase 2
V_{comp3}	Compressor scroll capsule voltage phase 3

Table 10 - Compressor VFD monitor points.

Frequency/speed	
F_{DWA}	Speed cold-head receiver Dewar A
Current	
I_{DWA-1}	Dewar A cold-head current phase 1
I_{DWA-2}	Dewar A cold-head current phase 2
Voltage	
V_{DWA-1}	Dewar A cold-head voltage phase 1
V_{DWA-2}	Dewar A cold-head voltage phase 2

Table 11 - Dewar A VFD monitor points.

Frequency/speed	
F_{DWB}	Speed cold-head receiver Dewar B
Current	
I_{DWB-1}	Dewar B cold-head current phase 1
I_{DWB-2}	Dewar B cold-head current phase 2
Voltage	
V_{DWB-1}	Dewar B cold-head voltage phase 1
V_{DWB-2}	Dewar B cold-head voltage phase 2

Table 12 - Dewar B VFD monitor points.

Start Scroll	Start Scroll capsule
Scroll Speed	Set speed of the Scroll capsule
Stop Scroll	Stop Scroll capsule

Table 13 - List of SPI commands with compressor VFD.

Start DWA	Start Dewar A cold-head
DWA speed	Set speed of Dewar A cold-head
Stop DWA	Stop Dewar A cold-head

Table 14 - List of SPI commands with Dewar A VFD.

Start DWB	Start Dewar B cold-head
DWB speed	Set speed of Dewar B cold-head
Stop DWB	Stop Dewar B cold-head

Table 15 - List of SPI commands with Dewar B VFD.

6 Operational Performance Requirements

6.1 Vacuum Pump Requirement

The purpose of the vacuum pump is to remove the air trapped inside the closed volume of the Front End cryostat. When the atmosphere is evacuated, heat transfer by convection between the outside walls and the inside components of the Dewar becomes negligible. In practice, there is a minimum vacuum required before the refrigerator can be started. If this threshold is not reached, the thermal loading is high enough to overcome its cooling power, preventing the electronics from reaching the desired temperatures. It has been established that a dewar pressure of 10^{-2} mbar is needed at the start for a successful cool down. Therefore, the vacuum pump selected must have a base pressure lower than this 10^{-2} mbar threshold.

The Front End concept for ngVLA has two cryostats, each with an approximate volume of 60–70 liters. It is desired to pump down both receivers in less than 15 minutes. The actual pump down time is difficult to estimate, because it depends on many factors (pumping orifice size, presence of multi-layer insulation (MLI), cleanliness of the surfaces, etc.). Nevertheless, a quick calculation shows that an empty volume of 130 liters will require a 2 l/s pumping speed to reach 10^{-2} mbar in approximately 14 minutes (Table 16). The minimum pumping speed is therefore specified at 2 l/s, but a larger capacity is recommended.

Vacuum pump minimum base pressure	10^{-2} mbar
Minimum pumping speed	2 l/s

Table 16 - Minimum requirements for the vacuum pump.

6.2 Onboard Vacuum Pump

The antenna will be equipped with a vacuum pump powerful enough to evacuate the Front End cryostats below the 10^{-2} mbar pressure limit required to start the cryocoolers. A combination of a roughing pump and turbo pump was initially considered, but the overall cost was too high and not justified on the antenna. A simpler dual-stage rotary vane pump will provide the vacuum required to start the refrigerator, and will cost less than half as much.

It is important to note that an oil pump will introduce some restriction on the antenna movement while in operation, because oil could spill out of the vent port if tilted to certain orientations. A solenoid valve that can be remotely operated will provide the vacuum seal between the pump and the cryostat. The valve will be computer controlled to open during cool down but to close as soon as the Dewar pressure goes below 2.0×10^{-3} mbar, at which point the cryo pumping by the refrigerator becomes more efficient than a mechanical pump. This is very important to avoid back streaming and contamination of the vacuum space with oil. A second solenoid valve is placed at the exhaust port to backfill the pump and vacuum line when the pump is turned off, to prevent the vacuum from sucking oil through the inlet port and into the line.

The vacuum pumps commercially available are designed to operate in a controlled environment and have a limited temperature range for operation. For example, the viscosity of the oil will change with the ambient temperature, affecting the performance of the pump or possibly causing premature failure if the pump is run outside its recommended operating range. The pump and control electronics should also be protected from rain or any excess moisture, and if the temperature of the enclosure is not controlled, a heating blanket should be used to warm up the oil in the pump before a cold start-up.

For the reference design, the Alcatel rotary vane vacuum pump model Adixen 2015SD was selected. The basic specifications are listed in the Table 17. The pump will be equipped with the oil level switch (OLS36) and the oil mist eliminator (OME 25HP) combined with the oil drain kit (ODK 2). The first option will monitor the oil level, while the second kit will help with the recovery of the oil that accumulates in the mist eliminator when the pump operates at high pressure [RD08].

Voltage	120 VAC @ 60 Hz
Startup current at 12°C	35A (recommended fuse protection 20A)
Current at maximum flow	5.7A
Power	3/4 HP, 0.55 kW
Rotation speed	1800 rpm @ 60Hz
Pumping speed	10.6 cmf / 5 l/s
Base pressure closed gas ballast	2.0 x 10^{-3} mbar
Environment storage	–5°C to +40°C
Operating (mineral oil)	+12°C to +40°C
Maximum relative humidity	80% up to 30°C decrease linearly to 50% at 40°C

Table 17 - Alcatel Adixen 2015SD vacuum pump specifications.

6.3 Vacuum Pump Equipment for the Integration Center and Service Vehicle

When a Front End cryostat is assembled for the first time or after being opened for repair, it is recommended to run the pump for an extended period to remove as many contaminants as possible and allow some of the internal components to outgas. It is therefore recommended to use a turbo pump with a scroll backing pump at the Front End integration center, to achieve a much lower cryostat pressure before cool down. In addition to a powerful vacuum pump, a heating blanket might be used to accelerate the outgassing of the Dewar walls, and obtain a better vacuum in a reduced amount of time.

For the integration center, we have selected the Agilent Varian vacuum system with TwistTorr 304FS turbo and TS 300 dry scroll pump. Table 18 lists the key specifications.

Voltage	120 VAC @ 60Hz
Power	450 VA max
Scroll pumping speed	8.8 cfm / 4.15 l/s
Scroll TS 300 Base pressure	1.3 x 10^{-2} mbar
TwisTorr 304FS max frequency	1350 Hz
TwisTorr 304Fs pumping speed	180 l/s
TwisTorr 304FS Base pressure	1.0 x 10^{-10} mbar
Environment storage	–20°C to +70°C / 0–95% humidity
Operating	+5°C to +4 °C / 0–90% humidity

Table 18 - Agilent TwisTorr 304FS turbo pump system.

6.4 Cryocooler Requirements

The Front End Design Description [AD05] presents the ngVLA receiver concept. A new type of feed-horn selected for Bands 3–6 allows all six frequency bands to fit in two cryostats. A thermal analysis done by Callisto [RD01] (Table 19) gives us preliminary numbers for the heat loads on both cryostats.

Cold-head	Dewar A (Band 1)	Dewar B (Bands 2–6)
1st stage	9.88 W at 50 K	18.4 W at 50 K
2nd stage	3.08 W at 15 K	4.3 W at 15 K

Table 19 - Calculated thermal loads for the ngVLA cryostats (ambient temperature 20°C and vacuum pressure 10^{-6} mbar).

These calculated values are only preliminary and some load reductions are possible by optimization of the receiver design. The sensitive electronics do not need to be cooled down to 15 K to give the desired sensitivity; 20 K is the temperature limit to be achieved by the second stage of the cryocooler. Based on this information, the following cooling capacities for the refrigerator have been selected (Table 20).

- **1st stage:** The cold-head shall have enough cooling capacity on the first stage when running at maximum speed to absorb 20W of heat and maintain the stage temperature at 80 K or below.
- **2nd stage:** The cold-head shall have enough capacity on the second stage when running at maximum speed to absorb 5W of heat and maintain the stage temperature at 20 K or below.

Cold-head	Cooling capacity	Temperature	Speed
1st stage	20 W	80 K	60 Hz
2nd stage	5 W	20 K	60 Hz

Table 20 - Cold-head specifications.

6.5 Cold-Head Selection

Several GM refrigerators on the market have the required cooling capacities, but fewer are designed to operate at variable speed. For the ngVLA reference design, we selected the Trillium 350CS (Figure 3; Table 21) because it has the right cooling capacities and can run at variable speed. This model has been used at the VLA for many years and has demonstrated good reliability. It is easy to maintain and could be repaired in-house at very reasonable cost in parts and labor: estimated at ~$250 and six hours, respectively [RD07].

Figure 3 - Trillium 350CS refrigerator.

Cold-head	Trillium 350CS
1st stage cooling capacity	20 W
2nd stage cooling capacity	5 W
Flow	12.5 scfm
Weight	22lbs

Table 21 - Trillium 350CS specifications at 60 Hz.

6.6 *Helium Compressor Requirements*

The helium compressor shall have enough flow capacity to run two Trillium 350CS refrigerators at nominal speed. Because energy cost is a major concern for ngVLA, the power consumption of the helium compressor shall not exceed 5kW when operating at 60 Hz. The Trillium 350CS has an estimated flow of 12.5 scfm when operating at 60 Hz [RD07]. Table 22 lists the performance requirements.

Compressor Speed	Supply pressure	Return pressure	Flow	Power
60 Hz	300 psi	<100 psi	>30 scfm	<5kW

Table 22 - Helium compressor specifications at 60Hz.

6.7 *Helium Compressor Selection*

The Scroll capsules that are used in modern helium compressors are manufactured mostly by two companies, Hitachi and Copeland, and are only available in a limited range of sizes. Numerous companies on the market use their Scroll capsules to build helium compressors for the cryogenic market. However, only a very limited number of these are designed for outdoor application. Because the radio astronomy market is small in comparison with the medical field (MRI) and the semiconductor industry (sputter deposition), the development of a custom model designed from the ground up for outdoor use would be cost prohibitive, especially given the limited applications for such an item.

For the reference design, the solution was to enter into a collaborative effort with Sumitomo SHI in Allentown, PA, to suitably modify one of their existing products. Basically, they took their mid-size compressor model, the FA-40, and added a commercial VFD for variable-speed operation. The flow and power measurements done at the factory on this hybrid unit have shown it has the right capacity for our application (Figure 4).

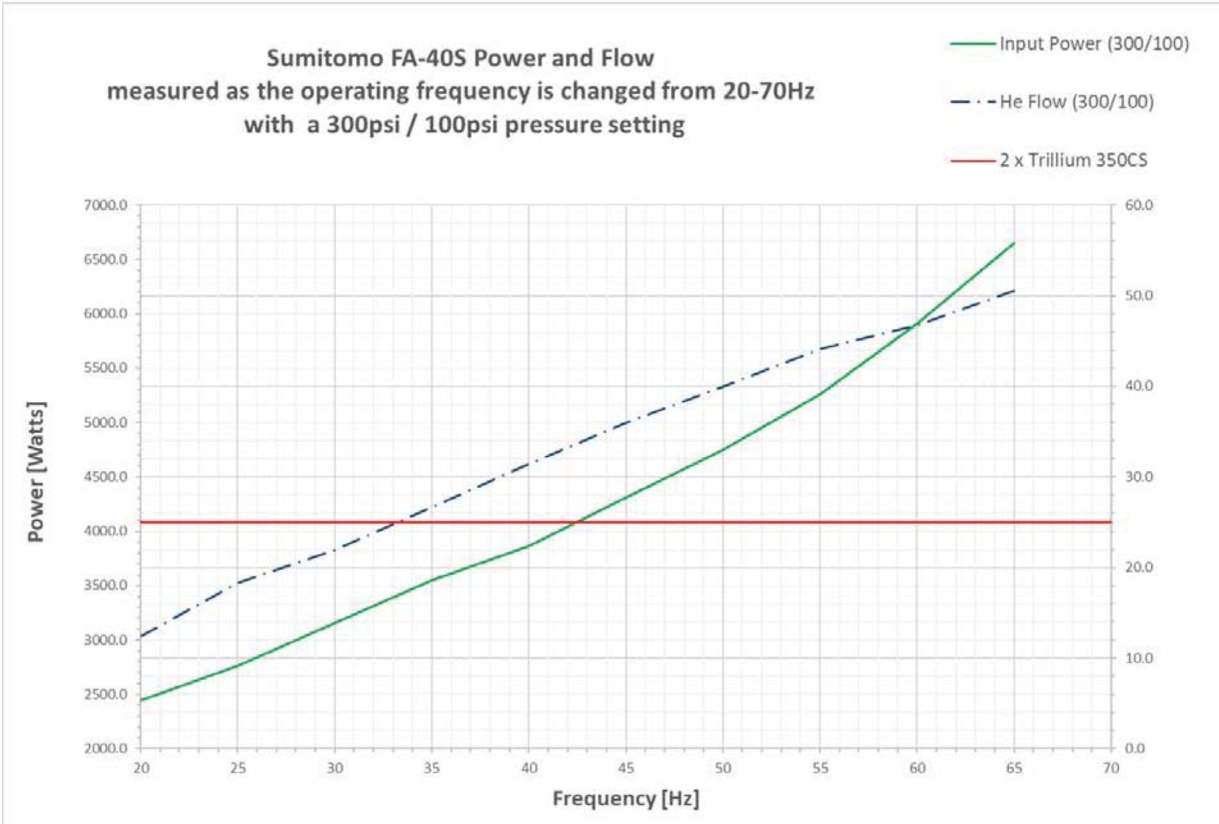


Figure 4 - Sumitomo FA-40 helium compressor flow and power measurement versus VFD operating frequency, 20-70 Hz.

The second phase of the collaboration will integrate the FA-40 compressor capsule within the outdoor enclosure developed for the FA-70 model (Figure 5), to create the first ngVLA helium compressor prototype (model "FA-40S").

Figure 5 - Sumitomo FA-70 outdoor enclosure.

Table 23 lists the preliminary specifications for the modified FA-40 compressor.

Model	FA-40S
Electrical supply	3-phase 200V at 60 Hz
Power consumption	4.8 kW at 60 Hz
Flow capacity	49.2 scfm at 60 Hz *
Cooling Air	22 m^3/min at 60 Hz **
Maintenance Interval	35,000 hours
Ambient temperature	-30°C to 45°C **

Table 23 - Sumitomo FA-40S specifications. Notes: * data from Copeland catalog, ** data from Sumitomo FA-70 compressor specifications.

7 Mechanical Interfaces

The various mechanical interfaces described below will be documented in greater detail in future ICDs.

7.1 Receiver/Front End Mechanical Interface

Each Front End assembly is equipped with one cold-head that can be removed for service. However, the cylinder housing the cold-head displacer shall be permanently attached to the cryostat because it has many hardware connections to the rest of the Dewar assembly. The mechanical interface for the Trillium 350Cs is described below and shown in Figure 6.

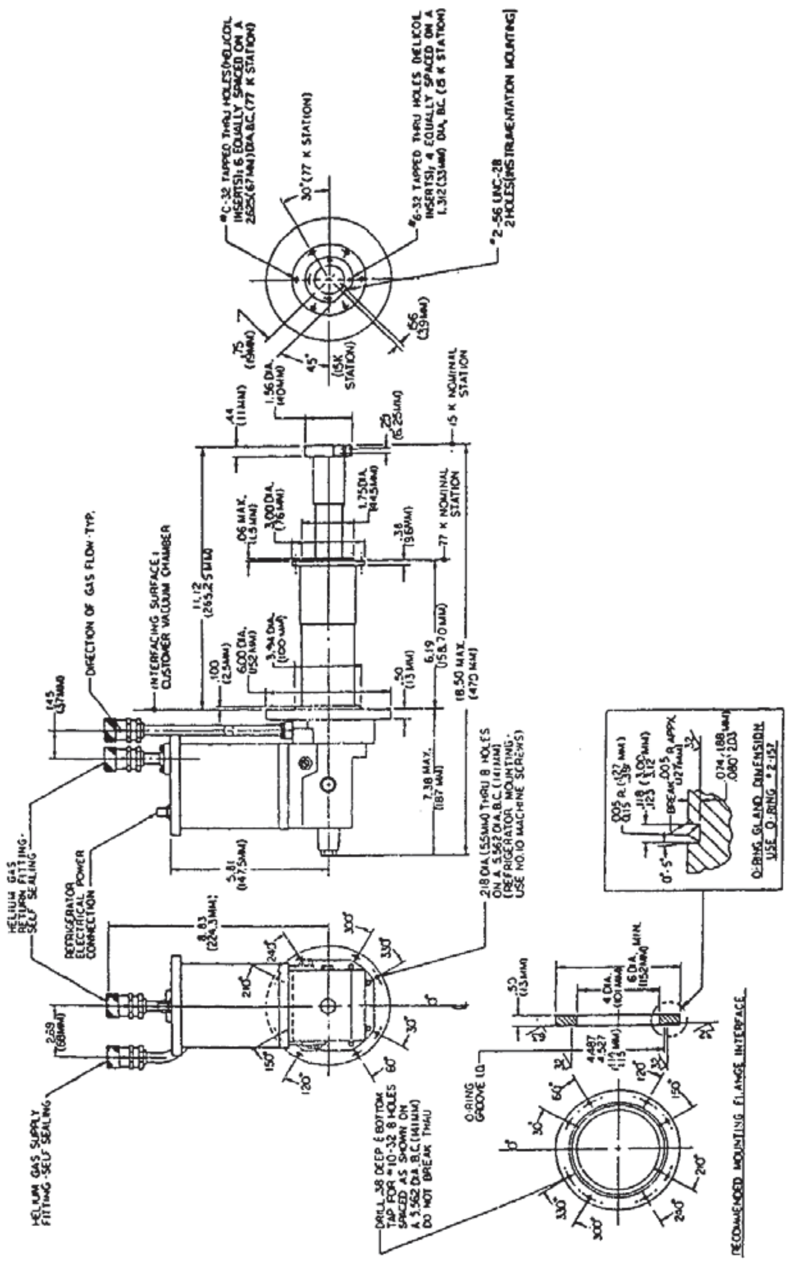


Figure 6 - Cold-head mechanical interface with cryostat.

7.2 Antenna Mechanical Interface

7.2.1 Required Space on the Antenna Platform

The antenna platform shall allow a 30 cm space behind the compressor outdoor unit for air suction, and a 100 cm space in front of the heat exchange for air discharge. An additional 15 cm space on the left side and 50 cm space on the right side shall be available; see Figure 7.

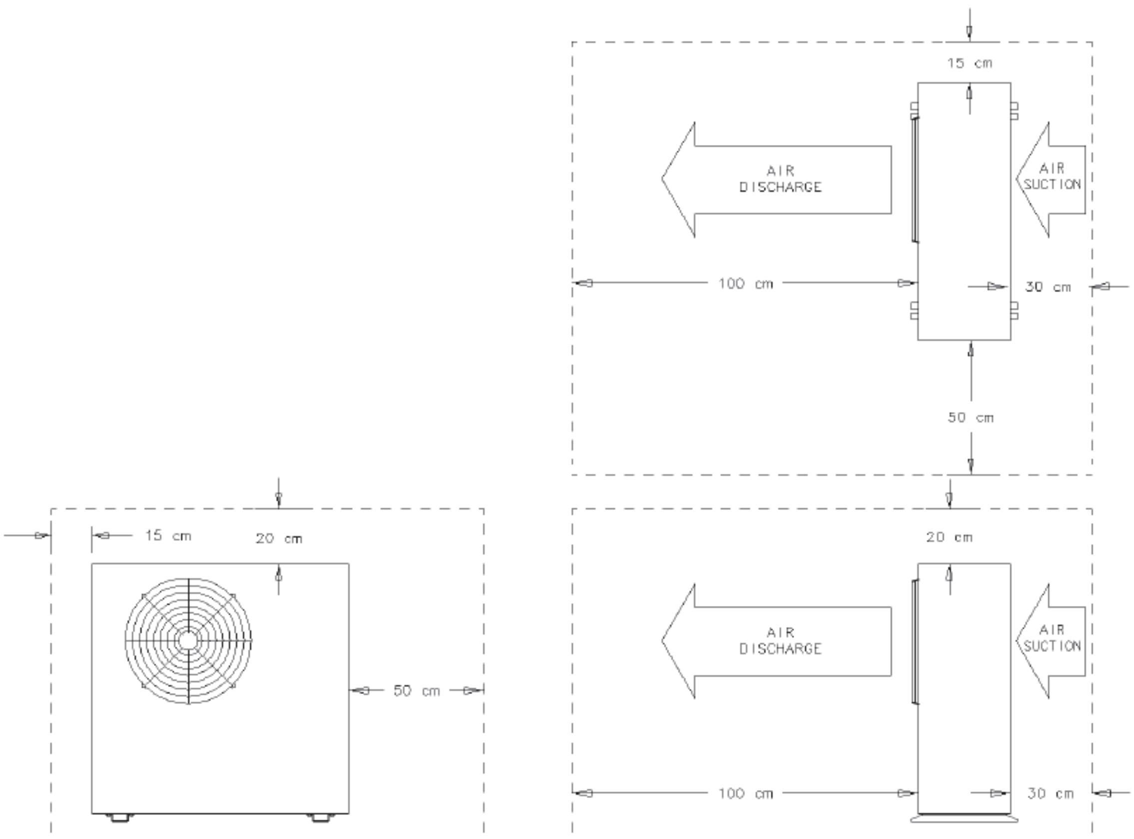


Figure 7 - Compressor space requirements on the antenna platform.

7.2.2 Mechanical Interface with the Antenna Platform

The helium compressor will be installed on an antenna platform above the azimuth bearing but below the elevation axis. The platform shall support the weight of the compressor and service personnel with the required safety factor (TBD). The mounting brackets that attach the compressor to the platform shall support the mechanical stresses induced by rotation of the antenna at full speed, followed by maximum deceleration, and the force applied by high winds on the compressor outdoor unit. Table 24 lists the most important parameters.

Inclination	Within 5 degrees of horizontal
Slew	180 deg/min
Wind	Max 50 m/s
Magnetic field	≤ 150 Gauss
Weight	≤ 150 kg

Table 24 - Mechanical limits for the compressor mount on the antenna platform.

7.2.3 Compressor M&C Enclosure Interface

The compressor M&C enclosure contains the Control and Power electronics for the cryogenics subsystem. It will be located on the antenna platform and have a cold plate where glycol is circulating for cooling.

7.3 Elevation Wrap and Helium Lines

The compressor is located on a platform behind the dish and above the azimuth bearing, and the Front End cryostats are located on a platform supported by the subreflector feedarm. The helium lines (two lines: one supply, one return) are run from the compressor to the receiver platform, through the elevation axis cable wrap. On the receiver platform, the supply line connects to a two-way manifold that splits the flow between the two refrigerators. A second two-way manifold recombines the refrigerator output flows into the return line. The helium lines shall be built with a combination of rigid seamless stainless steel tubing that is securely attached to the antenna structure and some flexible sections; see details below. The helium lines are part of the cryogenic subsystem, and their exact location and mounting points shall be described in a future antenna ICD.

7.3.1 Flexible Helium Lines

The various sections of flexible line are specified as follows:

- Between compressor and antenna platform, the flex-lines will allow easy connection to the compressor using Aeroquip 5400 series refrigerant couplings.
- Through the elevation wrap, a set of armored flex-lines will join the rigid sections of lines from the compressor platform and the sub-reflector feed harm. The armored flexible shell (Figure 8) will help maintain a uniform bending radius on the line through the elevation wrap, and will guarantee the minimum bend radius is not exceeded. The life expectancy of the flex-lines shall exceed 20 years of antenna operation (number of flex cycles is TBD).
  - Static bending radius 25 cm (10")
  - Dynamic bending radius 70 cm (28")
- Between the antenna feedarm and receiver platform, the flex-lines will allow free translation of the receiver platform for band selection, and easy connection to the refrigerators mounted to the cryostats.

Figure 8 - Armored flex-line cross-section view.

7.3.2 Rigid Helium Lines

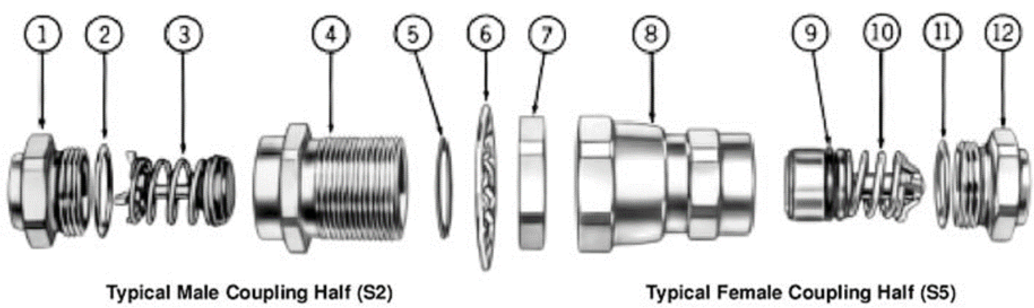
The rigid helium lines are made of seamless stainless steel 0.5" ID line that have been thoroughly cleaned inside to remove contaminants (oil and other chemical residues). The specified wall thickness is 0.065" with a working pressure of 4500 psig (Swagelok stainless steel seamless tubing).

7.3.3 Helium Line Fittings

The interconnection between two rigid lines will use Swagelok type compression gas fittings (Figure 9).

Figure 9 - Swagelok fittings for rigid helium lines.

The other connection will use Aeroquip 5400 series self-sealing gas fittings (Figure 10), standard for cryogenic equipment. The O-ring and gasket material shall be made out of butyl rubber to meet environmental requirements and avoid leaks in extremely cold weather conditions.



Component Part Numbers

Item No.	Dash Size ‣ / O.D. Tube Size ‣	–4 / 1/4"–3/8"	–8 / 1/4"–5/8"	–12 / 5/8"–7/8"	–16 / 7/8"–1 3/8"	Line Ref.
	Typical Male Half					1
1	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	2
2	O-Ring	22546–12	22546–17	22546–23	22546–28	3
3	Poppet Valve Assembly	5400–S20–4	5400–S20–8	5400–S20–12	5400–S20–16	4
4	Body	5400–17–4	5400–17–8	5400–17–12	5400–17–16	5
5	Gasket Seal	22008–4	22008–8	22008–12	22008–16	6
6	Lock Washer	5400–54–4S	5400–54–8S	5400–54–12S	5400–54–16S	7
7	Jam Nut	5400–53–4S	5400–53–8S	5400–53–12S	5400–53–16S	8
	Typical Female Half					9
8	Union Nut and Body Assembly	5400–S16–4	5400–S16–8	5400–S16–12	5400–S16–16	10
9	O-Ring	22546–10	22546–112	22546–116	22546–214	11
10	Valve and Sleeve Assembly	5400–S19–4	5400–S19–8	5400–S19–12	5400–S19–16	12
11	O-Ring	22546–12	22546–17	22546–23	22546–28	13
12	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	14

*Specify O.D. Tubing size of adapter required in 16th of an inch. Example: –4 coupling with 3/8" O.D. tubing is 6/16 or –6. Part number is then 202208–6–4.

Figure 10 - Aeroquip 5400 series couplings.

8 Electrical Interface

The cryogenics subsystem electrical power requirements from the antenna are shown in Table 25. The electrical power requirements will be described in more detail in a future antenna ICD.

Description	Voltage	Current max breaker protection	Frequency	Power consumption
Single phase	120 VAC ±5%	35 A	60 Hz	1 kW max
3-phase Delta config., 5 wires (Ph1, Ph2, Ph3, Neutral, GND)	200 VAC ±10%	25 A	60 Hz	5 kW max

Table 25 - Cryogenic subsystem power requirements.

9 Environmental Conditions and Corresponding Operating Modes

9.1 *Site Elevation*

The ngVLA will have a core array located at the Very Large Array site, on the plains of San Agustin (elevation 2100 m). The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona and northern Mexico. The cryogenic subsystem shall be designed to operate at altitudes ranging from sea level up to 2500 m.

9.2 *Limits of Operating Conditions*

The cryogenic subsystem shall operate normally within the environmental limits listed in Table 26.

Parameter	Req. #	Value
Solar Thermal Load	ENV0321	Exposed to full Sun
Wind	ENV0331	W ≤ 15 m/s average over 10 mins; ≤ 20 m/s gust
Temperature	ENV0332	–20°C ≤ T ≤ 45°C
Precipitation	ENV0333	5 cm/hr. over 10 mins
Ice	ENV0334	No ice accumulation on outdoor compressor unit

Table 26 - Normal operating conditions.

9.3 *Survival Conditions*

Subsystem survival conditions are detailed in Table 27. Outside of the limits of the operating conditions, some degradation in performance is acceptable. It is difficult to address every possible weather condition, but we can review a few scenarios and describe how the cryogenic subsystem is expected to respond.

Parameter	Req. #	Value
Wind	ENV0341	0 m/s ≤ W ≤ 50 m/s average
Temperature	ENV0342	–30°C ≤ T ≤ 50°C
Radial Ice	ENV0343	2.5 cm
Rain Rate	ENV0344	16 cm/hr. over 10 min
Snow load	ENV0346	100 kg/m^2 on horizontal surfaces
Hail stones	ENV0347	2.0 cm diameter

Table 27 - Survival conditions.

9.3.1 Extreme Heat

When the ambient temperature rises above 45°C the compressor might have difficulties maintaining the temperature of the Scroll capsule within the operating range. The cooling fan in front of the compressor's heat exchanger operates at variable speed: as the oil temperature increases with outside temperature, the compressor control electronics ramps the fan speed up to maximum. If the cooling fan is not capable of maintaining the system temperature below the upper limit, the speed of the Scroll capsule shall be decreased slowly to reduce the heat dissipation. The compressor M&C module will adjust the speed of the two cold-heads accordingly to maintain the delta pressure (Supply pressure minus Return pressure) and keep both receivers as cold as possible.

In an extreme case, the internal thermal protection will shut down the compressor to protect the Scroll capsule from overheating. The compressor will re-start automatically when the temperature drops below a manufacturer preset value. However, the compressor M&C will disable the compressor auto-restart if the ambient temperature is too high, in order to avoid repetitive ON/OFF cycles.

9.3.2 Extreme Cold

When the ambient temperature drops below –20°C, keeping the Scroll capsule properly lubricated might be problematic. The compressor M&C shall use information from internal temperature sensors and the nearest weather station to control the cooling fan. The fan cools the Helium and the oil that runs through the heat exchanger: when the fan slows down the cooling efficiency of the system drops and the temperature of the oil and helium gas should rise.

If stopping the fan is not enough to keep the oil temperature within range, the compressor M&C will need to start reducing the speed of the refrigerators. This is because when the cold-heads run slower, less helium gas flows through the lines that are exposed to the cold weather and more gas is recirculated internally, which should raise the internal system temperature. In very extreme conditions, both refrigerators may need to be turned off completely, to allow the compressor to run in bypass mode.

As a last resort, the compressor M&C might have to lower the speed of the Scroll capsule and bypass the heat exchanger to keep the Scroll capsule running. As long as the capsule is running and some oil is circulating, the time to get the system operational again when the weather improves is minimized.

9.3.3 Extreme Wind

In extreme wind conditions, the antenna will be parked and observing suspended. It is unlikely that high winds could damage the cooling fan, but the compressor M&C monitors the fan current and will power it off if needed. If the fan is turned off, the compressor will rely on the wind to cool the heat exchanger. The compressor M&C will then use the wind speed information provided by the weather station and the internal monitor points to adjust the speed of the capsule and the cold-heads.

Note: It is recommended an outdoor enclosure be placed over the helium compressor for protection against heavy rain, hail storms and high winds, and to avoid snow and ice accumulation directly on the structure.

10 Modes of Operation

10.1 Start-Up Mode

The start-up procedure will depend on the ambient temperature. The compressor M&C will use environmental data provided by the nearest weather station and internal monitor points to set the Scroll capsule start-up speed, and will determine if the heat exchanger should be bypassed or not. As the oil temperature increases, the scroll capsule speeds up and the oil starts flowing through the heat exchanger. The compressor M&C starts the cooling fan and adjusts its speed as needed. When the compressor is fully operational and ready, the cold-heads can be started.

10.2 Cool-Down Mode

The cool-down mode is also the high power mode. The Cool command is sent by the antenna M&C and the compressor M&C to start the cold-heads: they are initially run at maximum speed to minimize the cool down time. The compressor capsule speed and fan speed are adjusted to provide the right amount of flow at the right pressure in order to maintain optimum cooling efficiency. This is the phase when the power consumption is the highest.

10.3 Observing Mode

Observing mode starts when the cryostats are cold and ready for science. The individual Front End M&C modules relay temperature information to the compressor M&C that controls the speed of the cold-heads and the Scroll capsule. The system will constantly adjust the speed of the compressor and the refrigerators to maintain the sensitive electronics at the required temperature, and at the same time minimize the power consumption.

10.4 Warm-Up Mode

To warm up a cryostat to service its cold-head, or to replace it with a spare unit, it is sufficient to stop the cold-head drive. If both systems are turned off simultaneously, the compressor can be switched off. In cold weather, if the system will be down for a limited time, the compressor could be left running in bypass mode at low speed to keep the oil warm and minimize start-up time.

10.5 Recovery Mode

We consider recovery mode any start-up procedure after the cryogenics subsystem suffers an unscheduled shutdown. This situation is usually due to loss of power to the compressor. The compressor M&C will analyze its monitor points and collect information about environmental conditions to determine if it is safe to proceed with the start-up procedure.

10.6 Stand-By Mode

A cryostat may be placed in stand-by mode when it is not scheduled for observations for a period of time (length TBD). The antenna M&C directs the compressor M&C to run the cryostat warmer by slowing down the refrigerator(s). The second-stage temperature is nevertheless kept below 30 K to maintain active cryo pumping and prevent vacuum run-away. Stand-by is the lowest power mode, and is not considered an observing mode. The cryogenic subsystem shall be able to transition to observing mode in less than 30 minutes (TBC). The stand-by mode could be total, when both cryostats are not used or partial if only one of the cryostats is not needed.

10.7 Bypass Mode

Bypass mode is active in extremely cold weather conditions, when the Front End and other antenna subsystems are non-operational. In this mode, both cold-heads are turned off to keep the compressor oil warm and minimize start-up time when weather conditions improve. Bypass mode could also be used for troubleshooting and monitoring the compressor performance. In this mode, the helium is recirculating inside the compressor through an internal bypass valve.

11 EMC/RFI Requirements

The digital electronics in the M&C modules and high-power switching electronics in the VFD drives create RFI emissions and are a concern and RFI shielding is necessary. The following measures will be taken in this regard.

11.1 Shielding of Compressor Outdoor Unit

The compressor outdoor unit has a Scroll capsule that runs at variable speed due to a VFD located in the Cryo M&C Enclosure. The cable that carries the 3-phase power between them will have to be shielded and have a ground connection at both ends.

11.2 Shielding of Cryo M&C Enclosure

The Cryo M&C Enclosure contains the compressor M&C interface LRU, the VFD LRUSs for the Scroll capsule and the two cold-heads, as well as controllers for the cooling fan and vacuum pump. All the electronics listed above can generate RFI and must be contained within an RFI-tight enclosure(s). The connections to the M&C enclosure shall be done through special filtered connectors. The whole assembly must meet the VLA RFI requirements [AD07]. The validation of the shielded enclosure will be done in the VLA reverberation chamber with a specially designed test set.

11.3 Cooling of Cryo M&C Enclosure

The active electronics inside the M&C enclosure will generate heat. Because it is a shielded enclosure, it is recommended to use a cold plate cooled by Glycol, instead of forced-air cooling. It will be easier to keep the box RFI tight and weatherproof if air vents are not used.

12 Maintenance

12.1 Scheduled Maintenance

Scheduled cryogenics maintenance (Table 28) will be performed when the antenna is serviced. Because of the large number of antennas, one antenna will have a major overhaul every 35,000 hrs (four years).

Compressor charcoal trap adsorber replacement	≥ 35,000 hrs of operation
Compressor heat exchanger cleaning	≥ 35,000 hrs of operation
Compressor fan motor bearing replacement	≥ 35,000 hrs of operation
Cold-head replacement	≥ 35,000 hrs of operation
System static pressure recharge (He)	≥ 10,000 hrs (TBC)
Compressor oil refill	≥ 35,000 hrs of operation

Table 28 - Scheduled maintenance.

12.2 Onsite Maintenance

All scheduled maintenance shall be performed at the site when the antenna is serviced. Unscheduled repairs shall also be done at the site. When a compressor fails the unit will be replaced. This requires depressurization of the helium circuit.

12.3 Maintenance at the Service Center(s)

All compressor repairs that require depressurization of the helium circuit shall be done at the service center(s). Cold-head overhaul shall also be done at the service center(s).

13 Shipping/Transport and Acceptance Test

13.1 Shipping from Manufacturer to Integration Center

The compressor shall be mounted on a wood pallet with tilt sensors and shock sensors to ensure safe delivery by truck and early detection of possible abuse.

13.2 Transport between Integration Center and Antenna

The compressor will be transported from the integration center to the antenna in a truck equipped with a crane that will allow the compressor to be lifted up to the antenna platform.

13.3 Acceptance Test

The compressor shall be tested at the factory and delivered with a complete set of test data and a compliance report. The cold-heads shall also be tested at the factory and delivered with the load maps and the compliance reports.

The M&C enclosure will be tested in the reverberation chamber to ensure compliance with the VLA requirements. A recently-serviced compressor or cold-head will be tested at the integration center and will have to pass a series of acceptance tests prior to being released as a spare unit.

14 Appendix

14.1 Compressor Enclosure

For the reference design we are not considering an outside enclosure for the outdoor compressor unit; however, the possibility to add such an enclosure to the antenna platform will be evaluated during the design phase. Some of the parameters to consider for the enclosure include the following:

- Weather protection
  - Avoid snow/ice accumulation on compressor
  - Minimize exposure to rain water (corrosion)
  - Shield the cooling fan from high winds
  - Prevent damage from hailstorms
  - Reduce sun damage (UV)
- Impact on antenna design
  - Extra weight on platform
  - Extra volume on platform
  - Extra cost
  - Reduced accessibility
  - Increased maintenance time (enclosure must be removed to access compressor outdoor unit)

14.2 Abbrevations and Acronyms

Acronym	Description
AD	Applicable Document
LNA	Low Noise Amplifier
LRU	Line-Replaceable Unit
M&C	Monitor and Control
MLI	Multi Layer Insulation
MRI	Magnetic Resonance Imaging
MTBF	Mean Time Between Failure
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
RD	Reference Document
rpm	Revolution per minute
SPI	Serial Peripheral Interface
UV	UltraViolet
VFD	Variable Frequency Drive
VLA	Jansky Very Large Array

Integrated Receivers and Downconverters: Preliminary Technical Requirements

020.30.15.00.00-0001-REQ-A-INTEGR_RECVR_DOWNCONVERTER_TECH_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
M. Morgan	Electronics Div., NRAO	2019-10-31
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-15

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.25 12:36:45 -06'00'	Electronics Div., NRAO	2019-07-25
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:14:36 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-25

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:14:56 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-25

Change Record

Version	Date	Author	Affected Section(s)	Reason
1	201801-10	M. Morgan	All	First draft. Used ngVLA Antenna Specs as a template, and took some data from ngVLA memo #29, "An Integrated Receiver Concept for the ngVLA."
2	2018-03-29	M. Morgan	4.1, 4.2	Modified Band 5 LO frequencies.
3	2018-04-16	M. Morgan	5.4	Removed reference to TEC supply.
4	2018-04-26	M. Morgan	many	Increased Bands 4 and 5 to 8 bits, added two Band 4 modules for WVR, added 3.3 V digital supply.
5	2018-05-03	M. Morgan	4.6.3	Changed spurious spec to –43 dBm/MHz.
6	2018-05-16	M. Morgan	many	Re-harmonized with updated system requirements.
7	2018-06-24	M. Morgan	header	Corrected file number.
8	2018-07-03	M. Morgan	Fig. 1	Corrected Band 2 edge frequency.
9	2018-07-31	M. Morgan	4.10, 6	Added mass and physical dimension specs.
9.9	2018-09-06	S. Durand	All	Minor changes, number of antennas.
10	2018-10-01	M. Morgan	All	Updates from Internal Pre-Decadal Submission Review.
11	2018-10-19	M. Morgan	5.6, 2.1	Clarified number of fibers. Removed rev numbers in AD reference table.
12	2018-10-31	M. Morgan	header	Changed title block to show author/owner. Also deleted ngVLA project background.
A	2019-07-25	A. Lear	All	Prepared PDF for approvals and release.

Table of Contents

1 Introduction ... 4
1.1 Purpose ... 4
1.2 Scope ... 4
2 Related Documents and Drawings ... 4
2.1 Applicable Documents ... 4
2.2 Reference Documents ... 4
3 Overview of Technical Specifications ... 5
3.1 Document Outline ... 5
3.2 General Description ... 5
3.3 Summary of Integrated Downconverter Requirements ... 6
4 Functional and Performance Requirements ... 7
4.1 RF Frequency Ranges ... 7
4.2 LO Frequencies ... 8
4.3 IF Bandwidth ... 9
4.4 Analog Gain ... 9
4.4.1 Nominal Gain ... 9
4.4.2 Gain Flatness ... 9
4.4.3 Gain Adjustment ... 10
4.4.4 Gain Stability ... 10
4.5 Sensitivity ... 10
4.6 Spurious Signals ... 11
4.6.1 Image Rejection ... 11
4.6.2 Alias Rejection ... 11
4.6.3 Spurious Narrowband Tones ... 11
4.7 Digitization ... 12
4.7.1 Sample Rate ... 12
4.7.2 Bit Resolution ... 12
4.8 Operating Conditions ... 12
4.8.1 Nominal Operating Conditions ... 12
4.8.2 Limiting Operational Conditions ... 12
4.9 Monitor & Control Requirements ... 13
4.10 Mass and Physical Dimensions ... 13
5 Interface Requirements ... 14
5.1 Interface to the Cryogenic Front End Subsystem ... 14
5.2 Interface to Water Vapor Radiometer ... 14
5.3 Interface to the Timing Reference/LO Subsystem ... 15
5.4 Interface to the Monitor and Control Subsystem ... 15
5.5 Interface to the Power Supplies ... 16
5.6 Interface to the Data Transmission Subsystem ... 16
6 Verification and Quality Assurance ... 17
7 Appendix ... 20
7.1 Abbreviations and Acronyms ... 20

1 Introduction

1.1 Purpose

This document presents a preliminary set of technical specifications for the ngVLA Integrated Receiver and Downconverter (IRD) modules.

Many requirements flow down from the preliminary ngVLA System Requirements [AD01], which in turn flow down from the preliminary ngVLA Science Requirements.

The integrated receiver packages further amplify the signals provided by the cryogenic stage, down convert them where necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point from the focal plane (but possibly still inside the antenna base).

From there, they are time-stamped and launched onto a conventional network for transmission back to the array correlator and central processing facility. Hooks are needed to provide for synchronization of local oscillators (LOs) and sample clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

1.2 Scope

The scope of this document is the set of ngVLA Integrated Receiver and Downconverter modules. This consists of direct-sampled and sideband-separating modules for all telescope bands, which include warm amplification, filtering, power leveling, analog-to-digital conversion, and fiber-optic transmission. It also covers external splitters and combiners as needed to feed them from the cryogenic signal paths.

Cryogenic systems and thermal transitions, as well as front-end cabling, waveguide runs, and fiber-optic signal paths outside the IRD modules themselves are outside the scope of this work package, though interfaces must be considered. This specification establishes the performance, functional, design, and test requirements applicable to the ngVLA IRD modules.

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 latter shall be considered as a superseding requirement.

Reference No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	ngVLA System Environmental Specifications	020.10.15.10.00-0001-SPE

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev / Doc. No.
RD01	An Integrated Receiver Concept for the ngVLA	ngVLA Memo #29, Nov. 2017
RD02	Unformatted Digital Fiber-Optic Data Transmission for Radio Astronomy Front-Ends	PASP, vol. 125, no. 928, June 2013

3 Overview of Technical Specifications

3.1 Document Outline

This document presents the technical specifications of the ngVLA Integrated Downconverters. These parameters determine the overall form and performance of the downconverter modules.

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 Integrated Downconverter 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.

Requirements for the Verification and Test of the integrated modules, from the conceptual design through to prototype, are described in Section 6.

3.2 General Description

The integrated downconverters will take cryogenically amplified RF inputs ranging from 1.2 to 116 GHz in bands and perform all necessary conversions from RF to baseband, from analog to digital, and from copper to fiber in compact, integrated, line-replaceable units (LRUs). The lower bands may be digitized directly (without down conversion) in the first-, second-, and/or third-Nyquist zones, while the higher bands may be down converted with in-phase and quadrature (I and Q) baseband outputs. Final sideband-separation will be performed numerically by the backend (outside the scope of this work package) with calibrated amplitude and phase coefficients. The initial concept and frequency plan for this subsystem (now somewhat modified, and still evolving) was presented in [RD01].

Due to instantaneous digital bandwidth limitations, more than one downconverter module may be required to service a single RF feed band. Where needed, passive splitters/combiners will be provided within this scope to divide the RF band into more manageable chunks for the integrated modules.

The digitized I and Q or direct-sampled data streams will be transmitted by optical fiber as unformatted serial data. The mathematical basis of operation and methodology for parsing the bit stream at the receive end is described in detail in [RD02].

Auxiliary inputs to the integrated downconverters will include LOs, sample clocks, power supplies, and the monitor and control (M&C) serial bus. Sufficient on-board monitoring will be provided to isolate most failures to a single LRU.

3.3 Summary of Integrated Downconverter Requirements

The following table provides a summary of the major integrated downconverter requirements in order to provide the reader with a high-level view of the desired subsystem. Should there be a conflict between the requirements listed here and the descriptions in Sections 4 through 6, the latter shall take precedence.

Parameter	Summary of Requirement	Reference Reqs.
RF Input Frequency Bands	1.2–3.5 GHz 3.5–10.5 GHz 10.5–20.5 GHz 20.5–34 GHz 30.5–50.5 GHz 70–116 GHz	IRD0101 IRD0102 IRD0103 IRD0104 IRD0105 IRD0106
IF Bandwidth	3.5 GHz (RF < 10.5 GHz) 3.5 GHz per sideband, 2SB (10.5 < RF < 50.5 GHz) 7 GHz per sideband, 2SB (70 < RF < 116 GHz)	IRD0301–0302 IRD0303–0305 IRD0306
Image Rejection	>30 dB (calibrated)	IRD0611–0614
Gain (nominal)	60 dB (TBC)	IRD0411–0416
Gain Flatness	<2.7 dB slope, plus <2dB peak-to-peak ripple	IRD0421–0422
Gain Adjust	±12 dB min. (from nominal)	IRD0431
Noise Temperature	<1000 K	IRD0501–0506
Bit Resolution	8 bits (RF < 50.5 GHz) 4 bits (70 < RF < 116 GHz)	IRD0721–0725 IRD0726

4 Functional and Performance Requirements

All function and performance requirements apply to a properly functioning system, with nominal inputs and control settings (e.g., attenuator states), under normal operating environmental conditions (temperature, power, etc.), and with normal operational calibrations applied, unless otherwise stated.

4.1 RF Frequency Ranges

Parameter	Req. #	Value	Traceability
Band 1 RF Frequency	IRD0101	1.2–3.5 GHz	SYS0801–0806
Band 2 RF Frequency	IRD0102	3.5–10.5 GHz	SYS0801–0806
Band 3 RF Frequency	IRD0103	10.5–20.5 GHz	SYS0801–0806
Band 4 RF Frequency	IRD0104	20.5–34 GHz	SYS0801–0806
Band 5 RF Frequency	IRD0105	30.5–50.5 GHz	SYS0801–0806
Band 6 RF Frequency	IRD0106	70–116 GHz	SYS0801–0806

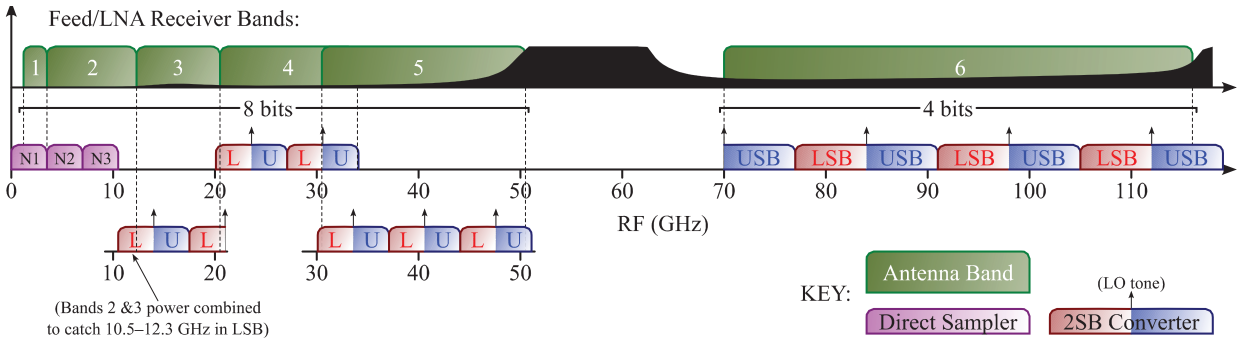
The total RF frequency range flows down from the system requirements, and the selection of band edges stem from a combination of engineering feasibility, hardware efficiency, and the system requirement that the band edges do not coincide with important spectral features.

It should be noted that the Band 2/3 transition at 10.5 GHz for the IRD modules do not coincide with those of the planned feed and cryogenic amplifier bands. This is because 10.5 GHz marks the transition from one type of integrated module (direct-sampled) and another (sideband-separating), which in turn is driven by the expected analog bandwidth of the digitizers.

A general frequency plan for the integrated receivers is shown in Figure 1 (next page). Unless otherwise noted, all references to RF bands within this document shall refer to the integrated module band ranges, not the cryogenic front-end band ranges.

The RF signal path will include a set of passive splitters and combiners to feed the correct bandwidth to each module. Note that the wider RF bands will require more than one module for complete frequency coverage. Although the reference design anticipates that all modules within a given RF band will be identical, this is not a requirement.

A subset of antennas (their number as yet undetermined) will require additional Band 4 modules to service the water vapor radiometer (WVR).



Band	Frequency	Receiver Type	# bits	Sample Rate
1	1.2–3.5 GHz	DS	8	7 GS/s
2	3.5–7.0 GHz	DS	8	7 GS/s
	7.0–10.5 GHz	DS	8	7 GS/s
3	10.5–20.5 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
4	20.5–34 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
WVR (4)	20.5–34 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
5	30.5–50.5 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
		2SB	8	7 GS/s
6	70–116 GHz	2SB	4	14 GS/s
		2SB	4	14 GS/s
		2SB	4	14 GS/s
		2SB	4	14 GS/s

Figure 1 - Integrated downconverter frequency plan. DS refers to direct-sampled receivers, while 2SB refers to sideband-separating receivers.

4.2 LO Frequencies

Parameter	Req. #	Value	Traceability
Band 3 LO Frequencies	IRD0201	14 and 21 GHz	SYS0906
Band 4 LO Frequency	IRD0202	23.6 and 30.6 GHz	SYS0906
Band 5 LO Frequencies	IRD0203	33.6, 40.6, and 47.6 GHz	SYS0906
Band 6 LO Frequencies	IRD0204	70, 84, 98, and 112 GHz	SYS0906
LO Frequency Tunability	IRD0205	±2 GHz	SYS0806

The LO frequencies above were selected to allow complete coverage of the RF bands in Section 4.1 with only minimal gaps at near-DC IF frequencies and at the edges between sidebands of adjacent downconverters. LOs were also selected, where reasonable, to be harmonically related to the sample clock frequencies to minimize the chance of spurious mixing products between the two. For simplicity, we do not require the LOs to tune over very wide ranges, but a minimal LO tuning requirement (IRD0205) permits access to these nominal gap frequencies at the discretion of the telescope operator (with the exception of the gaps at 3.5 GHz and 7 GHz between Nyquist zones of the direct-sampled receivers).

4.3 IF Bandwidth

Parameter	Req. #	Value	Traceability
Band 1 IF Bandwidth	IRD0301	3.5 GHz	
Band 2 IF Bandwidth	IRD0302	3.5 GHz	
Band 3 IF Bandwidth	IRD0303	3.5 GHz	
Band 4 IF Bandwidth	IRD0304	3.5 GHz	
Band 5 IF Bandwidth	IRD0305	3.5 GHz	
Band 6 IF Bandwidth	IRD0306	7 GHz	

Note that these bandwidths correspond to the maximum theoretical bandwidths sampled by the digitizers, and do not necessarily represent *alias-free* bandwidth. Bands 3 and above are sideband-separating, while the Band 2 module is expected to utilize two Nyquist zones with 3.5 GHz bandwidth each. Further, all modules are dual polarization. Finally, as noted earlier, some bands will be populated with more than one module. Consequently, the numbers above represent the IF bandwidth *per sideband or Nyquist zone*, *per polarization*, and *per module*, as applicable for each band.

4.4 Analog Gain

The net warm electronic gain is required to amplify the weak output spectra of the cryogenic system to a level at the digitizers that balances quantization efficiency and dynamic range. It is specified in terms of nominal (average) value, flatness, and adjustment range. The final values of these specs will depend on the gain specification of the cryogenic amplifiers and the full-scale range of the samplers.

4.4.1 Nominal Gain

Parameter	Req. #	Value	Traceability
Band 1 Nominal Gain	IRD0411	60 dB (TBC)	
Band 2 Nominal Gain	IRD0412	60 dB (TBC)	
Band 3 Nominal Conversion Gain	IRD0413	60 dB (TBC)	
Band 4 Nominal Conversion Gain	IRD0414	60 dB (TBC)	
Band 5 Nominal Conversion Gain	IRD0415	60 dB (TBC)	
Band 6 Nominal Conversion Gain	IRD0416	60 dB (TBC)	

Nominal gain is defined as the average analog signal gain between the RF inputs of the IRD modules and the inputs to the samplers over the RF operating frequency for each band defined in Section 4.1. The nominal setting of the internal step attenuators are determined post-fabrication as that setting which most closely achieves the desired gain. The modules will further be required to have enough attenuator control range leftover to meet the gain adjustability requirements in Section 4.4.3.

4.4.2 Gain Flatness

Parameter	Req. #	Value	Traceability
Gain Slope	IRD0421	<2.4 dB (80% BW) TBC	SYS1703
Gain Ripple	IRD0422	<2.4 dB peak-to-peak TBC	SYS1702

Gain slope is measured as the best fit line over that 80% of each IF band (defined in Section 4.3) which minimizes its value. Gain ripple is defined as the residual variation over the same 80% bandwidth after the slope is removed from the data. The system requirements for gain slope and ripple are 3 dB each. No budget for sharing this allowance across subsystems has been completed, but it can be assumed 80% of that can be allocated to the IRD system and 20% to the cryogenic front-ends, for two reasons. First, IRD comprises roughly two-thirds of the net analog gain (60 dB out of roughly 90 dB). Second, several lossy signal-conditioning components such as mixers, filters, and variable attenuators, must be further compensated by gain stages in the IRD.

4.4.3 Gain Adjustment

Parameter	Req. #	Value	Traceability
Gain Adjustment Range	IRD0431	±12 dB	
Gain Adjustment Step Size	IRD0432	≤1 dB	
Solar Mode Adjustment	IRD0433	+30 dB up to 10.5 GHz (TBC)	SYS1203

Analog gain shall be adjustable in discrete steps via integrated step attenuators. The nominal setting of these attenuators shall be determined on a per module basis to most closely meet the nominal gain targets, with enough range left over to meet the requirements above. An additional 30 dB attenuator shall be available in the lower frequency bands to support solar observations. At present, it is assumed the extra attenuation is not needed for the higher frequency bands.

4.4.4 Gain Stability

Parameter	Req. #	Value	Traceability
Gain Amplitude Stability	IRD0441	<0.01 dB per hour	SYS1701
Gain Phase Stability	IRD0442	<0.01 degrees over 300 sec	SYS1504
Allan Variance	IRD0443	TBD	

Gain amplitude and phase stability is required to reach the ngVLA's ultimate sensitivity goals, as well as to enable a low-overhead calibration policy in which bandpass and gain solutions for each antenna and receiver are stored for use in subsequent observations. The stability of gain amplitude and phase shall apply at any point in the pass-band, and shall be met under nominal environmental conditions (especially temperature gradient) given in Section 4.8.1. Allan variance is measured on amplitude only. As described in the system-level requirements, the phase drift specification is an rms residual, after subtraction of any linear trend over the specified time period.

4.5 Sensitivity

Parameter	Req. #	Value	Traceability
Band 1 Noise Temperature	IRD0501	<1000 K	SYS1011
Band 2 Noise Temperature	IRD0502	<1000 K	SYS1011, SYS1012
Band 3 Noise Temperature	IRD0503	<1000 K	SYS1012
Band 4 Noise Temperature	IRD0504	<1000 K	SYS1012
Band 5 Noise Temperature	IRD0505	<1000 K	SYS1012
Band 6 Noise Temperature	IRD0506	<1000 K	SYS1013

These noise temperatures ensure that the warm electronics contribute less than 1K to the system noise temperature, assuming the cryogenic input stage has 30 dB gain. Noise temperature shall be measured by Y-factor over the integrated noise of the IF bandwidth with the internal step attenuators at nominal setting.

4.6 Spurious Signals

Spurious signals in this document may include any unwanted signal power (aside from in-band noise) that leak into the signal path. These may include image bands, alias bands, and spurious CW or narrowband tones.

4.6.1 Image Rejection

Parameter	Req. #	Value	Traceability
Band 3 Image Rejection	IRD0611	>30 dB	SYS1704
Band 4 Image Rejection	IRD0612	>30 dB	SYS1704
Band 5 Image Rejection	IRD0613	>30 dB	SYS1704
Band 6 Image Rejection	IRD0614	>30 dB	SYS1704

Image rejection shall be measured with calibrated corrections applied and all internal attenuators and LOs at nominal settings.

4.6.2 Alias Rejection

Parameter	Req. #	Value	Traceability
Band 1 Alias-Free IF FBW	IRD0621	80%	SYS1703
Band 2 Alias-Free IF FBW	IRD0622	80%	SYS1703
Band 3 Alias-Free IF FBW	IRD0623	80%	SYS1703
Bands 4–6 Alias-Free IF FBW	IRD0624	80%	SYS1703
Band 1 Alias Rejection	IRD0625	>55 dB	
Band 2 Alias Rejection	IRD0626	>55 dB	
Band 3 Alias Rejection	IRD0627	>55 dB	
Bands 4–6 Alias Rejection	IRD0628	>55 dB	

"Alias-free" IF fractional bandwidth (FBW) is the percentage of the theoretical IF band defined in Section 4.3 in which the aliased signals are attenuated by the given alias rejection levels. The rejection, in turn, is measured relative to the corresponding in-band gain. It is inevitable that anti-aliasing filters will introduce gain slope at the edges of the IF band. The 80% fractional bandwidth specifications above flow down from the System Requirement SYS1703 that the IF slope shall be restricted over 80% of the band.

Note that at the broadest IF bandwidth (7 GHz), an 80% FBW specification allows for a gap of 0.2 x 7 GHz = 1.4 GHz, which is not "alias-free." The LO tuning requirement (IRD0205) ensures that all frequencies within the instrument's RF range (except for the Nyquist zone boundaries at 3.5 GHz and 7 GHz) are accessible with "alias-free" levels of rejection.

4.6.3 Spurious Narrowband Tones

Parameter	Req. #	Value	Traceability
Spurious Tone Power	IRD0631	<–43 dB/MHz above noise floor	SYS2104

Spurious tones in this context refers to any narrowband spurious signal, regardless of its source (e.g., mixing products, clock harmonics, switching transients, oscillations). The relative "spurious power" in a given spectral bin will be calculated as $(P–N)/N$, where P is the total power in the bin and N is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples to >10 dB below the spec limit.

4.7 *Digitization*

4.7.1 Sample Rate

Parameter	Req. #	Value	Traceability
Band 1 Sample Rate	IRD0711	7 GS/s	
Band 2 Sample Rate	IRD0712	7 GS/s	
Band 3 Sample Rate	IRD0713	7 GS/s	
Band 4 Sample Rate	IRD0714	7 GS/s	
Band 5 Sample Rate	IRD0715	7 GS/s	
Band 6 Sample Rate	IRD0716	14 GS/s	

4.7.2 Bit Resolution

Parameter	Req. #	Value	Traceability
Band 1 Bit Resolution	IRD0721	8 bits	SYS1034
Band 2 Bit Resolution	IRD0722	8 bits	SYS1034
Band 3 Bit Resolution	IRD0723	8 bits	SYS1034
Band 4 Bit Resolution	IRD0724	8 bits	SYS1034
Band 5 Bit Resolution	IRD0725	8 bits	SYS1034
Band 6 Bit Resolution	IRD0726	4 bits	SYS1035

Note that these represent the bit resolutions at the front-end. The correlator may requantize these data streams at lower resolution levels (with appropriate care for sensitivity and dynamic range).

4.8 *Operating Conditions*

All functional and performance specifications given herein are to be met at nominal operating conditions, while basic functionality is required over the limiting operational conditions.

4.8.1 Nominal Operating Conditions

Parameter	Req. #	Value	Traceability
Nominal Temperature	IRD0811	-15 C $\leq$ T $\leq$ 35 C	ENV0323
Nominal Temperature Gradient	IRD0812	<3.6°C per hour	ENV0324

Verification tests shall be considered successful if the measurement passes while environmental conditions are within the ranges of the nominal operating conditions, unless otherwise explicitly stated.

4.8.2 Limiting Operational Conditions

Parameter	Req. #	Value	Traceability
Limiting Temperature	IRD0821	-20 C $\leq$ T $\leq$ 45 C	ENV0332
Limiting Temperature Gradient	IRD0822	<3.6°C/Hr.	

The limiting operational conditions define the ranges over which basic functionality is assured without necessarily meeting specifications. They are not intended to define safe storage or working limits beyond which permanent damage may occur.

4.9 Monitor & Control Requirements

Parameter	Req. #	Value	Traceability
RF Signal Monitors	IRD0901	The integrated modules shall measure and report total signal power entering each RF input.	
IF Signal Monitors	IRD0902	The integrated modules shall measure and report total IF signal power entering each digitizer channel.	
Electronic Serial Number	IRD0903	The integrated modules shall report a unique electronic identification upon request.	
Standby Mode	IRD0904	The integrated modules shall be capable of entering a low-power standby mode on command. M&C communications shall still be functional in this mode.	
Automatic Initialization	IRD0905	The integrated modules shall automatically boot into a nominal operational mode on power-up, absent any command from M&C.	

The monitor points (IRD0901 and IRD0902) may comprise raw voltages or digital values in arbitrary units, subject to appropriate scaling and translation to recover meaningful values. No specific precision or accuracy is implied in these requirements.

4.10 Mass and Physical Dimensions

Parameter	Req. #	Value	Traceability
Physical Dimensions	IRD1001	Each integrated module shall fit within a physical envelope measuring 40 x 80 x 160 mm in size.	
Mass	IRD1002	Each integrated module shall weigh less than 1.5 kg.	
Connector Orientation	IRD1003	RF input connectors/flanges shall be located at one end of the physical envelope above, while the outputs and LO, clock, bias, and M&C inputs shall be located at the opposite end.	
Mounting Holes	IRD1004	Each integrated module shall include at least four clear holes (sized for #4 screws) oriented to mount against a temperature-controlled surface in contact with the largest face of the above physical envelope.	

5 Interface Requirements

This section provides information about the interfaces of the integrated modules. Interface Control Documents (ICDs) are required between the integrated modules 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 Integrated Receivers and Downconverters designer. Post CoDR, the ICD shall only be updated through formal project change control processes.

Unilateral aspects of the connector interfaces (e.g., M or F) shall refer to the connector on the integrated modules. Cables, waveguide, and fiber runs between the integrated modules and other electronic subsystems are not included in this work package.

5.1 Interface to the Cryogenic Front End Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Band 1 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 2 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 3 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 4 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 5 RF	Input	Flange Multiplicity	WR-22 (UG599) x2 (one per pol.)	
Band 6 RF	Input	Flange Multiplicity	WR-10 (UG387) x2 (one per pol.)	

The frequency ranges for these inputs are given in Section 4.1. The RF splitters and combiners are included in the Integrated Receivers and Downconverters subsystem.

5.2 Interface to Water Vapor Radiometer

Signal at Interface	Type	Parameter	Value	Comments
Band 4 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	

The Water Vapor Radiometer will be present on all antennas.

5.3 Interface to the Timing Reference/LO Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Sample Clock Reference	Input	Frequency Electrical Format Connector Multiplicity	156.25 MHz LVDS TBD x13 (TBC)	 Coaxial, shielded
Band 3 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD 2.92 mm (F) 50 Ω x2	
Band 4 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD 2.92 mm (F) 50 Ω x4	
Band 5 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD WR-22 (UG599) 50 Ω x3	
Band 6 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD WR-10 (UG387) 50 Ω x4	

The LO nominal frequencies and tuning ranges are given in Section 4.2.

5.4 Interface to the Monitor and Control Subsystem

Signal at Interface	Type	Parameter	Value	Comments
M&C Serial Bus	Input / Output	Protocol Connector Number of Pins Multiplicity	SPI (mode 0) Nano-D (F) TBD x15 (TBC)	May be combined on the same cable harness with power supplies.

5.5 Interface to the Power Supplies

Signal at Interface	Type	Parameter	Value	Comments
Analog Positive Supply	Input	Voltage Current Draw Multiplicity	+5 V <1 A (TBC) x13	Internally regulated for multiple voltages.
Digital Positive Supply	Input	Voltage Current Draw Multiplicity	+3.3 V <1 A (TBC) x15	Internally regulated.
Main Negative Supply	Input	Voltage Current Draw Multiplicity	–5 V <100 mA (TBC) x15	Primarily (exclusively?) for transistor gates.

5.6 Interface to the Data Transmission Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Digital IFs	Output	Data Format Data Content Connector Physical Format Nominal Wavelength Colors/Lanes Baud Rate Effective Bit Rate Modulation Multiplicity	Unformatted I/Q or Nyquist QSFP Single-Mode Fiber 1310 nm 4 28 Gbaud/lane 56 Gbps per lane PAM4 x15	PAM4 modulation carries 2 bits per symbol, so “effective” 56 Gbps per lane is achieved by transmitting 28 billion symbols per second. Number of fibers: 13 Nominal, plus 2 for WVR

6 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 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. The following table summarizes the expected verification method for each requirement.

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
IRD0101	Band 1 RF Frequency	*				
IRD0102	Band 2 RF Frequency	*				
IRD0103	Band 3 RF Frequency	*				
IRD0104	Band 4 RF Frequency	*				
IRD0105	Band 5 RF Frequency	*				
IRD0106	Band 6 RF Frequency	*				
IRD0201	Band 3 LO Frequencies	*				
IRD0202	Band 4 LO Frequency	*				
IRD0203	Band 5 LO Frequencies	*				
IRD0204	Band 6 LO Frequencies	*				
IRD0205	LO Frequency Tunability	*				
IRD0301	Band 1 IF Bandwidth	*				
IRD0302	Band 2 IF Bandwidth	*				
IRD0303	Band 3 IF Bandwidth	*				
IRD0304	Band 4 IF Bandwidth	*				
IRD0305	Band 5 IF Bandwidth	*				
IRD0306	Band 6 IF Bandwidth	*				
IRD0411	Band 1 Nominal Gain	*	*		*	
IRD0412	Band 2 Nominal Gain	*	*		*	
IRD0413	Band 3 Nominal Conversion Gain	*	*		*	
IRD0414	Band 4 Nominal Conversion Gain	*	*		*	
IRD0415	Band 5 Nominal Conversion Gain	*	*		*	
IRD0416	Band 6 Nominal Conversion Gain	*	*		*	
IRD0421	Gain Slope				*	

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
IRD0422	Gain Ripple				*	
IRD0431	Gain Adjustment Range	*	*		*	
IRD0432	Gain Adjustment Step Size	*				
IRD0433	Solar Mode Adjustment	*				
IRD0441	Gain Amplitude Stability				*	
IRD0442	Gain Phase Stability				*	
IRD0443	Allan Variance				*	
IRD0501	Band 1 Noise Temperature	*	*			*
IRD0502	Band 2 Noise Temperature	*	*			*
IRD0503	Band 3 Noise Temperature	*	*			*
IRD0504	Band 4 Noise Temperature	*	*			*
IRD0505	Band 5 Noise Temperature	*	*			*
IRD0506	Band 6 Noise Temperature	*	*			*
IRD0611	Band 3 Image Rejection				*	
IRD0612	Band 4 Image Rejection				*	
IRD0613	Band 5 Image Rejection				*	
IRD0614	Band 6 Image Rejection				*	
IRD0621	Band 1 Alias-Free IF FBW	*			*	
IRD0622	Band 2 Alias-Free IF FBW	*			*	
IRD0623	Band 3 Alias-Free IF FBW	*			*	
IRD0624	Bands 4–6 Alias-Free IF FBW	*			*	
IRD0625	Band 1 Alias Rejection	*			*	
IRD0626	Band 2 Alias Rejection	*			*	
IRD0627	Band 3 Alias Rejection	*			*	
IRD0628	Bands 4–6 Alias Rejection	*			*	
IRD0631	Spurious Tone Power				*	
IRD0711	Band 1 Sample Rate	*				
IRD0712	Band 2 Sample Rate	*				
IRD0713	Band 3 Sample Rate	*				
IRD0714	Band 4 Sample Rate	*				
IRD0715	Band 5 Sample Rate	*				
IRD0716	Band 6 Sample Rate	*				
IRD0721	Band 1 Bit Resolution	*				
IRD0722	Band 2 Bit Resolution	*				
IRD0723	Band 3 Bit Resolution	*				
IRD0724	Band 4 Bit Resolution	*				
IRD0725	Band 5 Bit Resolution	*				
IRD0726	Band 6 Bit Resolution	*				
IRD0811	Nominal Temperature	*				
IRD0812	Nominal Temperature Gradient	*	*			
IRD0821	Limiting Temperature	*				
IRD0822	Limiting Temperature Gradient	*				
IRD0901	RF Signal Monitors	*			*	
IRD0902	IF Signal Monitors	*			*	
IRD0903	Electronic Serial Number	*			*	
IRD0904	Standby Mode	*			*	

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
IRD0905	Automatic Initialization	*			*	
IRD1001	Physical Dimensions	*				
IRD1002	Mass			*		
IRD1003	Connector Orientation	*				
IRD1004	Mounting Holes	*				

7 Appendix

7.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
FBW	Fractional Bandwidth
FDR	Final Design Review
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
IRD	Integrated Receivers and Downconverters
KPP	Key Performance Parameters
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C	Monitor and Control
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SNR	Signal to Noise Ratio
TBC	To Be Confirmed
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

Integrated Downconverters and Digitizers Design Description

020.30.15.00.00-0002-DSN-A-INTEGR_RECVR_DOWNCONVERTER_REF_DSN

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
M. Morgan	Electronics Div., NRAO	2018-11-01
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-12

APPROVALS (Name and Signature)	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer 2019.07.25 12:37:44 -06'00'	Electronics Div., NRAO	2019-07-25
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:16:30 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-25

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:16:52 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-25

Change Record

Version	Date	Author	Affected Section(s)	Reason
1	2018-03-13	M. Morgan	All	Initial Draft, based on template provided.
2	2018-03-29	M. Morgan	5.1–5.3	Modified LO frequencies for Band 5.
3	2018-04-16	M. Morgan	4, 5.1, 5.2.3, 5.3.4	Removed references to thermoelectric coolers.
4	2018-04-26	M. Morgan	Many	Increased to 8 bits in Bands 4 and 5, and added two Band 4 modules for WVR. Added 3.3 V digital supply.
5	2018-05-24	M. Morgan	Header	Corrected file number.
6	2018-06-26	M. Morgan	Header	Recorrected file number.
7	2018-07-03	M. Morgan	Fig. 2	Corrected Band 2 edge frequencies.
8	2018-09-06	S. Durand	All	Minor changes.
9	2018-09-25	M. Morgan	5.2.1	Clarified that cooling fans on the pictured prototype will not be present in reference design version.
A	2019-07-25	A. Lear	All	Prepared PDF for approvals and release.

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 4
3 Subsystem Overview 5
4 Subsystem Design 5
4.1 Subsystem Block Diagram 7
4.2 Subsystem Components 8
4.2.1 Sideband-Separating (2SB) Receiver Modules 8
4.2.2 Direct-Sampled (DS) Receiver Modules 11
4.2.3 Other Components 12
4.3 Interfaces with Other Subsystems 12
4.3.1 Interface to the Cryogenic Front-End Subsystem 12
4.3.2 Interface to the Water Vapor Radiometer 13
4.3.3 Interface to the Timing Reference/LO Subsystem 13
4.3.4 Interface to the Monitor and Control Subsystem 13
4.3.5 Interface to the Power Supplies 14
4.3.6 Interface to the Data Transmission Subsystem 14
5 Appendix 15
5.1 Abbreviations & Acronyms 15
5.2 Bibliography 16

1 Introduction

1.1 Purpose

This document provides a description for the Integrated Downconverters and Digitizers subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the Integrated Downconverters and Digitizers subsystem, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev/Doc. No.
AD01	Integrated Receivers and Downconverters Preliminary Technical Specifications/Requirements	020.30.15.00.00-0001-REQ

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Experiments With Digital Sideband-Separating Downconversion	M. Morgan and J. Fisher, *Publications of the Astronomical Society of the Pacific*, vol. 122, no. 889, pp. 326–335, March 2010.
RD02	Unformatted Digital Fiber-Optic Data Transmission for Radio Astronomy Front Ends	M. Morgan, J. Fisher, and J. Castro, *Publications of the Astronomical Society of the Pacific*, vol. 125, no. 928, pp. 695–704, June 2013.
RD03	A highly-sensitive cryogenic phased array feed for the Green Bank Telescope	D. Roshi, W. Shillue, J. Fisher, M. Morgan, J. Castro, W. Groves, T. Boyd, B. Simon, L. Hawkins, V. van Tonder, J. Nelson, J. Ray, T. Chamberlain, S. White, R. Black, K. Warnick, B. Jeffs, and R. Prestage, 32nd URSI General Assembly and Scientific Symposium, Montreal, August 2017.
RD04	SO-QSFP28-PAM4-Dxxx datasheet	https://www.smartoptics.com/wp-content/uploads/2017/10/SO-QSFP28-PAM4-DWDM-R4.0.pdf
RD05	Eoptolink 200G-400G solutions	http://www.eoptolink.com/200g-400g

3 Subsystem Overview

The Integrated Receiver and Digitizer (IRD) packages further amplify the signals provided by the cryogenic stage, downconvert them where necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point from the focal plane (but possibly still inside the antenna base). From there, they can be time-stamped and launched onto a more conventional network for transmission back to the array correlator and central processing facility. Hooks are needed to provide for synchronization of local oscillators (LOs) and sample clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

This subsystem consists of direct-sampled and sideband-separating modules for all telescope bands, which include warm amplification, filtering, power leveling, analog-to-digital conversion, and fiber-optic transmission. It also includes external splitters and combiners as needed to feed them from the cryogenic signal paths. Cryogenic systems and thermal transitions, as well as front-end cabling, waveguide runs, and fiber-optic signal paths outside the IRD modules themselves, are outside the scope of this work package, though interfaces must be considered.

4 Subsystem Design

The design of the ngVLA IRD modules evolved from an internal research program (the Integrated Receiver Development program), which has been perfecting the techniques used in their construction for more than a decade at the time of this writing. The original program aimed to leverage the advantages of modern electronic integration and digital signal processing, to digitize as closely to the antenna feed-point as possible without comprising ultimate performance, and to re-optimize legacy receiver architectures in light of these new techniques and in anticipation of future telescope facilities such as the ngVLA.

Integration and digital signal processing (DSP) are deemed complementary in this program, in that the latter provides for greater signal fidelity and precision in concert with detailed calibrations than purely analog techniques, while the former guarantees the long-term stability and uniformity of those calibrations. This resulted also in compact, low-power, field-replaceable receiver units which were a perfect fit for ngVLA's maintenance and operability requirements.

Paramount to the integrated receiver subsystem design is coverage of all operating bands on the telescope with the minimum number of discrete integrated modules. This minimizes construction, testing, operating, and maintenance costs as well as reducing the complexity of the data transport and timing distribution subsystems. The limiting factor here is digitizer bandwidth and sample rate. The ngVLA has a requirement to digitize instantaneously 20 GHz of bandwidth, with a goal of sampling the entire frequency range of any given RF band simultaneously (Band 6 in particular covering more than 20 GHz of bandwidth). This is more than can be sampled instantaneously at the bit depth required with a single analog-to-digital converter (ADC) having reasonable performance and power dissipation. Thus, the system will consist of low-loss splitters following the cryogenic front-end feeding a number of integrated receiver modules in parallel.

Due to the compact, integrated construction, it is unwise to perform downconversion in multiple steps. Integrated modules, though they have many advantages, do not typically have as good of isolation between inputs as individually connectorized components. Multiple local oscillator tones, then, tend to produce a copious spread of mixing products that inevitably lead to spurious tones in the output spectrum.

We therefore process the higher frequency bands using a single-stage, direct-to-baseband downconversion with in-phase and quadrature (I and Q) channels. These channels are then processed numerically in the back-end to produce upper and lower sidebands more precisely than an analog hybrid ever could. The IRD program has a long track record of producing clean output spectra with 50–60 dB sideband suppression using this technique (e.g. [RD01]).

At the lower frequency bands, downconversion is an unnecessary complexity, usually requiring triple-balanced mixers to achieve the required IF bandwidth while isolating it from the RF and LO inputs which overlap with it in frequency space. For these bands, instead, we use a direct-digitization approach in the second or third Nyquist-zone of the sampler.

To minimize power requirements and the risk of self-interference with integrated digital and high-gain analog electronics, the IRD program developed a novel approach to digital data transmission. Specifically, it delivers unformatted digital data streams over optical fiber without any of the usual bit-scrambling, packetizing, or formatting (e.g. 8b/10b) used in the data-communications industry. This "low-overhead" digital design [RD02] relies on the statistical characteristics of Gaussian-distributed white noise—which dominates the signal in any properly designed radio astronomy receiver, even those heavily laced with man-made interference—to parse the bit stream at the receive-end of the fiber, away from the focal plane where power and interference are less harmful. Numerous demonstrations of this concept have been built and proven, and it has now been fielded in a user instrument on the Green Bank Telescope [RD03].

A critical element of the low-overhead serial link described above is the Serial ADC (SADC). This essentially marries a conventional ADC and a conventional Serializer (or SerDes) without any of the usual, intervening, complex digital logic. Implemented to date using off-the-shelf parts, fully realizing this idea's potential benefits relies on integrating these two components on a single piece of Silicon. This avoids the wasted size, weight, and power (SWaP) associated with chip-to-chip parallel interfaces. The functional components of this proven technique (the ADC and the Serializer) already exist commercially, making this a development with very low technical risk, but one that requires a significant investment in producing the ASIC. Such a development has been initiated with a contract IP vendor. The projected power dissipation of this chip is 25 times less than that consumed by off-the-shelf solutions.

The unformatted fiber optic links will likely not interface directly with the array correlator/signal processor. Rather, they will interface with the long-distance data transmission subsystem which will carry the data the rest of the way on more conventional (possibly commercial) links. The data transmission subsystem interface could be inside the antenna base or some tens of kilometers away where it will join with links from other telescopes in the array. The latter will most likely be the case at least for the antennas in the array core within reach of the signal processing center.

4.1 Subsystem Block Diagram

A block diagram of the Integrated Receivers/Downconverters and Digitizers Subsystem is shown in Figure 1, with all electrical interfaces included. The internal block diagrams of the sideband separating (2SB) and direct-sampled (DS) receiver modules appear in Section 4.2. The gray boxes provide information about subsystem inputs and outputs.

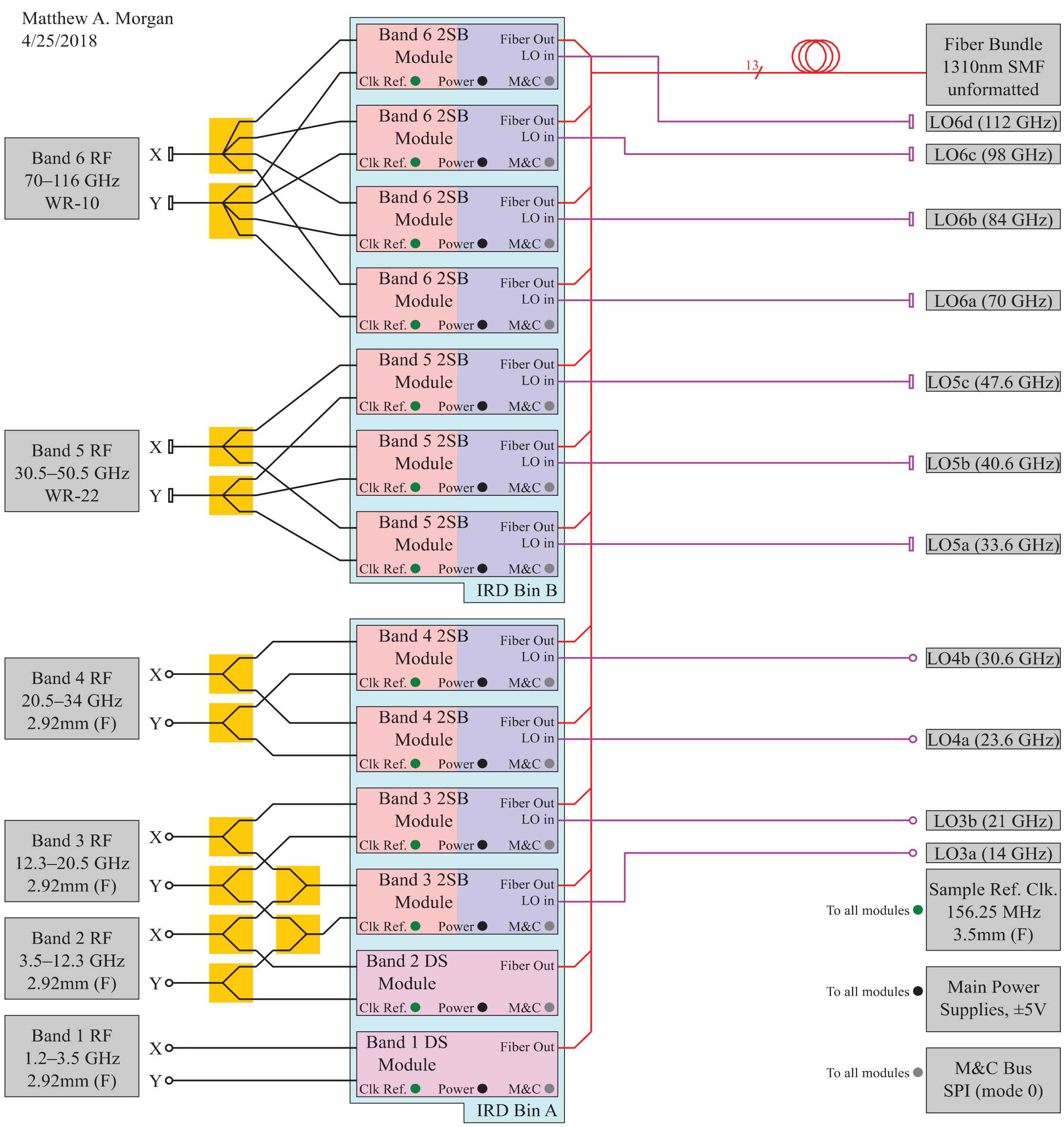
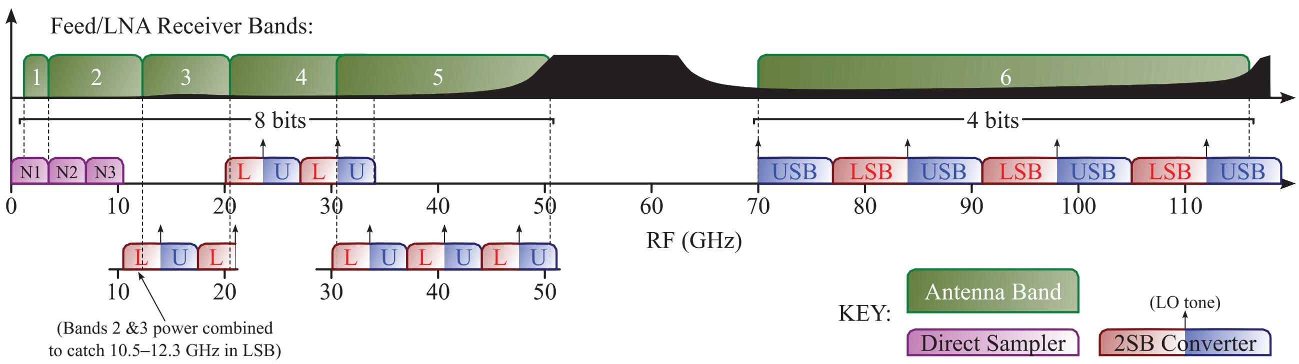


Figure 1 - Block diagram of Integrated Receivers/Downconverters and Digitizers subsystem.

4.2 *Subsystem Components*

By far, the most significant major components of the IRD subsystem are the receiver modules. As described above, the architecture and frequency distribution of these receiver modules have been designed to cover the required bandwith with the minimum amount of hardware. Figure 2 summarizes the resulting frequency. Note that antennas outfitted with a water vapor radiometer will need an additional two Band 4 modules, included in the table but not shown in the spectrum plot of Figure 2.



Band	Frequency	Receiver Type	# bits	Sample Rate
1	1.2–3.5 GHz	DS	8	7 GS/s
2	3.5–7.0 GHz	DS	8	7 GS/s
	7.0–10.5 GHz	DS	8	7 GS/s
3	10.5–20.5 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
4	20.5–34 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
WVR (4)	20.5–34 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
5	30.5–50.5 GHz	2SB	8	7 GS/s
		2SB	8	7 GS/s
		2SB	8	7 GS/s
6	70–116 GHz	2SB	4	14 GS/s
		2SB	4	14 GS/s
		2SB	4	14 GS/s
		2SB	4	14 GS/s

Figure 2 - Integrated Receiver/Downconverters and Digitizers frequency plan.

4.2.1 Sideband-Separating (2SB) Receiver Modules

A block diagram of a typical 2SB receiver module is shown in Figure 3. Each module has two RF inputs, one for each polarization. These inputs are broadband filtered to limit the power to downstream components, then amplified.

Preferably following the warm RF amplifier is a step attenuator for level control. This ensures that any changes here have minimal effect on the calibration coefficients for sideband-separation. At the highest frequencies, where step-attenuators may not be readily available, this level-control could be moved into the IF signal path. In that case, the M&C software should be programmed to step the attenuators in the I and Q signal paths synchronously after initial balancing in the lab—again, to ensure minimal impact on the calibration coefficients. Although some uncorrected amplitude imbalance will result from non-uniformity of the step-sizes of the two attenuators, the effect should be sufficiently small that the modules will still easily meet the sideband-rejection specification. All 2SB modules will support a power adjustment range of ±12 dB from nominal. The lower frequency bands may need an additional 30 dB switchable attenuator to support solar observing. This 30 dB of extra attenuation will undoubtedly degrade the noise figure, but this is not a concern for the solar-observing scenario.

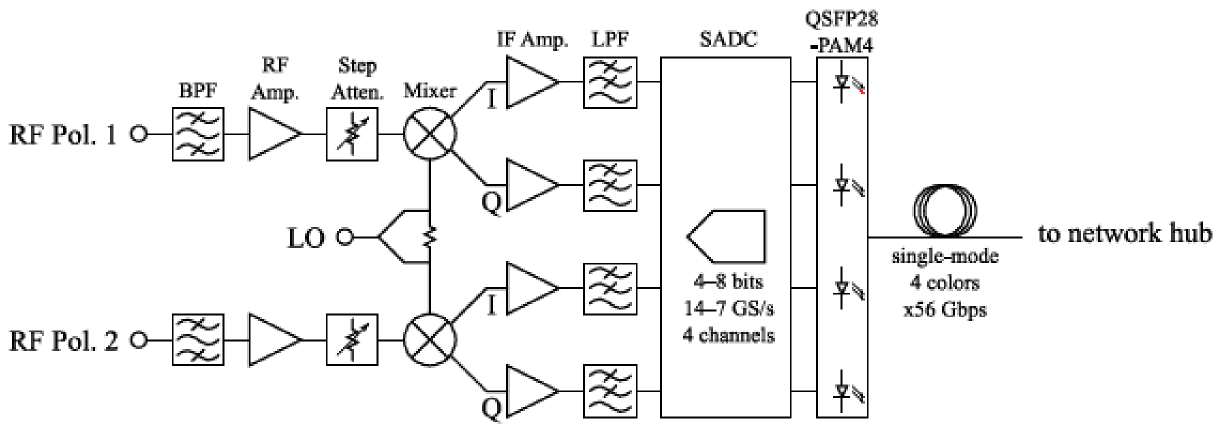


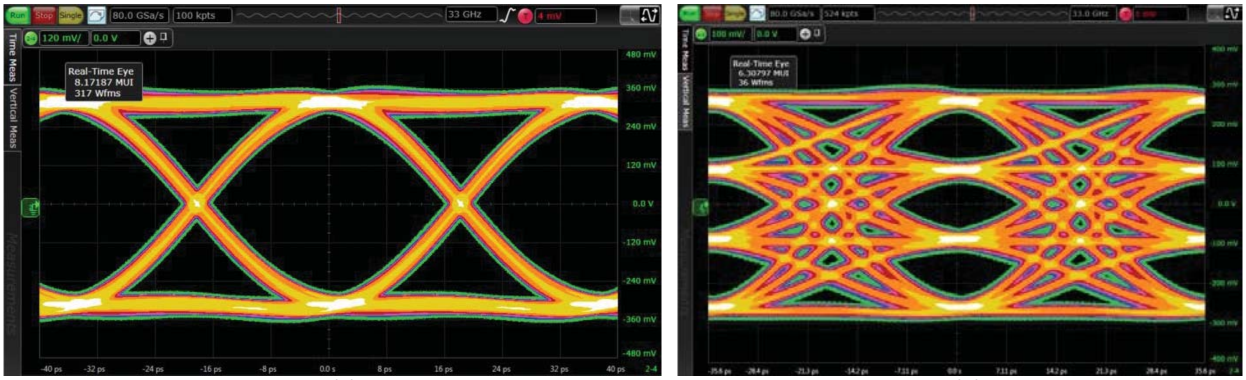
Figure 3 - Block diagram of a sideband-separating (2SB) receiver module.

The mixers implement a single-LO, direct-to-baseband I/Q downconversion. Additional warm-amplification and anti-alias filtering is present at baseband. This is followed by the Serial-ADC (SADC) chip described earlier, either two dual-channel SADCs or a single quad-channel SADC to capture I and Q from both polarizations. The SADC chip is progammable to support multiple bit depths and sample rates. For the highest bands needing the widest bandwidths, we anticipate 4-bit sampling at 14 GS/s. For lower bands, where human interference is more likely an issue, we will use 8-bit sampling at 7 GS/s.

Both sample rates are compatibile with the emerging industry standard serial rate of 56 Gbps per lane. These serial outputs are therefore fed into a quad-channel fiber-optic transceiver capable of transmitting 56 Gbps per lane, where four optical wavelengths are combined onto a single fiber. Although relatively new, such transceivers conforming to the QSFP28 form-factor (shown in Figure 4) are now becoming available with reaches of 500m up to 80 km [RD04–05]. These transceivers modulate the optical carrier at 28 giga-symbols per second using four-level pulse-amplitude modulation (PAM4), thus achieveing the serial rate of 56 Gbps.

Figure 4 - Quad Small Form-Factor Pluggable (QSFP28) optical transceiver.

A comparison of the eye-diagrams for the more common binary NRZ modulation and the PAM4 modulation are shown in Figure 5. The implementations of our unformatted serial link in actual telescope hardware to date have been limited to the NRZ waveform, but calculations show that the PAM4 waveform would be even more robust in our links due to the higher density of transitions for the clock recovery loop to lock onto (see Figure 6).



(a) (b)

Figure 5 - Comparison of (a) binary NRZ and (b) PAM4 optical modulation schemes.

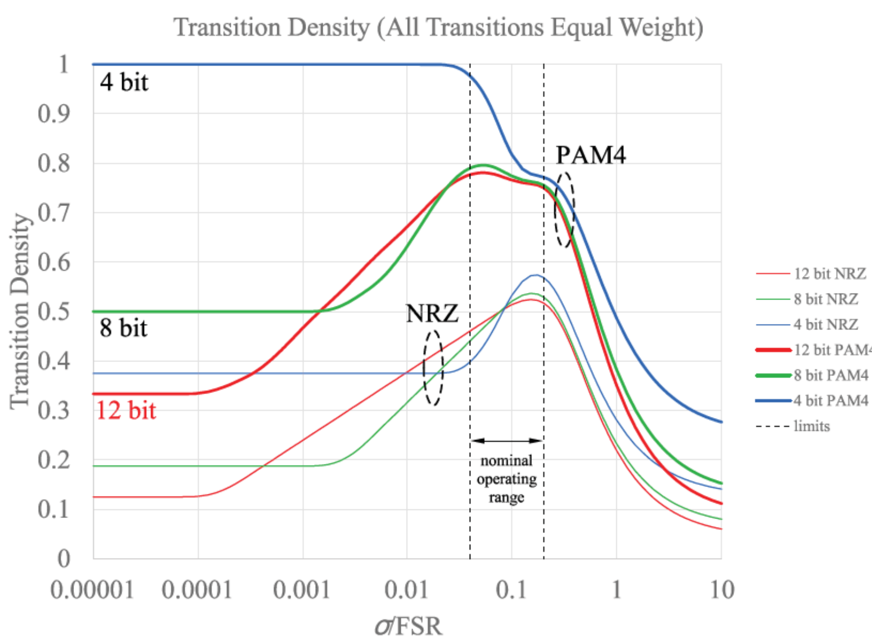
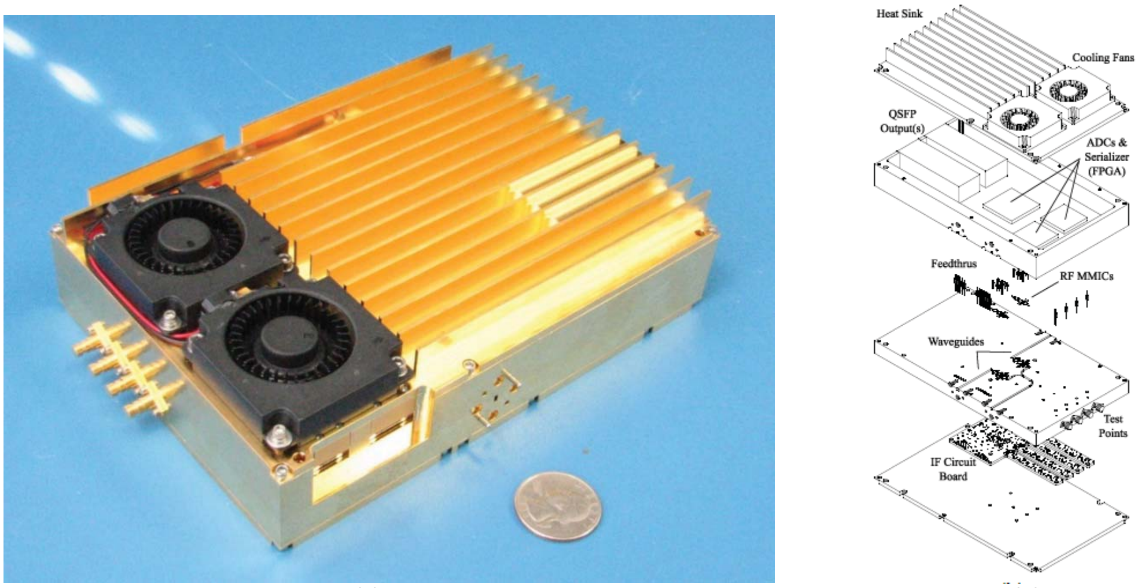


Figure 6 - Transition density for Gaussian-distributed white noise as a function of rms signal amplitude, for both NRZ and PAM4 encoding.

Although the SADC chip which is critical to realizing the SWaP benefits of the proposed design is not yet available, prototyping on fully-functional (but not full-spec) receiver modules has already begun. An example is shown in Figure 7. The internal details of the construction are shown in Figure 7(b).

This dual-polarization module operates in W-band (75–110 GHz) and may be considered an early prototype for the ngVLA Band 6. It utilizes a Kintex7 FPGA to implement the unformatted serialization of the ADC outputs at 8 Gbps. When the SADC chip becomes available, the same function as this FPGA plus the two ADCs will be implemented on a single chip in a 4mm package and consuming 1/25th the power. This module has two QSFP output connectors (which are really redundant since only one has enough channels to service the whole module).



(a) (b)

Figure 7 - Prototype W-band IRD 2SB receiver module. (a) Photo. (b) Exploded view of internal construction. Note that this is only a prototype. The cooling fans are needed here since the power-saving Serial ADC ASIC was not yet available. The reference design version will be smaller, consume less power, and be cooled without fans by attachment to a temperature-controlled plate.

4.2.2 Direct-Sampled (DS) Receiver Modules

The SADC will have wide analog input bandwidth to support direct-sampling up to the third Nyquist zone for the lower ngVLA bands. A block diagram for such a receiver module is shown in Figure 8. This module begins with a filter or diplexer depending on the RF band (the diplexer is shown), which roughly isolates the individual Nyquist zones for sampling. This is followed by warm amplification, power leveling, additional amplification, and a final anti-aliasing filter before feeding into the SADC chip and QSFP fiber transceiver. From the SADC forward, the data path is the same as it was for the 2SB modules.

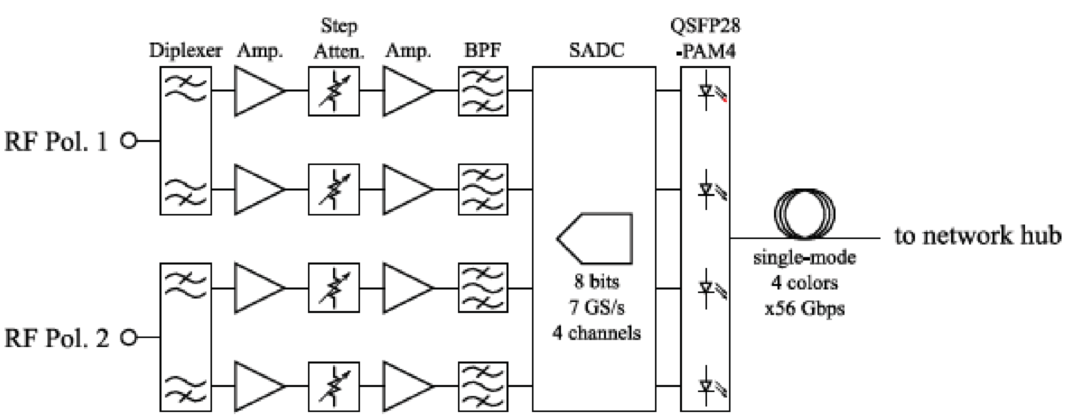


Figure 8 - Block diagram of a direct-sampled (DS) integrated receiver module.

Band 1 will only need two channels (corresponding to the first Nyquist zone for two polarizations) instead of the usual four. Since the commercially available QSFP modules inherently support four duplex, this leaves two lanes unoccupied. The reference design has no predetermined used for these lanes; however, one transmit-receive pair could be configured simply to operate in a loopback mode as part of a round-trip delay measurement in support of the time distribution subsystem, at no extra cost to the IRD modules. Both the 2SB and DS receiver modules are considered line-replaceable units (LRUs) in this design.

4.2.3 Other Components

Other subsystem components include the splitters/combiners that interface these modules to the front-end cryogenics, and the internal interconnects between them and the 2SB/DS receiver modules.

4.3 Interfaces with Other Subsystems

This section provides information about the interfaces of the integrated modules. Interface Control Documents (ICDs) are required between the integrated modules 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 Integrated Receivers and Downconverters designer. Post CoDR, the ICD shall only be updated through formal project change control processes.

Unilateral aspects of the connector interfaces (e.g., M or F) shall refer to the connector on the integrated modules. Cables, waveguide, and fiber runs between the integrated modules and other electronic subsystems are not included in this work package.

4.3.1 Interface to the Cryogenic Front End Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Band 1 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 2 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 3 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 4 RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	
Band 5 RF	Input	Flange Multiplicity	WR-22 (UG599) x2 (one per pol.)	
Band 6 RF	Input	Flange Multiplicity	WR-10 (UG387) x2 (one per pol.)	

The frequency ranges for these inputs are given in Figure 2. The RF splitters and combiners shown in Figure 1 are included in the IRD subsystem.

4.3.2 Interface to the Water Vapor Radiometer

Signal at Interface	Type	Parameter	Value	Comments
WVR RF	Input	Connector Impedance Multiplicity	2.92 mm (F) 50 Ω x2 (one per pol.)	

4.3.3 Interface to the Timing Reference/LO Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Sample Clock Reference	Input	Frequency Electrical Format Connector Multiplicity	156.25 MHz LVDS TBD x15 (TBC)	 Coaxial, shielded
Band 3 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD 2.92 mm (F) 50 Ω x2	
Band 4 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD 2.92 mm (F) 50 Ω x4	
Band 5 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD WR-22 (UG599) 50 Ω x3	
Band 6 LO	Input	Power Level Phase Noise Connector Impedance Multiplicity	>+13 dBm (CW) TBD WR-10 (UG387) 50 Ω x4	

The LO nominal frequencies are given in Figure 1. Each is nominally fixed to simplify calibration and operations, however a ±2 GHz tuning range is supported in order to provide overlap of the adjacent frequency bands so that no frequency "blind spots" exist (except for two narrow slivers between the Nyquist zones of Bands 1 and 2).

4.3.4 Interface to the Monitor and Control Subsystem

Signal at Interface	Type	Parameter	Value	Comments
M&C Serial Bus	Input / Output	Protocol Connector Number of Pins Multiplicity	SPI (mode 0) Nano-D (F) TBD x15 (TBC)	May be combined on the same cable harness with power supplies

4.3.5 Interface to the Power Supplies

Signal at Interface	Type	Parameter	Value	Comments
Analog Positive Supply	Input	Voltage Current Draw Multiplicity	+5 V <1 A (TBC) x15	Internally regulated for multiple voltages.
Digital Positive Supply	Input	Voltage Current Draw Multiplicity	+3.3 V <1 A (TBC) x15	Internally regulated.
Main Negative Supply	Input	Voltage Current Draw Multiplicity	–5 V <100 mA (TBC) x15	Primarily (exclusively?) for transistor gates.

4.3.6 Interface to the Data Transmission Subsystem

Signal at Interface	Type	Parameter	Value	Comments
Digital IFs	Output	Data Format Data Content Connector Physical Format Nominal Wavelength Colors/Lanes Baud Rate Modulation Multiplicity	Unformatted I/Q or Nyquist QSFP Single-Mode Fiber 1310 nm 4 56 Gbps per lane PAM4 x15	PAM4 modulation carries 2 bits per symbol, so “effective” 56 Gbps per lane is achieved by transmitting 28 billion symbols per second.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ADC	Analog-to-Digital Converter
ASIC	Application Specific Integrated Circuit
DBE	Digital Back End
DSP	Digital Signal Processing
DTS	Data Transmission System
IF	Intermediate Frequency
IRD	Integrated Receiver/Downconverter and Digitizer
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRZ	Non-Return to Zero (binary modulation)
NSF	National Science Foundation
PAM4	Four-level Pulse Amplitude Modulation
PLL	Phase Locked Loop
QSFP28	Quad Small Form-factor Pluggable 28 (giga-symbols per second)
RD	Reference Document
RF	Radio Frequency
SADC	Serial Analog-to-Digital Converter
SerDes	Serializer/Deserializer
SWaP	Size, Weight, and Power
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

5.2 Bibliography

For more information on the prototypes and techniques employed by the IRD subsystem, the reader is referred to:

M. Morgan and J. Fisher, "Statistical Word Boundary Detection in Serialized Data Streams," U.S. Patent No. 8,688,617, April 1, 2014. People's Republic of China Patent No. 201180046318.8, February 5, 2017.

M. Morgan, S. Wunduke, J. Castro, T. Boyd, and W. Groves, "Compact cm-wave and mm-wave integrated receivers," 32nd URSI General Assembly and Scientific Symposium, Montreal, August 2017.

J. Castro, M. Morgan, J. Ford, and V. van Tonder, "Digital sideband separating downconversion for the Green Bank Telescope phased array feed," URSI National Radio Science Mtg., Boulder, CO, January 2016.

M. Morgan, J. Fisher, and J. Castro, "Unformatted Digital Fiber-Optic Data Transmission for Radio Astronomy Front Ends," *Publications of the Astronomical Society of the Pacific*, vol. 125, no. 928, pp. 695-704, June 2013.

M. Morgan and J. Fisher, "Experiments With Digital Sideband-Separating Downconversion," *Publications of the Astronomical Society of the Pacific*, vol. 122, no. 889, pp. 326-335, March 2010.

M. Morgan and S. Wunduke, "An integrated receiver concept for the ngVLA," *ngVLA Memo #29*, November 2017.

M. Morgan and J. Fisher, "Word-Boundary Detection in a Serialized, Gaussian-Distributed, White-Noise Data Stream," *Electronics Division Technical Note #213*, October 2009.

M. Morgan and J. Fisher, "Simplifying Radio Astronomy Receivers," *NRAO eNews*, vol. 2, no. 3, March 2009

J. Fisher and M. Morgan, "Analysis of a Single-Conversion, Analog/Digital Sideband Separating Mixer Prototype," *Electronics Division Internal Report #320*, June 2008.

Digital Backend/Data Transmission System: Technical Requirements

020.30.25.00.00-0001-REQ-A-DBE_DTS_TECHNICAL_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
J. Jackson	Electronics Div., NRAO	2019-04-24
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-25

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer R. Selina 2019.07.24 12:11:14 -06'00'	Electronics Division, NRAO	2019-07-24
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:40:44 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:41:10 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
1	2018-05-11	J. Jackson	All	Initial draft
2	2018-06-04	J. Jackson	All	Continued work, many changes
3	2018-07-09	J. Jackson	All	Cleanup
4	2018-09-24	J. Jackson	All	Continued editing, new requirements
5	2018-09-24	S. Durand, J.Jackson	All	Small edits
6	2018-09-24	J. Jackson	All	Reorganized Requirements tables
7	2018-11-21	J. Jackson	3.4.1/4.3 5.1 3.2 Multiple 4.1 4.1 4.1 3.4.2 4.3 Numerous	Fixed typo per RID IPDSR-21 Clarified baud rate per RID IPDSR-22 Added LBA stations per RID IPDSR-66 Typos fixed per RID IPDSR-71 Reworded DEB009 per RID IPDSR-74 DBE005/6 edited per RID IPDSR-72 DBE001/2 edited per RID IPDSR-69 Removed 3.4.2 (empty) Removed untraceable requirements & specs per RID IPDSR-78 Added refs and updated tables per IPDSR-79
8	2018-11-27	J. Jackson	Various	A few cleanup edits for release
9	2019-04-24	S. Durand	All	Small edits
10	2019-04-24	J. Jackson	4.2 4.4 4.6 5.2	Timestamp Jitter Specification RFI/EMC Specifications MTBF Specification Clock & Timecode specs
11	2019-05-30	R. Selina	3.1, 6, 9	Minor edits for release
A	2019-07-24	A. Lear	All	Incorporate minor edits by M. McKinnon; prepare document for approvals & release

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
3 Overview of DBE/DTS Technical Requirements 7
3.1 Document Outline 7
3.2 Project Background 7
3.3 General DBE/DTS Work Package Description 7
3.4 Summary of DBE/DTS Work Package Requirements 8
3.4.1 General Functional Specifications 8
4 DBE/DTS Functional and Performance Requirements 9
4.1 Functional Requirements 9
4.2 Performance Requirements 9
4.3 I/O Requirements 10
4.4 Spurious Signals/Radio Frequency Interference Generation 10
4.5 Environmental Conditions 10
4.5.1 Normal Operating Conditions 10
4.5.2 Specific Environmental Requirements 10
4.6 Maintenance and Reliability Requirements 10
4.7 Monitor and Control Requirements 10
4.8 Lifecycle Requirements 11
5 Interface Requirements 12
5.1 Interface to the Integrated Downconverter/Digitizer Subsystem 12
5.2 Interface to the Reference Signal Subsystem 12
5.3 Interface to the Antenna Structure 13
5.3.1 Electrical Infrastructure 13
5.3.2 HVAC 13
5.3.3 RFI Mitigation 13
5.4 Interface to the Monitor and Control System 13
6 Safety 14
6.1 General 14
6.2 Safety Design Requirements 14
6.2.1 Fire Safety 14
6.2.2 Mechanical Safety 14
6.2.3 Electrical Safety 14
6.2.4 Handling, Transport, and Storage Safety 14
7 Design Requirements 15
7.1 Analyses and Design Requirements 15
7.1.1 Reliability Availability Maintainability Analysis 15
7.2 Electromagnetic Compatibility Requirements 15
7.3 Materials, Parts, and Processes 15
7.3.1 Fasteners 15
7.3.2 Paints 15

7.3.3 Surface Treatment ... 15
7.3.4 Name Plates and Product Marking ... 15
7.3.5 Labels ... 16
8 Documentation Requirements ... 16
8.1 Technical Documentation ... 16
8.2 Software and Software Documentation ... 16
9 Verification and Quality Assurance ... 17
10 Appendix ... 19
10.1 Maintenance Definitions ... 19
10.2 Abbreviations and Acronyms ... 20

1 Introduction

1.1 Purpose

This document presents a set of technical requirements for the design of the ngVLA Digital Backend/Data Transmission System (DBE/DTS) work package. Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow down from the preliminary ngVLA Science Requirements [AD01].

The science goals 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 preliminary analysis of these use cases and the flow down recursively to the science, system and subsystem requirements.

1.2 Scope

The scope of this document is the ngVLA DBE/DTS work package. This describes an opto-electronics system that receives unformatted data streams from the Integrated Downconverter/Digitizer Subsystem, performs substantial processing and data reduction on them, then formats and modulates them onto optical carriers for transmission to the Array Center via private and/or commercial fiber optic infrastructure.

This requirements document establishes the performance, functional, design, and test requirements applicable to the ngVLA DBE/DTS work package. It also includes interface requirements that must be defined.

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 this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Protection Against Electric Shock – Common Aspects for Installation and Equipment	IEC 61140:2016
AD07	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
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	Integrated Downconverters and Digitizers Design	020.30.15.00.00-0002-DSN
AD14	ngVLA Memo 29: An Integrated Receiver Concept for the ngVLA	ngVLA Memo 29
AD15	System Requirements	020.10.15.10.00-0003-REQ
AD16	System Environmental Specifications	020.10.15.10.00-0001-SPE
AD17	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD18	System-Level Electrical Requirements	020.10.15.10.00-0005-REQ
AD19	System-Level Mechanical Requirements	020.10.15.10.00-0006-REQ

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	Subsystem Reference Design Description: Digital Back End/Data Transmission System	020.30.25.00-0002-DSN

3 Overview of DBE/DTS Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA DBE/DTS work package. These parameters determine the overall form and performance of the DBE/DTS work package.

The functional and performance requirements, 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 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 DBE/DTS work package 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 DBE/DTS work package 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, from the conceptual design through to prototype, are described in Section 10.

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. Operations will be conducted from both the VLA Control Building and the Array Operations Center in Socorro, NM.

3.3 General DBE/DTS Work Package Description

This work package leads to the design of a Digital Back End/Data Transmission System Subsystem that receives data from the Integrated Downconverter/Digitizer subsystem, performs the primary digital processing required at the antenna, and prepares data for transmission across private and public telecommunications infrastructure. This subsystem is concentrated in a single, highly integrated RFI shielded module located in the pedestal area of each ngVLA antenna.

Digital data streams produced in the Integrated Downconverter/Digitizer (IRD) Modules located in the Front End (FE) are received in the DBE/DTS module via 13 single-mode fibers. Clock recovery and de-serialization is performed on the data which is then fed to digital processing blocks where functions such as channelization, digital downconversion, re-quantization, RFI tagging or excision, etc. can be performed.

Processed data is then formatted into standard telecommunication formats (i.e. Ethernet, SONET) and placed back into the optical domain for transmission over private or commercial fiber-optic networks.

3.4 Summary of DBE/DTS Work Package Requirements

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

3.4.1 General Functional Specifications

Parameter	Summary of Requirement	Reference Reqs.
Single Channel Input Data Rate	56,000 Mbps (on each optical carrier from IRD)	IRD0711-716 IRD0721-726
Number of Input Channels	46 (4 each from Bands 2–6 IRD modules, 2 from Band 1 IRD module)	IRD0711-716 IRD0721-726
Input Data Sample Rate/Bit Depth	7×10^9 8-bit samples/sec or 14×10^9 4-bit samples/sec	IRD0711-716 IRD0721-726
Input Data Format	Unformatted raw data	IRD0711-716 IRD0721-726

4 DBE/DTS Functional and Performance Requirements

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

4.1 Functional Requirements

Parameter	Req. #	Value	Traceability
Clock Recovery	DBE001	The DBE shall perform clock recovery on the unformatted data streams received from the IRD modules as described in [AD13] and [AD14].	
Coarse Sideband Separation	DBE002	The DBE must perform coarse sideband separation into upper and lower sidebands using the IQ pairs received from the IRD modules as described in [AD13] and [AD14].	
Digital LO for Mixer	DBE003	The DBE must generate a LO for the sub-band selection digital mixer and track and control its phase.	
Sub-Band Selection	DBE004	Using a digital mixer and digitally generated LO, the DBE must be able to tune and select multiple sub-bands.	
RFI Flagging	DBE005	The DBE must be capable of identifying and flagging data in the presence of known or suspected radio frequency interference; details TBD.	
RFI Excision	DBE006	The DBE should be capable of performing digital signal processing to excise certain destructive radio frequency interference from the data stream using specially designed excision algorithms; details TBD.	
Oversampling Polyphaser Filter	DBE007	The DBE polyphaser filters must have an oversampling capability to eliminate concerns with dead zones between sub-bands.	
Apply Timestamp	DBE008	The DBE must apply a timestamp based on the reference clock and timing inputs to data before transmission to the central signal processor.	
Data Encoding	DBE009	The DBE must encode data into format(s) compatible with the data transmission medium being used. This mainly refers to antennas connected to commercial networks.	
Data Transmission	DBE010	The DBE must output optical data streams that can be placed directly on fiber to the array center or is compatible with COTS data transmission equipment at the site.	

4.2 Performance Requirements

Parameter	Req. #	Value	Traceability
Upper/Lower Sideband Isolation	DBE200	>43 dB	
Timestamp Jitter	DBE201	6.4 ns	

4.3 I/O Requirements

Parameter	Req. #	Value	Traceability
Input Data Sample Rate/Bit Depth	DBE103	7×10^9 8-bit samples/sec or 14×10^9 4-bit samples/sec	IRD0711-716 IRD0721-726

4.4 Spurious Signals/Radio Frequency Interference Generation

Parameter	Req. #	Value	Traceability
Enclosure RFI Shielding @100 MHz	DBE114	Max EIRP Emission –126 dBm	EMC3010, SYS2104
Enclosure RFI Shielding @1 GHz	DBE115	Max EIRP Emission –126 dBm	EMC3010, SYS2104
Enclosure RFI Shielding @10 GHz	DBE116	Max EIRP Emission –102 dBm	EMC3010, SYS2104

4.5 Environmental Conditions

4.5.1 Normal Operating Conditions

Parameter	Req. #	Value	Traceability
Operating Temperature Range	DBE112	–15 to +35°C	ENV0323
Altitude, etc.	DBE119	2500 meters	ENV0351

4.5.2 Specific Environmental Requirements

Parameter	Req. #	Value	Traceability
Storage Temperature Range	DBE113	–20 to +70°C	020.10.15.10.00-0001-SPE System-Level Environmental Specifications

4.6 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Mean Time Between Failures	DBE120	MTBF ≥ 35,040 hrs.	SYS2402

The maintenance and reliability requirements support high-level requirements that limit the total array operating cost. Monitor points/sensors should be included in the MTBF/MTTR analysis, but sensors and other components that can be reasonably deemed ancillary to operation may be removed from the determination of compliance with the MTBF requirement. "Failure" will be defined as a condition that places the system outside of its performance specifications or into an unsafe state, requiring repair.

4.7 Monitor and Control Requirements

The DBE/DTS work package shall measure, report, and monitor parameters that allow for determination of its status and may help predict or respond to failures.

Parameter	Req. #	Value	Traceability
Input Power Supply Voltage	DBE900	The DBE/DTS module shall measure, report, and monitor the input DC supply voltage to the module.	SYS2701
Input Optical Power Monitor	DBE901	The DBE shall report actual optical power or digital status indicating optical power on all inputs is within an acceptable limit. Subject to power monitoring capability of the optical receiver.	

Parameter	Req. #	Value	Traceability
Input Clock Power	DBE902	The DBE shall report actual power or digital status indicating power on the clock input is within an acceptable limit.	
Input Timing Signal	DBE903	The DBE shall report that a valid timing signal is received at an appropriate level and passes all built-in error checking.	
Module Temperature(s)	DBE904	The DBE shall report actual temperatures of heatsinks, power supply, internal ambient temperatures and the status of any internal over temperature protection circuits.	
Electronic Serial Number	DBE905	The integrated modules shall report a unique electronic identification upon request.	
Standby Mode	DBE906	The DBE shall be capable of entering a low-power standby mode on command. M&C communications shall still be functional in this mode.	
Automatic Initialization	DBE907	The DBE Module shall automatically boot into a nominal operational mode on power-up, absent any command from M&C.	
Data Transmission Link Status	DBE908	The DBE module shall report the connection status of the 100 Gbps Ethernet links used for data transmission.	
Clocking System Status	DBE909	The DBE module shall report the lock/tuning status of any clock generation circuitry in the module. This includes FPGA clocking resources and any external PLL oscillators used in the module.	
Data Quality Sampling	DBE910	The DBE module shall be capable of grabbing a chunk of sampled data from multiple points in the system and of sufficient size to be processed into useful diagnostic data. This could either be passed as raw data or processed locally into formats useful for diagnostics. Results are transmitted via the M&C network.	

The expectation with self-monitoring is that the M&C system will expose lower-level sensors to the M&C system when queried. The cadence of access is flexible, and is not expected at high rates (typical access might be on second to minute scales). Any high-cadence monitoring should generally be internal to the DBE/DTS work package control system with a summary output on the interface.

Other features of the M&C interface are specified in the Monitor and Control ICD. Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning.

4.8 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	DBE1801	The DBE/DTS work package shall be designed to be operated and supported for a period of 20 years.	SYS2801
Life Cycle Optimization	DBE1802	The DBE/DTS work package design shall minimize its lifecycle cost for 20 years of operation.	SYS2802

5 Interface Requirements

This section provides information about the interfaces of the DBE/DTS work package. Interface Control Documents (ICDs) are required between the DBE/DTS work package 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 DBE/DTS work package designer, and approved by ngVLA, as part of the DBE/DTS work package reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Integrated Downconverter/Digitizer Subsystem

Data processed by the DBE/DTS subsystem is produced in the 13 integrated downconverter/digitizer (IRD) modules located near the receivers in the antenna. These produce data in one of two formats:

- 8-bit samples at 7 Giga samples per second, or
- 4-bit samples at 14 Giga samples per second.

The data streams are modulated onto optical carriers at 1310 nm. The outputs of these IRD modules are optically combined onto 16 single mode fibers. These fibers enter through 16 terminals of a 36-fiber APC type ruggedized circular connector. Each of these data streams arrives at the DBE/DTS PCBs on a single mode fiber containing an LC type connector that connects to one of the QSFP28 form factor optical transceivers. The optical transceivers achieve 56 Gbps transfer rates using four-level PAM4 modulation.

Signal at Interface	Type	Parameter	Value	Comments
Digital IFs	Input	Data Format Data Content Connector Physical Format Nominal Wavelength Colors/Lanes Baud Rate Effective Bit Rate Modulation # of fibers	Unformatted I/Q or Nyquist QSFP Single-Mode Fiber 1310 nm 4 (2 from Band 1) 28 Gbaud/Lane 56 Gbps/Lane PAM4 13	PAM4 modulation carries 2 bits per symbol, so "effective" 56 Gbps per lane is achieved by transmitting 28 billion symbols per second. Number of fibers: 13 nominal

5.2 Interface to the Reference Signal Subsystem

The DBE/DTS module receives a 156.25 MHz CW clock from the antenna reference subsystem. This signal arrives as a 156.25 MHz CW signal modulated onto a 1310 nm optical carrier. It enters the module on one terminal of a 36-fiber APC type ruggedized circular connector on the front face of the module. The reference fiber is connected to an optical receiver to be converted to an electrical 156.25 MHz clock that feeds all of the FPGAs.

The DBE/DTS module also receives a timecode signal from the antenna reference subsystem. This is a digital timing signal modulated onto a 1310 nm optical carrier. It enters the module on one terminal of a 36-fiber APC type ruggedized circular connector on the front face of the module. The timecode fiber is connected to an optical receiver to be converted to an electrical timecode signal that feeds the FPGAs.

Signal at Interface	Type	Parameter	Value	Comments
Master Clock	Input	Frequency Signal Type Level Connector Phase Noise/Jitter	156.25 MHz Sine Wave (CW) 0 dBm SMA 2.5 ps	 SYS5001
Time Code	Input	Signal Type Format Connector Resolution	Optical/Digital IRIG-A Part of fiber circular connector ≤1ms	 (or similar)

5.3 *Interface to the Antenna Structure*

5.3.1 Electrical Infrastructure

Electrical power to the DBE/DTS module(s) is a single –48 VDC connection from the –48 VDC power subsystem in the antenna pedestal room. This enters the module through a two-terminal filtered, locking type power connector on the front face of the module. Battery backup is provided through the –48 VDC power subsystem. No addition batteries are used for the DBE/DTS subsystem. The –48 VDC input to the module is over-current protected by a single-use fuse internal to the module. The input connector will be keyed to assure correct polarity, so no reverse polarity protection is required.

Signal at Interface	Type	Parameter	Value	Comments
Main Power	Input	Signal Type Nominal Level Current Connector	DC Voltage –48 Volts DC 10 Amps Max Filtered locking circular connector	020.10.15.10.00-0005-REQ System-Level Electrical Requirements

5.3.2 HVAC

The DBE/DTS module has external heatsink fins on both sides of the enclosure. Forced-air cooling in the rack will move air across these fins. The module is sealed so no air penetrations or air filtering is required. The module is designed with internal thermal protection to shut down or reduce power dissipation in the event of HVAC failure.

5.3.3 RFI Mitigation

The module is RFI shielded to prevent interference with the astronomical signals received by the antenna. Shielding effectiveness is outlined in Section 4.1.

5.4 *Interface to the Monitor and Control System*

The M&C connection uses Gigabit Ethernet connection to the antenna M&C Ethernet switch. Two fibers (transmit and receive) connect to the module via two terminals of the 36-fiber APC type ruggedized circular connector on the module face. Internally the fibers connect to an SFP+ type transceiver connected to the internal M&C processor.

6 Safety

6.1 General

Parameter	Req. #	Value	Traceability
Weight	DBE121	≤50 lbs	020.10.15.10.00-0006-REQ System-Level Mechanical Requirements

6.2 Safety Design Requirements

6.2.1 Fire Safety

The module will have a sealed metal enclosure with fusing to minimize fire risk in internal electronics or external wiring. Thermal protection will minimize power dissipation in the event of HVAC or internal component failure.

6.2.2 Mechanical Safety

The module weight will be kept below 50 lbs. to minimize the requirement for two-person lift. Secure handles will be provided to enable easy transportation of the module. The enclosure will be designed to minimize sharp edges.

6.2.3 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard. Electrical installations and equipment shall be specifically built and/or derated to safely perform their intended functions under the applicable environmental conditions. Insulation shall be coordinated in conformity with IEC 60664 [AD07] while taking into account the altitude of up to 2500 m above sea level.

The –48 VDC will be protected with fuses to protect both internal electronics and external power supply infrastructure from damage in the event of a failure in the module. Reverse polarity protection on the power input is provided by a keyed connector. Switching regulator modules will be implemented with all fuses and noise suppression or safety (X and Y type) film capacitors as recommended by the manufacturer.

6.2.4 Handling, Transport, and Storage Safety

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

7 Design Requirements

7.1 Analyses and Design Requirements

7.1.1 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. The ngVLA project will apply the Parts Count Method for predicting system reliability as described in MIL-HDBK-217F, but the designer may propose to use other methods. For non-electronic parts, the values of NPRD-95 [AD11] 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.

The ngVLA equipment will typically operate at 2200 m 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 mean time to repair (MTTR), assuming that any scheduled preventive maintenance is performed.

7.2 Electromagnetic Compatibility Requirements

The ngVLA DBE/DTS work package element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).

7.3 Materials, Parts, and Processes

7.3.1 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.

7.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

7.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

7.3.4 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 ngVLA approval.

For Line Replaceable Units (LRUs; see Section 11.1), it is highly desirable that the serial number of the LRU be ascertainable over the monitor and control interface (See Section 5.4)

7.3.5 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled.

8 Documentation Requirements

8.1 Technical Documentation

All documentation related to the DBE/DTS work package 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 CAD system used is AutoDesk Inventor and/or AutoCAD.

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

8.2 Software and Software Documentation

The DBE/DTS work package software and any other specially developed software are deliverables. 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 on-line 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.

9 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.

The following table summarizes the expected verification method for each requirement.

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
DBE001	Clock Recovery				X	
DBE002	Coarse Sideband Separation				X	
DBE003	Digital LO for Mixer				X	
DBE004	Sub Band Selection				X	
DBE005	RFI Flagging					X
DBE006	RFI Excision					X
DBE007	Oversampling Polyphase Filter				X	
DBE008	Apply Timestamp				X	
DBE009	Data Encoding				X	
DBE010	Data Transmission					X
DBE101	Single Channel Input Data Rate	X				
DBE102	Number of Input Channels	X				
DBE103	Input Data Sample Rate/Bit Depth	X				
DBE104	Input Data Format	X				
DBE105	Output Data Format	X				
DBE106	Number of Output Channels	X				
DBE107	Output Channel Data Rate	X				
DBE108	Maximum Total Data Rate	X				
DBE109	Min DC Power Supply Voltage	X				
DBE110	Max DC Power Supply Voltage	X				
DBE111	Max Supply Current (@ –48VDC)	X				
DBE112	Operating Temperature Range	X				
DBE113	Storage Temperature Range	X				

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
DBE114	Enclosure RFI Shielding @ 100 MHz				X	
DBE115	Enclosure RFI Shielding @ 1 GHz				X	
DBE116	Enclosure RFI Shielding @ 10 GHz				X	
DBE117	Physical Dimensions	X				
DBE118	Humidity	X				
DBE119	Altitude, etc.	X				
DBE120	Mean Time Between Failures	X				
DBE121	Weight	X				
DBE200	Upper/Lower Sideband Isolation		X			X
DBE201	Timestamp Jitter		X			X
DBE900	Input Power Supply voltage				X	
DBE901	Input Optical Power Monitor				X	
DBE902	Input Clock Power				X	
DBE903	Input Timing Signal				X	
DBE904	Module Temperature(s)				X	
DBE905	Electronic Serial Number				X	
DBE906	Standby Mode				X	
DBE907	Automatic Initialization				X	
DBE908	Data Transmission Link Status				X	
DBE909	Clocking System Status				X	
DBE910	Data Quality Sampling				X	

10 Appendix

10.1 Maintenance Definitions

10.1.1 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 ease of handling, etc.) by technician-level maintenance staff.

A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual. LRU exchange shall be possible by two trained people within four working hours. LRU replacement should be possible using standard tools identified in a maintenance manual for the Digital Backend work package.

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

10.1.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to keep the digital backend work package operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

10.2 Abbreviations and Acronyms

Acronym	Description
APC	Angle Polished Cut Fiber Connector
CDR	Critical Design Review
CoDR	Conceptual Design Review
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DBE	Digital Back End
DTS	Data Transmission System
EIRP	Equivalent Isotropic Radiated Power
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMP	Electromagnetic Pulse
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FPGA	Field Programmable Gate Array
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
M&C, M/C	Monitor and Control
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
ngVLA	Next Generation VLA
PCB	Printed Circuit Board
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SFP, SFP+, QSFP, etc.	Small Form-Factor Pluggable Optical Transceiver & Connector Standard
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
UPS	Uninterruptible Power Supply
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

Digital Back End/Data Transmission System Reference Design Description

020.30.25.00.00-0002-DSN-A-DBE_DTS_REF_DESIGN

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
J. Jackson, M. Luce, A. Erickson, E. Ford, R. Selina	Electronics Div., NRAO	2018-12-04
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-25

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.24 12:10:27 -06'00'	Electronics Div., NRAO	2019-07-24
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:38:32 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.24 12:38:48 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-24

Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	2018-02-12	E. Ford	All	Initial draft, feedback on Sections 3 & 4
1	2018-05-08	J. Jackson	All	First main draft
2	2018-06-04	J. Jackson	All	Many changes
3	2018-07-01	J. Jackson	All	Many changes
4	2018-07-09	J. Jackson	All	Editing, interfaces, fixed change record table
5	2018-08-17	J. Jackson	All	Added text on Sideband Separating Mixer and some general editing
6	2018-09-11	J. Jackson	All	Added SysML diagrams and performed significant final editing
7	2018-09-24	S. Durand	All	Small edits
8	2018-09-27	J. Jackson	All	Reformatting, added SysML structural drawing & text
9	2018-11-06	J. Jackson	5.4 6 Multiple 5.7.2 5.6 3 2.1 5.3 2.2 & 5 5 5 4 & 2.2	Fixed Ethernet specs per RID IPDSR-253 Removed empty section 6 per RID IPDSR-283 Typos fixed per RID IPDSR-156 Text updated per RID IPDSR-282 Text updated per RID IPDSR-280 Added SMF per RIDs IPDSR-272 and 227 RD03 Doc # added per RID IPDSR-139 Updated text per RID IPDSR-275 Updated per RID IPDSR-070 Text updated per RID IPDSR-142 Deleted original Fig 5 per RID IPDSR-155 Defined D501 module per RID IPDSR-276
10	2018-11-15	J. Jackson	Many	General edits
11	2018-11-28	M. Luce A. Erickson	4 & 5	Major edits
12	2018-12-04	J. Jackson	All	General cleanup, added to abbreviations table Rearranged references
13	2019-05-30	R. Selina	All	Minor edits for release; replaced a few figures for readability
A	2019-07-24	A. Lear	All	Incorporated minor edits by M. McKinnon; prepared PDF for signatures and release

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 4
3 Subsystem Overview 5
4 Subsystem Design 6
4.1 IRD Data Stream 8
4.2 Digital Processing 9
4.2.1 SERDES 9
4.2.2 Unformatted Link Interface 9
4.2.3 Side-Band Separation 9
4.2.4 Down-Conversion 10
4.2.5 RFI Excision/Flagging 11
4.2.6 Data Encoding and Retransmission 11
4.3 RFI Tagging and Excision 11
4.4 Data Transmission System 11
4.5 Subsystem Block Diagram 12
4.6 Mechanical Packaging 13
4.7 Subsystem Components 14
4.7.1 High-Level Bill of Materials 14
4.8 Interfaces with other Subsystems 14
4.8.1 Power Supply 14
4.8.2 LO/Reference 14
4.8.3 Integrated Downconverter/Digitizer 14
4.8.4 Data Output 14
5 Appendix 15
5.1 Abbreviations and Acronyms 15

1 Introduction

1.1 *Purpose*

This document provides a description for the Digital Back End/Data Transmission System (DBE/DTS) subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 *Scope*

The scope of this document covers the entire design of the Digital Back End/Data Transmission System Subsystem, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and its interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 *Applicable Documents*

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

Reference No.	Document Title	Rev/Doc. No.
AD01	Digital Back End and Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD02	ngVLA Memo 29: An Integrated Receiver Concept for the ngVLA	ngVLA Memo 29
AD04	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK

2.2 *Reference Documents*

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	M. Morgan and J. Fisher, "Statistical Word Boundary Detection in Serialized Data Streams"	U.S. Patent No. 8,688,617, 4/1/2014. People's Republic of China Patent No. 201180046318.8, 2/5/2017.
RD02	M. Morgan, J. Fisher, and J. Castro, "Unformatted Digital Fiber-Optic Data Transmission for Radio Astronomy Front Ends"	*Publications of the Astronomical Society of the Pacific*, vol. 125, no. 928, pp. 695–704, June 2013.
RD03	Integrated Downconverters and Digitizers Design Description	020.30.15.00.00-0002-DSN
RD04	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK

3 Subsystem Overview

The Digital Back End/Data Transmission System receives data from the Integrated Downconverter/ Digitizer subsystem, performs primary digital processing required at the antenna, and prepares data for transmission across private and public telecommunications infrastructure. This subsystem is concentrated in a single, highly integrated RFI shielded module located in the pedestal of each ngVLA antenna.

The module is designated as D501 on the Antenna Electronics Pedestal Enclosure Block Diagram [RD04]. Digital data streams produced in the Integrated Downconverter/Digitizer (IRD) modules located in the Front End (FE) enclosure are received in the D501 DBE/DTS module via 16 single-mode fibers.

Clock recovery and de-serialization is performed on the data, which is then fed to digital processing blocks for functions such as channelization, digital downconversion, re-quantization, and RFI tagging or excision. Finally, processed data is formatted into standard telecommunication formats (e.g., Ethernet, SONET) and returned to the optical domain for transmission over private or commercial fiber optic networks.

Figure 1 and Figure 2 show a SysML block diagram of the Antenna Electronics, highlighting the logical, behavioral, and structural beginnings of the detailed structural design. The network switch block shown is located at the array center ahead of the Central Signal Processing subsystem; the remainder is located at each antenna. The behavioral blocks represent the types of signal processing expected to be performed in the Digital Backend Module FPGA(s).

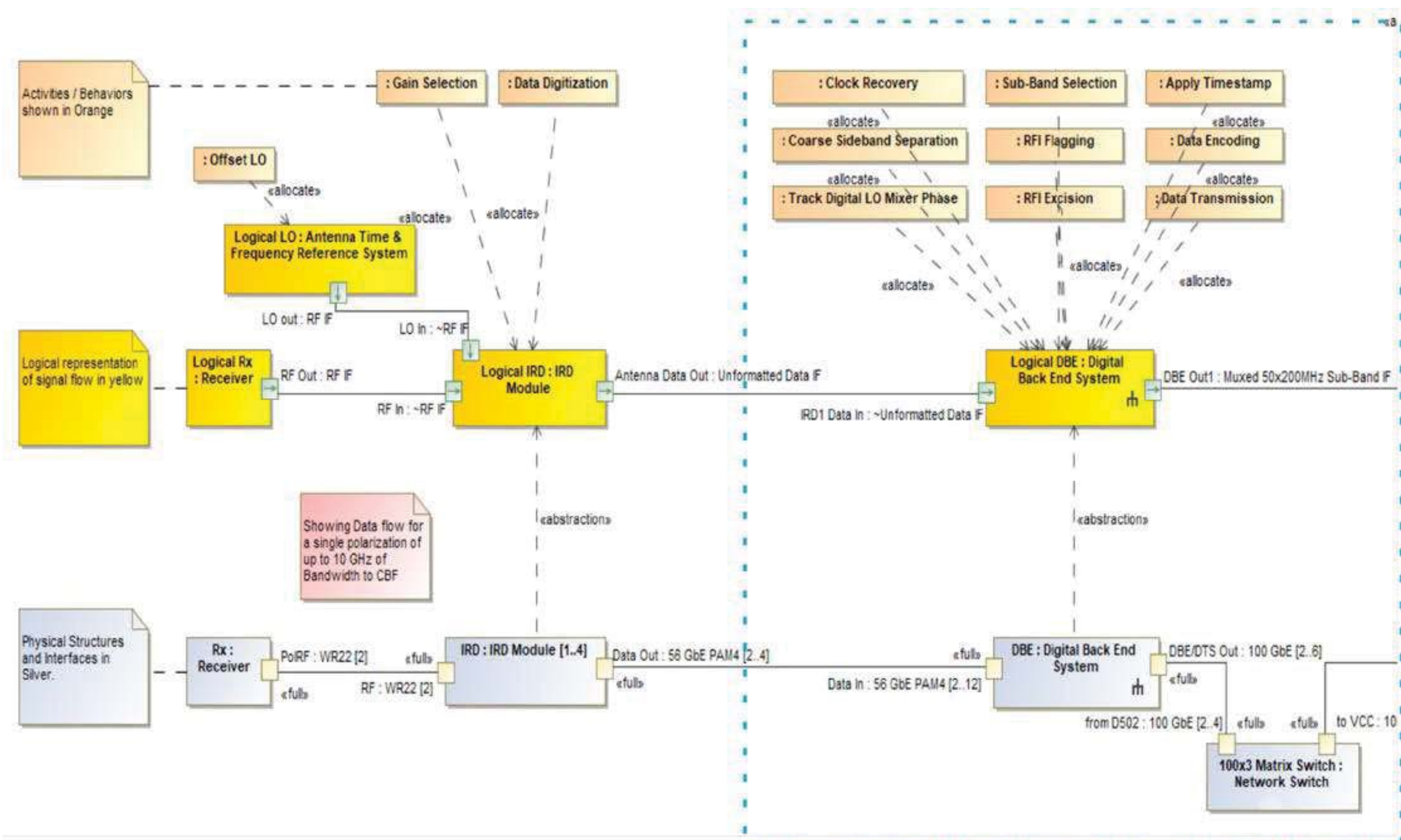


Figure 1 - SysML representation of signal path ahead of the Central Signal Processing subsystem. Behavioral, logical, and structural aspects are shown. Components of the Digital Back End work package are shown in the highlighted block.

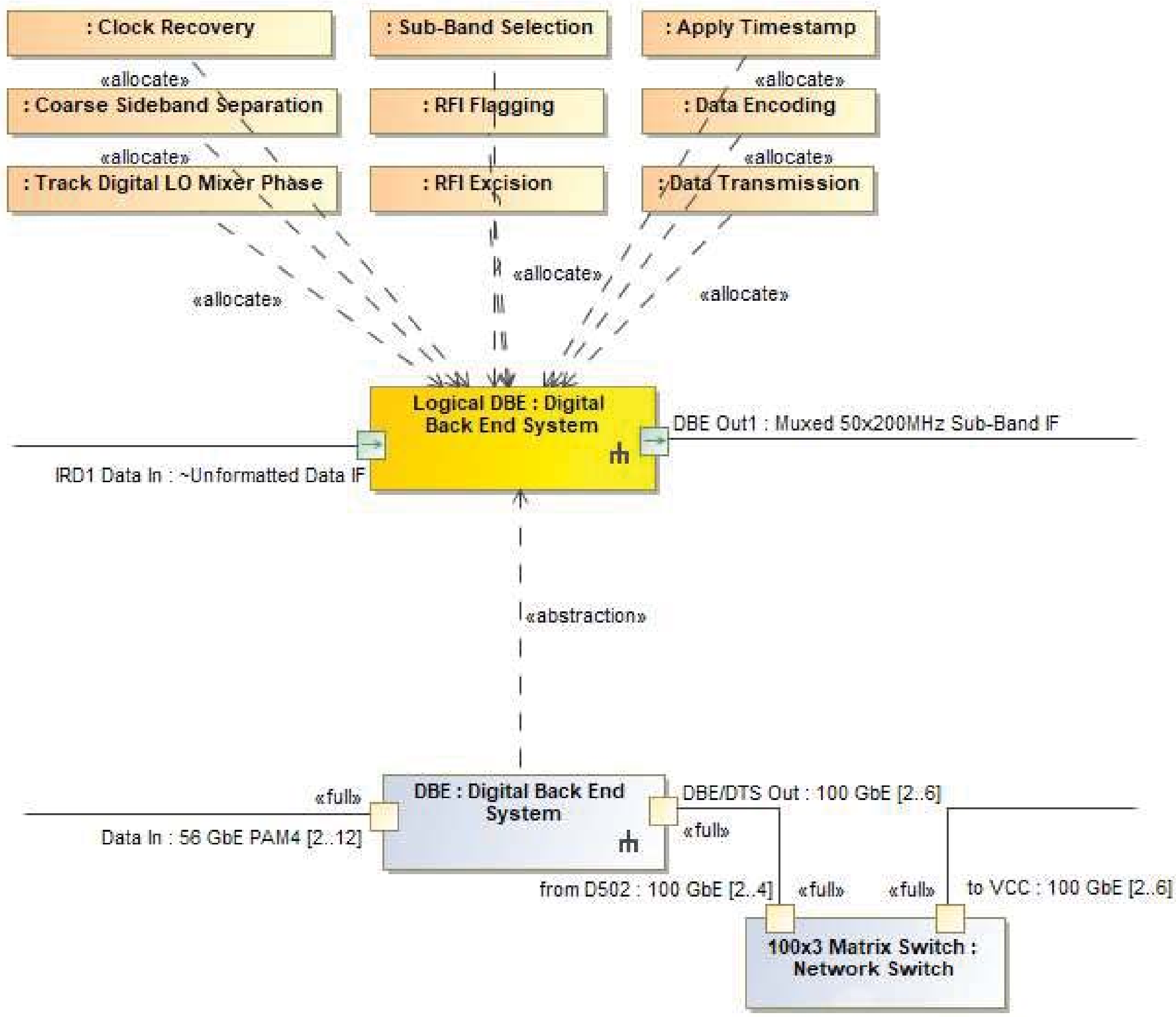


Figure 2 - Close up of SysML representation of DBE subsystem.

4 Subsystem Design

Figure 3 (next page) shows the SysML structural diagram of the Digital Back End (DBE) Module signal path. The optical input modules receive the unformatted optical streams from the IRD modules. All of the digital processing is performed locally in the antenna. Then the data are transmitted to the optical transceivers that interface with the fiber optic cables or to the commercial networking infrastructure that leaves the antenna.

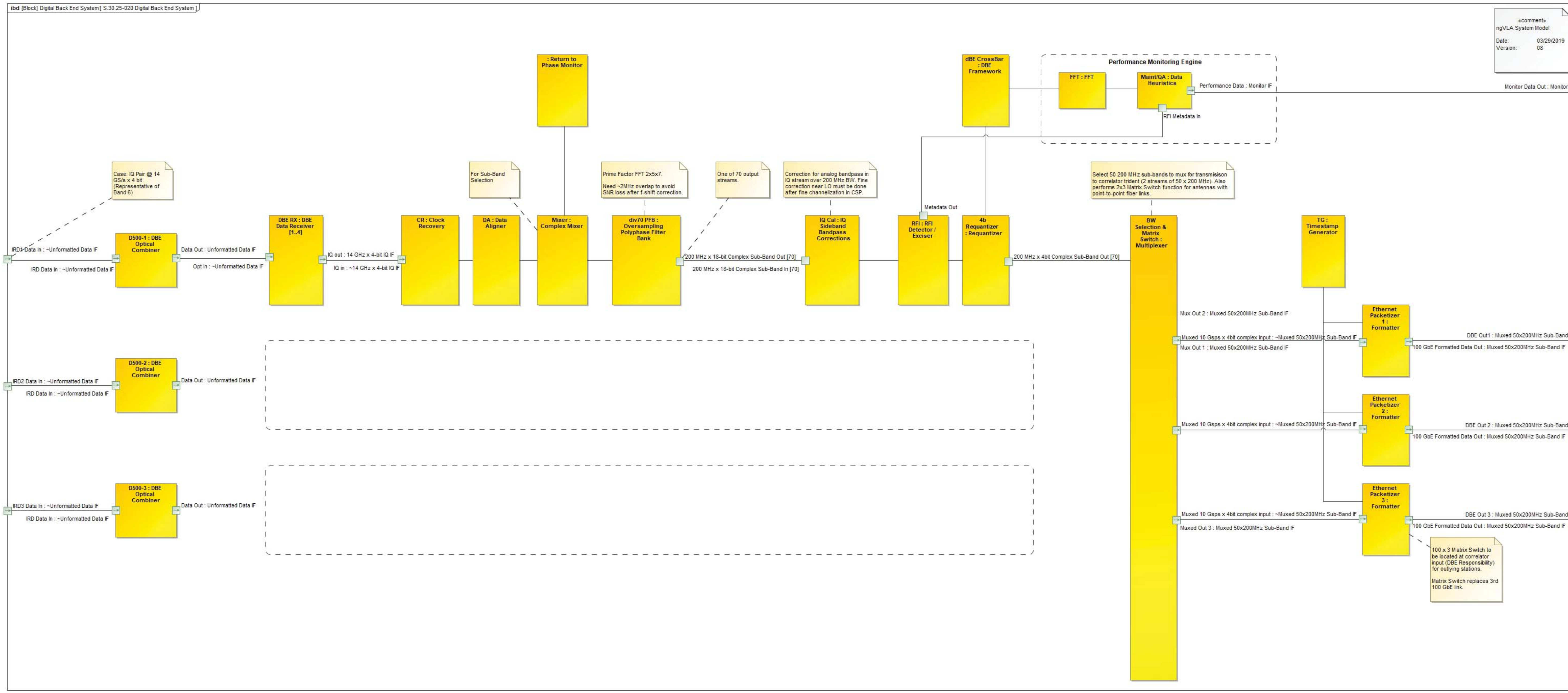


Figure 3 - SysML structural diagram of the Digital Back End module.

The DBE module, itself heavily shielded against RFI, will be further enclosed in a shielded rack in the antenna pedestal. Inside, the optical streams from all IRD modules feed into quad-channel fiber-optic transceivers hosted on printed circuit boards (PCB). The transceivers utilize four wavelengths on a single fiber, one color per lane. They modulate the optical carrier at 28 gigasymbols per second using four-level pulse-amplitude modulation (PAM4), achieving a serial rate of 56 Gbps per lane. These are described in detail in the Integrated Downconverters and Digitizers Reference Design Description (RD03). Physically, the transceivers conform to the QSFP28 form-factor, as shown in Figure 4, and are becoming available with maximum transmission distances between 500 m and 80 km [RD04–05].

Figure 4 - Quad Small Form-Factor Pluggable (QSFP28) optical transceiver.

After conversion to copper (remaining 56 Gbps PAM4) in the fiber transceivers, the IRD data streams will enter one or more large field programmable gate arrays (FPGA) on the PCB via high-speed serializer/deserializer (SERDES) inputs. Once inside the FPGA, the data stream will be processed in multiple ways.

The central digital processing pipeline consists of:

1. SERDES and IRD unformatted link interface,
2. side-band separation,
3. down-conversion, and
4. data encoding and retransmission (SERDES)

A separate processing stream will tap the central data stream for the purposes of RFI excision and flagging. A monitor and control (M&C) processor will also be hosted on a PCB inside the DBE. It will provide all necessary connectivity to the ngVLA monitor/control system. Lastly, the module will include power supplies as necessary for all included hardware.

4.1 IRD Data Stream

The fibers coming from the IRD modules will contain optical carriers of different colors, each carrying 56 Gbps of data. Each pair of those carriers represents raw samples (time-series) from the I and Q outputs of a mixer. At Band 6, these will be 4-bit samples (14 GS/s, or 7 GHz of bandwidth in each I and Q). For simplicity, only one I/Q pair from Band 6 will be transmitted. The data path for each I/Q pair is identical.

4.2 Digital Processing

4.2.1 SERDES

Data from the 44 QSFP28 modules are fed into the high-speed SERDES inputs of FPGAs. These blocks convert the streaming serial data into parallel samples for processing within the FPGA, as Figure 5 shows.

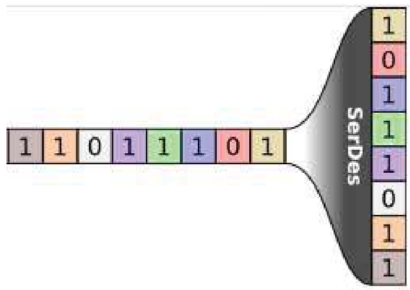


Figure 5 - SERDES functionality.

The current state of the art for production hardware is 58 Gbps/block; technology has been demonstrated for blocks up to 112 Gbps.

4.2.2 Unformatted Link Interface

The IRD subsystem group will deliver a portable FPGA firmware block that acts as a wrapper around the FPGA's built-in Clock and Data Recovery circuitry. This firmware block ensures that the channels are aligned with MSB and LSB in a known, correct state. A monitor/control interface is available to this block for reporting status and receiving commands.

The output from this firmware block will be I and Q time-series samples on parallel pins. To realize a practical design, these streams will be demultiplexed into many more parallel streams at a much slower rate (sequential samples will be clocked out in parallel).

4.2.3 Side-Band Separation

Although sideband separation can be done on time-series data, it is conceptually simpler to do it in the frequency domain. Therefore, the next functional block will be a poly-phase filter bank (PFB) or FFT function. The complex spectra generated in the Fourier transform block accumulate prior to sideband separation. After accumulation, the next functional block separates upper (USB) and lower (LSB) sidebands with a complex mixer (a weighted cross-sum of I and Q spectra), as Figure 6 shows. The weights, or calibration coefficients, are receiver- and frequency-dependent but fairly smooth and can be interpolated.

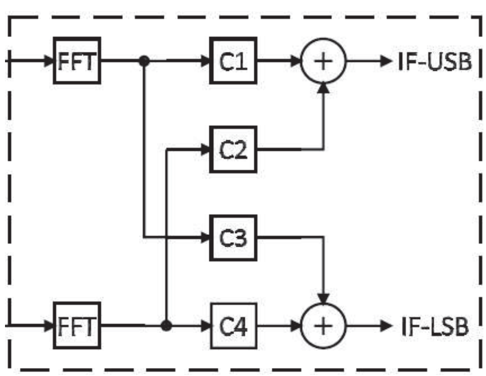


Figure 6 - Side-band separation processor.

4.2.4 Down-Conversion

After side-band select, the data-streams will be down-converted into 50 sub-bands to CSP input specifications (020.40.00.00.00-0001-SPE). Each sub-band will be 200MHz wide and include full bit resolution. This down-conversion will be performed in an over-sampled poly-phase filter bank. This type of PFB provides the desired channelization with a flat pass-band response, and minimizes the spectral image components that are typically found in critically sampled poly-phase filter banks. As Figure 7 shows, the oversampled PFB separates the filter edges in frequency space, reducing the filter overlap which introduces spurious images.

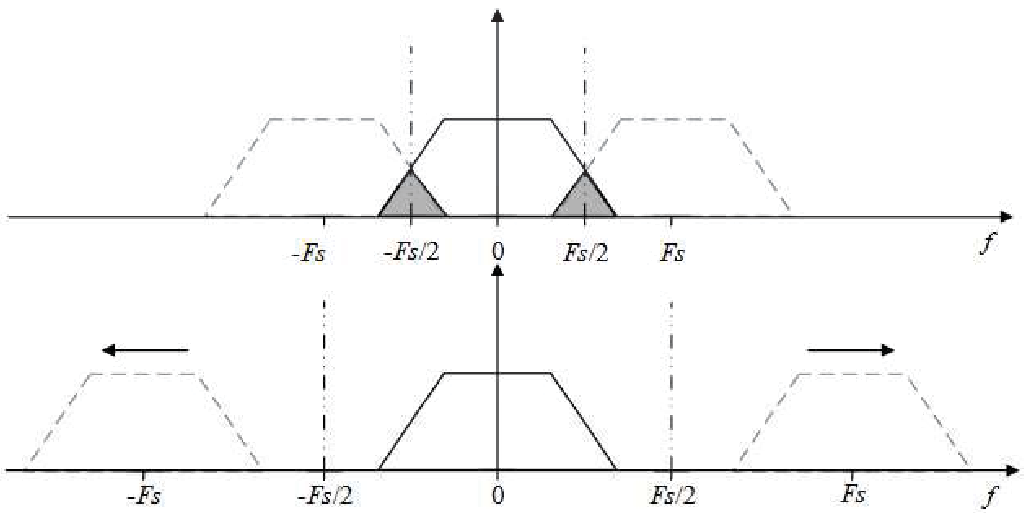


Figure 7 - Critically sampled (M=D) vs. oversampled (M=D×I) PFB.

The most common design approach to these filters simply adds an interpolator (I) after the poly-phase commutator, as shown in Figure 8.

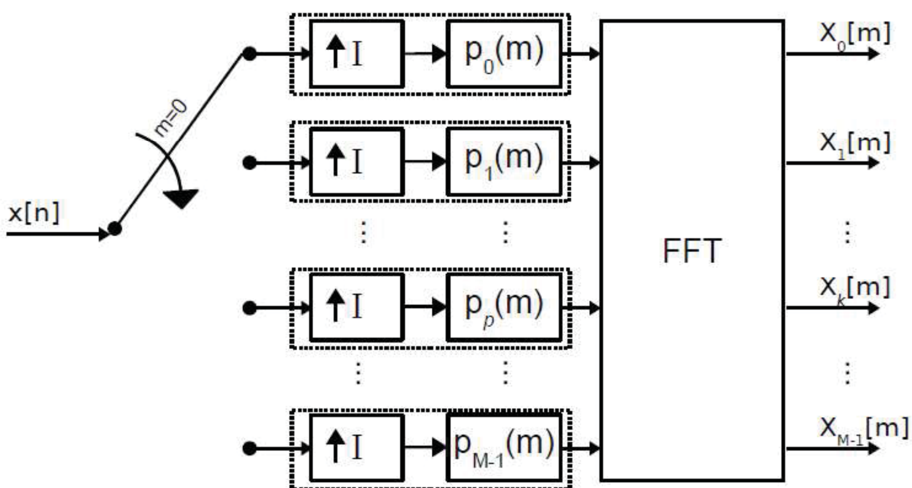


Figure 8 - Oversampled PFB block diagram.

The added interpolator inserts zero padding ($I - 1$ zeros per sample) to the input stream. Otherwise, the poly-phase structure is very similar to the critically sampled case implemented elsewhere in NRAO systems. This can be implemented in an FPGA using multiple copies of a critically sampled poly-phase filter bank, with some complexity in prototype filter generation.

4.2.5 RFI Excision/Flagging

Digital circuitry inside the FPGA will be reserved for RFI processing. This block will be inserted into the DSP processing pipeline at the appropriate stage. Possible algorithms will be discussed in Section 4.3.

4.2.6 Data Encoding and Retransmission

The last functional block of digital processing will receive data from the down-conversion block and package it for further transmission. This will involve re-quantization, possibly of selectable bit-depth, and packet payload generation. The packets will then flow through an Ethernet IP block and out of the FPGA through another SERDES block (in serializer mode) in standard 802.3 Ethernet format.

4.3 RFI Tagging and Excision

Radio-frequency interference (RFI) will be present in many and changing forms during the lifetime of ngVLA. Cellular networks and satellite downlinks will be the sources of the most prominent signals in correlated data because the same signals will be visible to many antennas, and the signals will be present over an entire integration period. Generally, automatic flagging algorithms can identify these signals in the data at data processing time.

There are also many signals that are expected to affect science data that have high energy but low time occupancy, such as vehicular radar and aviation transponders. These signals are not easily flagged in correlated data, but can negatively affect the science data. Detecting the signals in a high-time-resolution and antenna-specific domain can allow data processing to more intelligently process data to improve science data quality. Firmware in the DBE's signal processing FPGAs will detect these signals using well-known algorithms including spectral kurtosis and spectral peak detection. Flags indicating RFI presence and properties will be transmitted on the Monitor and Control data stream for inclusion into the observation metadata.

4.4 Data Transmission System

Once all local processing and reduction of data is complete, the data streams are fed into the Data Transmission System (DTS) for routing back to the Correlator and Signal Processing system located at the array center. Two configurations shall considered:

The antenna is connected directly to the correlator via NRAO or commercially owned dark fiber.
The data from the antenna is required to be transported through public communications infrastructure.

For antennas in the array core connected directly with dedicated fiber, the data will arrive in sequential order through a single deterministic path. The data will be transmitted using four 100 Gb/s fiber optic Ethernet links using the UDP transport layer protocol. All data will be placed on a single SMF fiber using 100 Gb/s wavelength controlled Ethernet Transceivers on 100 GHz spacing Dense Wavelength Division Multiplexed (DWDM) carriers. Transmission capacity required from each antenna is 400 Gb/s total.

For antennas that cannot be directly connected, the DTS becomes dependent on the telecommunications carrier chosen to service that infrastructure. The network link will be affected by the carrier's local and long haul configuration between the antenna and the array center. NRAO does not have control of the network configuration or the routing of data on the third party carrier's infrastructure. The vendor could either provide dedicated wavelengths on their fibers or require that data be passed through their networks. Data may arrive out of sequence, with unknown transmission delays, error rates and missing packets. The present design can accommodate a 250 ms delay and tolerates dropped packets. Transmission capacity from the antenna is ideally 400 Gb/s but could be restricted depending on cost and capacity of the commercial carrier and infrastructure local to the antenna.

4.5 Subsystem Block Diagram

Figure 9 shows a block diagram of the hardware structure inside a D501 module. Data stream processing will reside on a high performance PCB. This PCB will contain all of the optical receivers necessary for receiving data from the IRD modules, optical transceivers for the Ethernet links leaving the antenna, and a large FPGA. The FPGA will perform clock recovery, data stream alignment, digital signal processing, and Ethernet framing.

The module will contain a separate PCB to provide all necessary monitor and control. The M&C board will interface to the antenna M&C Ethernet switch via standard SFP modules. It will contain a high performance microprocessor as defined in the M&C subsystem documentation (020.30.45.00.00-0004-DSN). A high-performance microprocessor is necessary in this application because this board will be tasked with acquiring and analyzing multiple data samples for diagnostic and system setup purposes. It will run an embedded variant of the LINUX operating system.

The last PCB in the module will be a high efficiency power supply that converts the antenna's –48 VDC to the voltages for hardware in this module. It will be consistent with the power supply designs described in the DC Power Supply subsystem documentation (020.30.50.00.00-0002-DSN). The power supply PCB will be tailored to provide the unique low-voltage, high-current supply voltages needed by the components in this module.

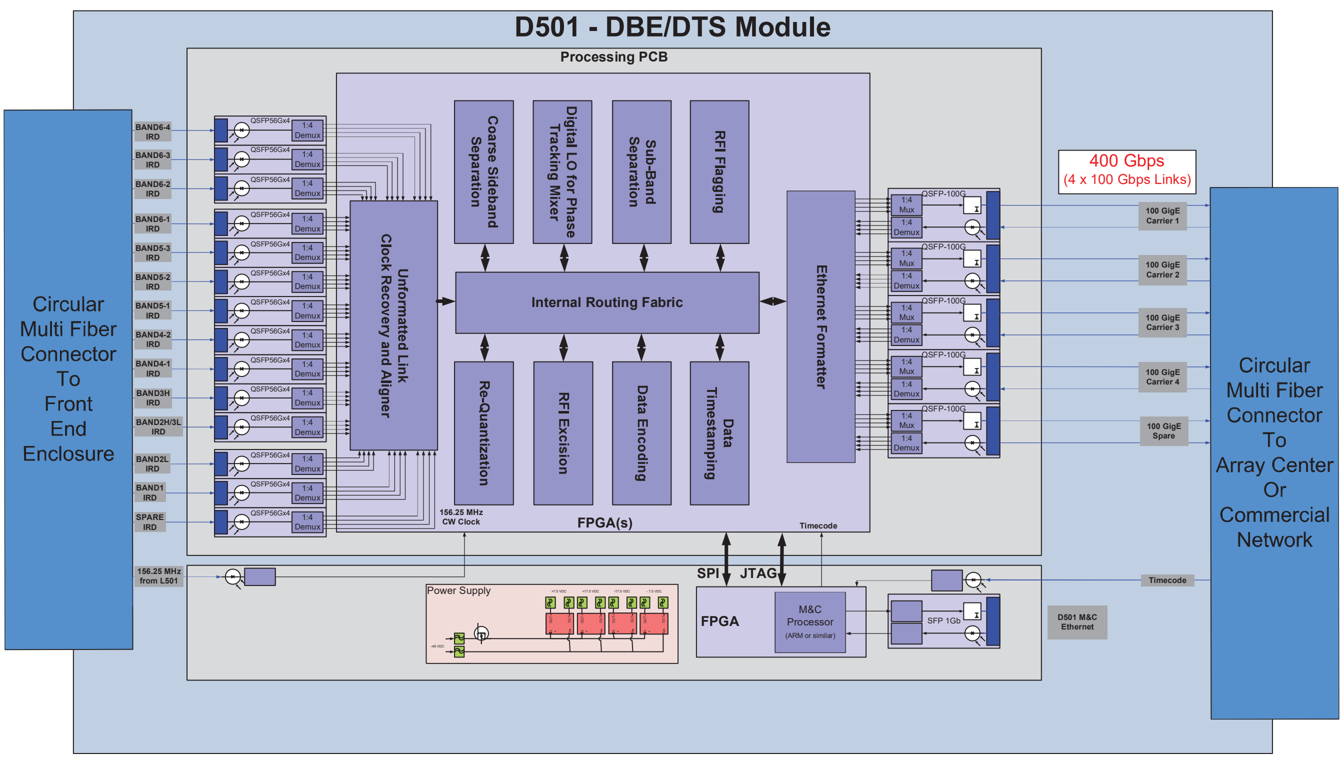


Figure 9 - Block diagram of antenna DBE/DTS subsystem.

4.6 Mechanical Packaging

The D501 DBE Module consists of high-speed digital components, a high-performance microprocessor, and switching power supplies. All of these will contribute to high levels of radio frequency interference that are in-band to the ngVLA, and must be attenuated.

Figure 10 shows a prototype module design based on the Advanced RFI Containment System (ARCS) module system designed for the ngVLA project. This enclosure is heavily shielded to prevent interference with the telescope from the electronics inside. The DBE PCBs will attach to heatsinks inside this module. Two multi-fiber connectors and a filtered Cannon power connector allow signaling and power across the module's RFI shielding.

Module dimensions and aspect ratio are for demonstration purposes and will depend on the space available in the pedestal area enclosure available in the selected antenna design.

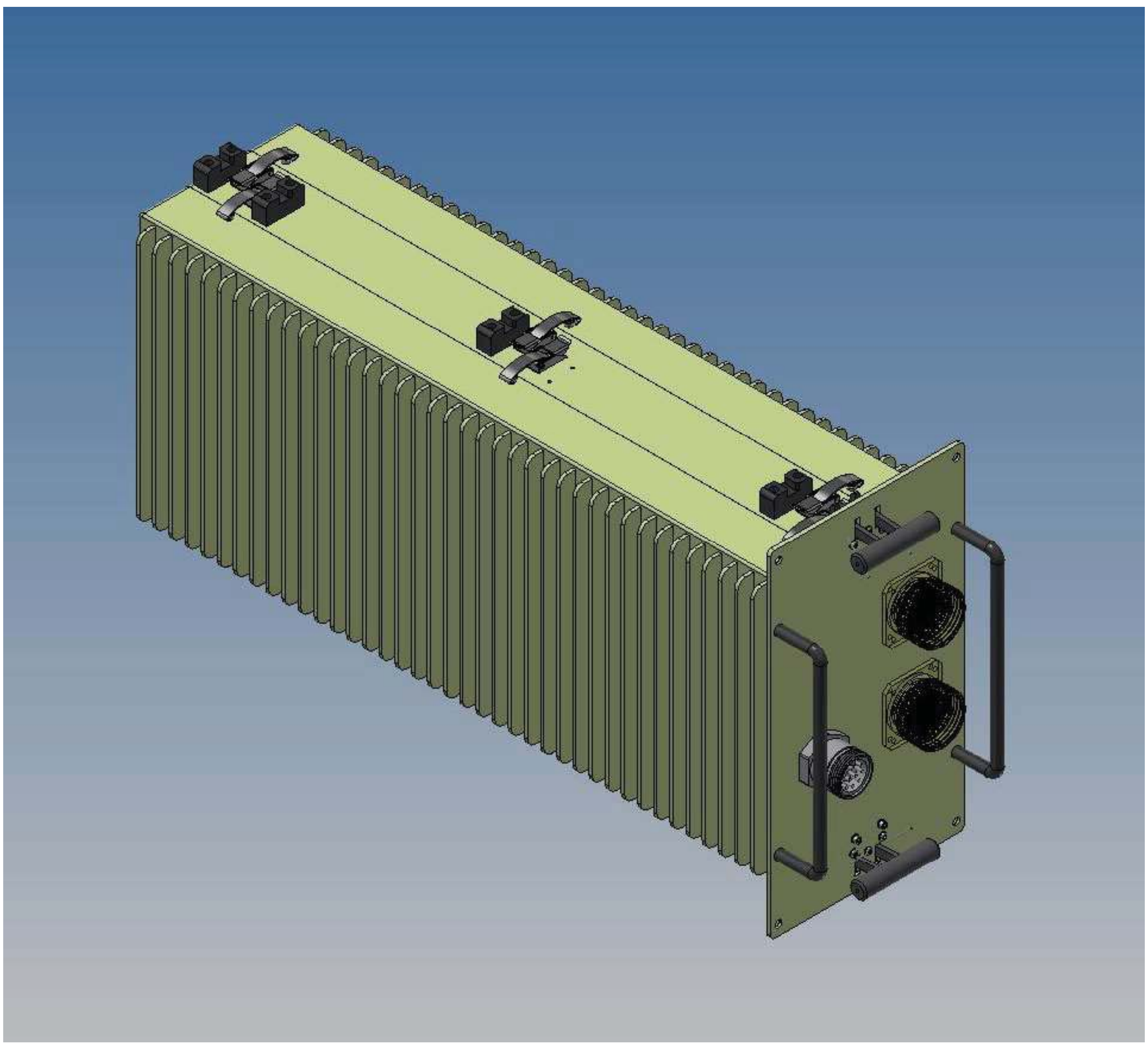


Figure 10 - 3D rendering of D501 module.

4.7 Subsystem Components

4.7.1 High-Level Bill of Materials

- RFI-shielded module metalwork
- Polarization processing PCB (2x), with 2 FPGAs
- Power supply PCB
- Monitor and control PCB
- 16 x 56 Gb/s QSFP modules
- 8 x 40 Gb/s extended range SFP modules
- Power and RF interconnect cable and connectors
- Multi-fiber cables and connectors

4.8 Interfaces with other Subsystems

4.8.1 Power Supply

The D501 will receive –48VDC @10 amps from the power supply subsystem.

4.8.2 LO/Reference

The D501 will require a 156.25 MHz CW tone @0dBm from the LO/Reference subsystem for the generation of internal clocks. The module will also require an optical timecode reference from the LO/Reference subsystem. Specifics of this time code are TBD.

4.8.3 Integrated Downconverter/Digitizer

The D501 will receive data from the Integrated Downconverter/Digitizer modules optically at 56 Gb/s. Power and wavelengths will be determined from specifications of the QSFP fiber transceiver modules chosen for the design.

4.8.4 Data Output

Output data from the D501 will be via standard 100 Gb/s Fiber Optic Ethernet links for antennas connected to NRAO-owned fiber (or located in the central building with the correlator as may be the case for antennas located near the array center). Outlying antennas could be changed to other formats depending on the requirements of commercial fiber infrastructure at each site.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ARCS	Advanced RFI Containment System
CSP	Central Signal Processor Subsystem
DBE	Digital Back End
DSP	Digital Signal Processing
DTS	Data Transmission System
ER-QSFP	Extended Range Quad Small Form-Factor Pluggable Fiber Optic Transceiver
FE	Front End System
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
IF	Intermediate Frequency
IRD	Integrated Downconverter/Digitizer Module
LO	Local Oscillator
LRU	Line Replaceable Unit
LSB	Lower Sideband
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
LSB	Lower Sideband
ngVLA	Next Generation VLA
NSF	National Science Foundation
PFB	Poly Phase Filter Bank
PLL	Phase Locked Loop
QSFP	Quad Small Form-Factor Pluggable Fiber-Optic Transceiver
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
SERDES	High Speed Serial/De-Serializer Input of an FPGA
SMF	Single Mode Fiber
SR-QSFP	Short Range Quad Small Form-Factor Pluggable Fiber-Optic Transceiver
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

DC Power Supply Preliminary Technical Requirements

020.30.50.00.00-0001-REQ-A-DC_POWER_SUPPLY_PRELIM_REQS

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
P. Lopez	Electronics Div., NRAO	2018-11-16
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-23

APPROVALS (Name and Signature)	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer 2019.07.17 16:26:28 -06'00'	Electronics Division, NRAO	2019-07-17
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:40:25 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-17

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:40:42 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-17

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-15	P. Lopez	All	Initial draft
02	2018-06-07	S. Durand	All	Basic edits
03	2018-07-01	P. Lopez	2.2	Updated reference document titles and document numbers
04	2018-09-01	S. Durand	All	Basic edits
05	2018-09-25	P. Lopez	All	Basic edits
06	2018-11-16	P. Lopez	All 3.3 5.3 5.4 5.1 2.1 & 2.2	Document number update; removed "Not all antennas will have WVR"; corrected typos; updated document names and numbers
07	2019-04-23	S. Durand	All	Basic edits
08	2019-05-30	R. Selina	4, 5	Updated requirement numbering; other minor edits throughout
A	2019-07-17	A. Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 5
3 Overview of the DC Power Supply Technical Requirements 6
3.1 Document Outline 6
3.2 Project Background 6
3.3 General DC Power Supply System Description 6
3.4 Summary of DC Power Supply System Requirements 7
3.5 Definitions of External Environmental Conditions 7
3.5.1 Precision Operating Conditions 7
3.5.2 Normal Operating Conditions 7
3.5.3 Limits to Operating Conditions 7
3.6 General Technical Requirements 8
3.6.1 General Requirements 8
4 DC Power Supply Functional and Performance Requirements 9
4.1 Functional Requirements 9
4.1.1 P500 Functional Specifications 9
4.1.2 P501 Functional Specifications 10
4.1.3 P502 Functional Specifications 10
4.1.4 P503 Functional Specifications 11
4.2 Additional Requirements 11
4.3 Maintenance and Reliability Requirements 12
4.4 Monitor and Control Requirements 12
4.5 Lifecycle Requirements 12
5 Interface Requirements 13
5.1 Interface to Digital Back End and Data Transmission System Subsystems 13
5.2 Interface to Front End Subsystem 13
5.3 Interface to Integrated Downconverter/Digitizers Subsystem 13
5.4 Interface to the Local Oscillator subsystems 13
5.5 Interface to the WVR subsystem 14
5.6 Interface to the Antenna 14
5.6.1 Electrical Infrastructure 14
5.6.2 RFI Mitigation 14
5.6.3 HVAC and Cooling System 14
5.7 Interface to the M&C System 14
6 Appendix 15
6.1 Abbreviations and Acronyms 15
6.2 Maintenance Definitions 15
6.2.1 Maintenance Approach 15
6.2.2 Periodic Preventive Maintenance 15

1 Introduction

1.1 Purpose

This document presents a set of preliminary technical requirements for the ngVLA DC Power Supply system reference design. Many requirements flow down from the preliminary System Requirements [AD02], which in turn flow down from the preliminary Science Requirements [AD01].

The science goals 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 draft reflects a preliminary analysis of these use cases, and the flow down recursively to the science, system, and subsystem requirements.

1.2 Scope

The ngVLA DC Power Supply system consists of the equipment that creates and provides the power to all Antenna Electronics deliverables on the ngVLA antennas. This requirements document establishes the performance, functional, design, and test requirements applicable to the DC Power Supply system. It also includes preliminary interface requirements that must be defined.

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 this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	Science Requirements	020.10.15.05.00-0001-REQ
AD02	System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Protection Against Electric Shock: Common Aspects for Installation and Equipment	IEC 61140:2016
AD05	System-Level Electrical Requirements	020.10.15.10.00-0005-REQ
AD07	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
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	System Electromagnetic Compatibility and RF Interference Mitigation Requirements	020.10.15.10.00-0002-REQ
AD14	Environmental Specifications	020.10.15.10.00-0001-SPE

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
RD02	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK
RD03	Antenna time & Frequency Reference Requirements	020.35.20.00.00-0001-REQ
RD04	Digital Back End Requirements	020.30.25.00.00-0001-REQ
RD05	Front End Requirements	020.30.03.01.00-0001-REQ
RD06	Independent Phase Cal System Requirements	020.45.00.00.00-0001-SPE
RD07	Integrated Down Converter Requirements	020.30.15.00.00-0001-REQ
RD08	Monitor and Control Requirements	020.30.45.00.00-0002-REQ

3 Overview of the DC Power Supply Technical Requirements

3.1 Document Outline

This document presents the DC Power Supply system technical requirements, which determine overall form and performance.

Section 4 details the functional and performance specifications, along with explanatory notes. The notes elaborate on the requirements' meaning, intent, and scope. The notes form an important part of the requirements definition and should guide the verification procedures. In many cases, the notes contain explanation or analysis of how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. This makes the required analysis and trade-space available apparent to scientists and engineers guiding evolution of the DC Power Supply system concept.

Section 5 describes requirements pertinent to interfacing systems. 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.

3.2 Project Background

The Next Generation Very Large Array is a project of the National Radio Astronomy Observatory 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 263 reflector antennas of 18 meters and 6 meters diameter, operating in a phased or interferometric mode.

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, northern Mexico, and across the US. Operations will be conducted from both the VLA Control Building and the Array Operations Center in Socorro, NM.

3.3 General DC Power Supply System Description

The DC Power Supply System (specifically, P500) receives 208V 3-phase AC @17A and converts it to –48V DC. Lithium batteries will be used as a backup source for the 48V if the AC is lost. A battery charger will be used to charge the batteries when AC is available. The batteries and battery charger will be located in the pedestal area of each antenna. The 48V is then fed into three power supply modules (P501, P502, and P503) that convert the 48V to +32.5V, ±17.5V, +15.5V, ±7.5V, ±5.5V, and +3.8V depending on the module. Each power supply module has monitor and control (M&C) and temperature sensors for shutdown in case of over current or over temperature. The P500 also powers the fire alarm, Ethernet switch, Digital Back End (DBE), and Data Transmission System (DTS).

The P501 module powers the Front End (FE) Low Noise Amplifier (LNA) noise diodes, and bias voltages for Bands 1–6. The P501 also powers the Local Oscillator (LO) Reference Sample Clock Generator and LO A–K Generator modules as well as the Integrated Downconverter/Digitizers (IRD) for Bands 1–6. The P501 will be located next to the IRDs in the Front End Enclosure.

The P502 module powers the LO Clock Receiver module, two Band 4 IRDs, the Water Vapor Radiometer (WVR) antenna amplifier, and cooling system. The P502 will be located in the WVR Enclosure.

The P503 module powers the LO Reference Receiver Generator and Distribution module and the four Monitor & Control modules located in the pedestal area of each ngVLA antenna.

3.4 Summary of DC Power Supply System Requirements

The following sections summarize the major requirements to provide a high-level view of the desired system. Should a conflict exist between the requirements listed here and the descriptions in Sections 4 and 5, the latter shall take precedence.

3.5 Definitions of External Environmental Conditions

Based on historical VLA site weather data and other public weather databases, the following definitions of environmental conditions are adopted. The power supplies shall conform to these requirements.

3.5.1 Precision Operating Conditions

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

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

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

3.5.2 Normal Operating Conditions

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

Parameter	Req. #	Value
Solar Thermal Load	ENV0321	Exposed to full sun, 1200 W/m^2
Wind Speed	ENV0322	W ≤7 m/s average over 10 mins; 10 m/s peak gusts
Ambient Temperature	ENV0323	–15 C ≤ T ≤ 45 C
Ambient Temperature Rate of Change	ENV0324	3.6°C/Hr
Precipitation	ENV0325	No precipitation

3.5.3 Limits to Operating Conditions

A third category establishes 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. The relevant performance specifications are discussed in the ngVLA Environmental Specifications document [AD14].

3.6 General Technical Requirements

The DC Power Supply system receives 208V 3-phase AC @17A and converts it to –48VDC. Lithium ion batteries will be used as a backup source for the 48V if AC is lost. A battery charger will be used to charge the batteries when AC is available. The batteries and battery charger will be located in the pedestal area of each antenna. The 48V is then regulated and power is delivered to all antenna electronics equipment. Each power supply module has M&C, power control relays, and temperature sensors so it can be shut down for over-current or over-temperature.

3.6.1 General Requirements

Parameter	Req. #	Summary of Requirement	Reference Reqs.
AC Input	PSU0001	208V 3 Phase AC @17A	
AC to DC Conversion	PSU0002	208V 3 Phase AC to –48VDC	
DC Regulation	PSU0003	–48V DC will be regulated down to voltages that each module as required.	
M&C for Battery System	PSU0004	Required to monitor battery system health	SYS2701
M&C for Power Supply Modules	PSU0005	Required to monitor power supply module health	SYS2701
Design Life	PSU0006	Design for an expected operational life no less than 20 years, excluding batteries	SYS2701
Maintenance Interval	PSU0007	Preventive maintenance interval of no shorter than 2 years, with a goal of 4 years	SYS2401
Mean Time Between Failure (MTBF)	PSU0008	Antenna electronics: MTBF of 35,040 hrs each	SYS2402
Modularization	PSU0009	Line Replaceable Units (LRUs) to facilitate site maintenance	SYS2403
Altitude Range	PSU0010	Sea level to 2500 meters	ENV0351
Lightning Protection	PSU0011	Protect against lightning electromagnetic impulse	ENV0512
Equipment Protection Against Dust	PSU0012	Exposed equipment shall be protected against windblown dust, ashes, and grit	ENV0541
Rodent Protection	PSU0013	Exposed equipment shall be designed to prevent rodent damage	ENV0551
Transportation Environment	PSU0014	Designed to withstand typical loads and environments encountered during transportation	ENV0581
Mechanical Shock	PSU0015	Designed to survive mechanical shock levels	ENV0582
Equipment Shielding	PSU0016	All equipment shall be shielded and have AC power line and communication lines filtered at the chassis	ENC0327
EMC Test Frequencies	PSU0017	RFI suppression shall extend from 50 MHz up to 12 GHz	NRAO IPG Memo 34, EMC0328
Hazard Analysis	PSU0018	Hazard analysis shall be performed for all high-power systems; include lock-outs for service by technicians	SYS2703
Storage Requirements	PSU0019	10 ^{o}C to 25 ^{o}C for batteries –5 ^{o}C to 45 ^{o}C for power supply modules	

4 DC Power Supply Functional and Performance Requirements

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

4.1 Functional Requirements

4.1.1 P500 Functional Specifications

Parameter	Req. #	Value	Traceability
AC Input Requirements	PSU0101	208V 3 Phase @17Amps AC	
AC to DC Conversion	PSU0102	208V 3 Phase AC to –48 VDC (–46.0 to –54.2 VDC) Maximum –60 ADC	[AD05]
DBE Load Power Requirements	PSU0103	–46 to –54.2 VDC, 5 ADC	
Fire Alarm Load Power Requirements	PSU0104	–46 to –54.2 VDC, 2 ADC	
Ethernet Switch Load Power Requirements	PSU0105	–46 to –54.2 VDC, 2 ADC	
P501 Load Power Requirements	PSU0106	–46 to –54.2 VDC, 18 ADC	
P502 Load Power Requirements	PSU0107	–46 to –54.2 VDC, 14 ADC	
P503 Load Power Requirements	PSU0108	–46 to –54.2 VDC, 14 ADC	
Battery System Capacity (Li-ion batteries)	PSU0109	40 Ah @20-hour rate	
Battery Lifetime	PSU0110	3–6 Years	
Backup Power Available	PSU0111	40 Ah assuming fully charged	
Battery-Only Load Support	PSU0112	10 minutes	
Low Voltage Disconnect Voltage	PSU0113	40.5 VDC	
Pedestal Environmental Temp	PSU0114	$15^oC \leq T \leq 20^oC$	
Forced Air Inlet Temp	PSU0115	$4^oC \leq T \leq 14^oC$	
Forced Air Outlet Temp	PSU0116	$T \leq 18^o$	
P500 Dissipation Including Battery	PSU0117	165 Watts	
Fire Alarm Shunt Trip	PSU0118	Disconnects AC & DC loads	
Emergency Communication Time Battery Backup	PSU0119	Min 1 Minutes Max 2 Minutes	

4.1.2 P501 Functional Specifications

Parameter	Req. #	Value	Traceability
Input Power Requirement	PSU0201	–46 to –54.2 VDC, 18 ADC	
FE (Band 1–6) Load Power Requirements	PSU0202	+32V (28V) @ 0.5 A, +17.5V (+15V, +12V) @ 6 A (2.5A, 3.5A) +5.5V (3.3V) @ 0.5 A –5.5V (–3.3V) @ 0.5 A	[AD05]
IRD (x13) Load Power Requirements	PSU0203	+5.5V (+5V) @ 1 A +3.8 (+3.5V) @ 1 A –5.5V (–5V) @ 0.1 A	
LO Modules Load Power Requirements	PSU0204	+17.5V (+15V) @ 2.5 A +5.5V (+5V) @ 1.5 A –5.5V (–5V) @ 0.25 A –17.5V (–15V) @ 0.25 A	
SA501 Environmental Temperature	PSU0205	$14^{o}C \leq T \leq 16^{o}C$	
Cooling Technique	PSU0206	Single cold plate; temp 4–14 ^{o}C	
P501 Dissipation	PSU0207	~195 Watts	
M&C for Power Supply Modules	PSU0208	Required to monitor power supply module health	

4.1.3 P502 Functional Specifications

Parameter	Req. #	Value	Traceability
Input Power Requirement	PSU0301	–46 to –54.2 VDC, 14 ADC	
Load Power Requirements for FE (Band 4)	PSU0302	+32 (28V) @ 0.3 A +17V (+12V) @ 0.3 A +5.5V (3.3V) @ 0.01 A –5.5V (–3.3V) @ 0.5 A	[AD05]
Load Power Requirements for IRD (x2)	PSU0303	+5.5V (+5V) @ 1 A +3.8 (+3.5V) @ 1 A –5.5V (–5V) @ 0.1 A	
Load Power Requirements for LO Module	PSU0304	+17.5V (+15V) @ 2.5 A +5.5V (+5V) @ 1.5 A –5.5V (–5V) @ 0.25 A –17.5V (–15V) @ 0.25 A	
WVR Cooling System	PSU0305	+15.5V (+12V) @11.4 A	
SA502 Environmental Temperature	PSU0306	$14\ ^{o}C \leq T \leq 16^{o}C$	
Cooling technique	PSU0307	Single cold plate Temp 4–14 ^{o}C	
P502 Dissipation	PSU0308	~145 Watts	
M&C for Power Supply Modules	PSU0309	Required to monitor power supply module health	

4.1.4 P503 Functional Specifications

Parameter	Req. #	Value	Traceability
Input Power Requirement	PSU0401	–46 to –54.2 VDC, 14 ADC	
Load Power Requirements for LO System	PSU0402	+17.5V (+15V) @ 2.5 A +7.5V (5V) @ 1.5 A –7.5V (–5V) @ 0.25 A –17.5V (–15V) @ 0.25 A	[AD05]
Load Power Requirements for M&C System	PSU0403	+17.5V (+15V) @ 1 A +7.5V (5V) @ 2 A –17.5V (–15V) @ 1 A	
SA503 Environmental Temperature	PSU0404	14ºC ≤ T ≤ 16ºC	
Cooling Technique	PSU0405	Forced air in pedestal rack; Temp 4–14 ºC	
P503 Dissipation	PSU0406	~145 Watts	
M&C for Power Supply Modules	PSU0407	Required to monitor power supply module health	

4.2 *Additional Requirements*

Parameter	Req. #	Value	Traceability
Battery System Location	PSU0501	Antenna Pedestal	
Battery Operating Temperature Requirements	PSU0502	10ºC to 25ºC for batteries (15ºC ≤ T ≤ 20ºC is specified for the pedestal environment)	[AD05]
DC Filtering on Outputs	PSU0503	Hermetically glass sealed High EMI feedthrough data line filters Max operating range: 100 VDC @ 20 A Capacitance of 2.6 µF	

The weight of the batteries and battery charging system require that the battery system be located in the equivalent of the antenna pedestal room. The lithium batteries require that the operating temperature be 10ºC to 25ºC to maintain battery lifecycle.

4.3 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
MTBF	PSU0601	Antenna electronics: 35,040 hours each	SYS2402
Modularization	PSU0602	Replaceable by 2 qualified technicians with minimal tools	Ops Con

The maintenance and reliability requirements support high-level requirements that limit total array operating cost.

4.4 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Self-Monitoring	PSU0701	The DC Power Supply system 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

The self-monitoring expectation is that the M&C system expose lower-level sensors to the M&C system when queried. The access cadence is flexible and is not expected at high rates (typical access might be on second to minute scales). Any high-cadence monitoring should generally be internal to the DC Power Supply System control system with a summary output on the interface.

Other M&C interface features will be specified in the Monitor and Control ICD.

4.5 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	PSU0801	The DC Power Supply system shall be designed to be operated and supported for 20 years, excluding batteries	SYS2701
Lifecycle Optimization	PSU0802	The DC Power Supply design shall minimize its lifecycle cost for 20 years of operation, including batteries	SYS2701

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, maintenance, and decommissioning.

5 Interface Requirements

This section describes the DC Power Supply system interfaces. ICDs are required between the DC Power Supply 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 DC Power Supply system designer and approved by ngVLA as part of the DC Power Supply system reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to Digital Back End and Data Transmission System Subsystems

The Digital Back End (DBE) and Data Transmission System (DTS) request –48V from the DC Power Supply. The total current requested is 5 amps. The DBE/DTS system is located in the pedestal room and will receive power from the P500.

5.2 Interface to Front End Subsystem

The Front End (FE) system requests +32V, +17V, +5V, and –5V from the DC Power Supply for Bands 1–6. The FE system will receive power from the P501, located in the FE Enclosure.

- The +32V will be regulated down to +28V with a current draw around 0.5A for the noise diodes.
- The +17V will be regulated down to +15V and +12V. The +15V current draw will be about 2.5A. The +12V current draw will be about 3.5A. The total current draw from the +17V will be about 6A.
- The +5V will be regulated down to +3.3V. The +3.3V current draw will be around 0.5A. The total current draw for the +5V will be 0.5A.
- The –5V will be regulated to –3.3V. The –3.3V current draw will be about 0.5A. The total current draw for the –5V will be 0.5A.

5.3 Interface to Integrated Downconverter/Digitizers Subsystem

The Integrated Downconverter/Digitizers (IRD) system request +5V, +3.3V, and –5V from the DC Power Supply. Thirteen of the IRDs will receive power from the P501 in the FE Enclosure and the two WVR IRDs will receive power from the P502 in the WVR Enclosure.

- The +5V will be regulated down to multiple internal voltages. The IRD will draw 1A from the +5V.
- The +3.3V will be regulated down to an internal voltage that it can use. The +3.3V will draw 1A.
- The –5V will also be regulated down to an internal voltage it can use. The –5V current draw will be about 100 mA.

5.4 Interface to the Local Oscillator subsystems

The Local Oscillator (LO) system Reference Sample Clock Generator, A-K LO Generator, and LO Clock Receiver modules request +17V, +5V, –5V, and –17V from the DC Power Supply. The Reference Sample Clock Generator module and A-K LO Generator module are located in the FE enclosure and will be powered by the P501. The other LO Clock Receiver module is located in the WVR enclosure and will be powered by the P502.

- The +17V will be regulated down to +15V and will draw about 2.5A.
- The +5V will be regulated down to multiple internal voltages and will draw about 1.5A.
- The –5V will be regulated down to an internal voltage that it can use, and will draw about 0.25A.
- The –17V will be regulated down to –15V and will draw about 0.25A.

The LO system Reference Receiver, Generator, and Distributor module requests +17V, +7V, –7V, and –17V from the DC Power Supply System. This module is located in the pedestal room and will be powered by the P503.

- The +17V will be regulated down to +15V and will draw about 2.5A.
- The +7V will be regulated down to multiple internal voltages and will draw about 1.5A.
- The –7V will be regulated down to an internal voltage that it can use and will draw about 0.25A.
- The –17V will be regulated down to –15V and will draw about 0.25A.

5.5 *Interface to the WVR subsystem*

The Water Vapor Radiometer (WVR) system uses an LO Sample Clock Generator and Distributor (see Section 5.4), two Band 4 IRDs (see Section 5.3), the Band 4 receiver, and a cooling system.

The Band 4 receiver is powered by the P502 located in the WVR Enclosure and requests +32V, +17V, +5.5V, and –5.5V from the DC Power Supply.

- The +32V will be regulated down to +28V and will draw about 0.03A.
- The +17V will be regulated down to +12V and will draw about 0.3A.
- The +5V will be regulated down to +3.3V. The +3.3V current draw will be about 0.01A.
- The –5V will be regulated to –3.3V. The –3.3V current draw will be about 0.5A.

The WVR cooling system requests +15V from the DC Power Supply. The +15V will be regulated down to +12V @ around 12A. The WVR cooling system will receive power from the P502 that is located in the WVR Enclosure.

5.6 *Interface to the Antenna*

5.6.1 Electrical Infrastructure

208V 3-Phase AC @17A is required for the AC to DC battery charging system. The ICD shall describe both the mechanical and electrical specifications of the electrical interfaces.

5.6.2 RFI Mitigation

RFI suppression shall extend from 50 MHz up to 12 GHz (NRAO IPG Memo 34).

5.6.3 HVAC and Cooling System

The P500 located in the antenna pedestal room rack requires 165 Watts of cooling and will be cooled via forced air.

The P501 in the antenna FE Enclosure requires 195 Watts of cooling and will be cooled via cold plate.

The P502 in the antenna WVR Enclosure requires 145 Watts of cooling and will be cooled via cold plate.

The P503 in the antenna pedestal room rack requires 145 Watts of cooling and will be cooled via forced air.

5.7 *Interface to the M&C System*

The DC Power Supply will use a Module Interface Board (MIB) to interface with the M&C system. Each power supply module will be capable of remote power on/off and powering down due to over-current or over-temperature conditions. Each module will have a different set of over-current specifications depending on the electronics connected to it. Other conditions that power the module on/off will be listed in the ICD.

6 Appendix

6.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
DBE	Digital Back End
DTS	Data Transmission System
FE	Front End
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IRD	Integrated Downconverter/Digitizers
LO	Local Oscillator
LNA	Low Noise Amplifier
LRU	Line Replaceable Unit
M&C	Monitor and Control
MIB	Module Interface Board
MTBF	Mean Time Between Failure
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
PPE	Personal Protective Equipment
RD	Reference Document
RFI	Radio Frequency Interference
SAC	Science Advisory Council
SWG	Science Working Group
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

6.2 Maintenance Definitions

6.2.1 Maintenance Approach

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 by technician-level maintenance staff.

LRU exchange shall be possible by two trained/qualified people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the DC Power Supply. A step-by-step procedure for safe exchange of every LRU shall also be provided in the maintenance manual and will list Personal Protective Equipment (PPE). The LRUs will be maintained by the ngVLA project (without industrial support).

6.2.2 Periodic Preventive Maintenance

The Power Supply system will use monitor points to check on the health of the batteries and Power Supply. These monitor points will help determine when maintenance is required for each antenna's Power Supply system. Monitor point thresholds will be listed in the Power Supply Manual.

DC Power Supply Reference Design Description

020.30.50.00.00-0002-DSN-A-DC_POWER_SUPPLY_REF_DESIGN

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
P. Lopez	Electronics Div., NRAO	2018-11-16
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-04-23

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.18 08:46:55 -06'00'	Electronics Division, NRAO	2019-07-18
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.18 11:50:22 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-18

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.18 11:50:39 -06'00'	Asst. Director for NM-Operations, NRAO	2019-07-18

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-15	P. Lopez	All	Initial draft
02	2018-06-13	S. Durand	All	Small edits
03	2018-07-01	P. Lopez	2.2	Updated reference document titles and document numbers
04	2018-09-21	S. Durand P. Lopez	All	More small edits
05	2018-09-24	S. Durand	All	More small edits
06	2018-10-24	P. Lopez	All 4, 5.2.3 4 2.1 & 2.2	Document number update Removed “Not all antennas will have WVR” Updated P500 – P503 descriptions Updated document names and numbers
07	2018-11-13	S. Durand	All	Small edits
08	2019-05-30	R. Selina	All	Minor edits throughout for release
A	2019-07-17	A. Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 5
3 DC Power Supply System Overview 6
4 DC Power Supply System Design 6
4.1 DC Power Supply System Block Diagram 7
4.2 DC Power Supply System Components 7
4.2.1 P500 Power Supply 7
4.2.2 P501 Power Supply 8
4.2.3 P502 Power Supply 8
4.2.4 P503 Power Supply 9
4.3 DC Power Supply System Interfaces with Other Subsystems 9
4.3.1 Antenna Non-Electronics 9
4.3.2 Digital Back End (DBE)/Data Transmission Systems (DTS) 10
4.3.3 Front End (FE) 10
4.3.4 Integrated Downconverter/Digitizers (IRD) 10
4.3.5 LO Reference Receiver, Generator, and Distributor 10
4.3.6 Monitor and Control (M&C) 10
4.3.7 Water Vapor Radiometer (WVR) 10
5 Abbreviations and Acronyms 11

1 Introduction

1.1 Purpose

This document describes the DC Power Supply subsystem reference design and covers the design approach, functions, key components, interfaces, and associated risks. This document forms part of the ngVLA design documentation package submission.

1.2 Scope

The scope of this document is the entire design of the DC Power Supply system as part of the ngVLA design. It details the subsystem design, how it functions, and interfaces with the necessary hardware and software systems. This document does not include specific technical requirements, which are documented in [AD14].

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	Science Requirements	020.10.15.05.00-0001-REQ
AD02	System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Protection Against Electric Shock: Common Aspects for Installation and Equipment	IEC 61140:2016
AD07	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
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	System Electromagnetic Compatibility and RF Interference Mitigation Requirements	020.10.15.10.00-0002-REQ
AD14	DC Power Supply Preliminary Technical Requirements	020.30.50.00.00-0001-REQ

2.2 *Reference Documents*

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	Antenna Electronic Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
RD02	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK
RD03	Antenna Time & Frequency Reference Requirements	020.35.20.00.00-0001-REQ
RD04	Digital Back End Requirements	020.30.25.00.00-0001-REQ
RD05	Front End Requirements	020.30.03.01.00-0001-REQ
RD06	Independent Phase Cal System Requirements	020.45.00.00.00-0001-SPE
RD07	Integrated Down Converter Requirements	020.30.15.00.00-0001-REQ
RD08	Monitor and Control Requirements	020.30.45.00.00-0002-REQ

3 DC Power Supply System Overview

A block diagram of the DC Power Supply system is shown in Figure 1. The system (specifically, P500) receives 208V 3-phase AC @17A and converts it to –48V DC. Lithium batteries will be used as a backup source for the 48V if the AC is lost. A battery charger will charge the batteries when AC is available. The batteries and battery charger will be located in the pedestal area of each antenna.

The 48V is then fed into three power supply modules (P501, P502, and P503) that convert the 48V to +32.5V, ±17.5V, +15.5V, ±7.5V, ±5.5V, and +3.8V depending on the module. Each power supply module has Monitor and Control (M&C) and temperature sensors so they can be shut down for over-current or over-temperature conditions. The P500 is also used to power the fire alarm, Ethernet switch, Digital Back End (DBE), and Data Transmission System (DTS).

The P501 power supply module powers the Front End (FE) Low Noise Amplifier (LNA) noise diode, and bias voltages for Bands 1–6. The P501 also powers the Local Oscillator (LO) Reference Sample Clock Generator and LO A–K Generator modules and the Integrated Downconverter/Digitizers (IRD) for Bands 1–6. The P501 will be located next to the IRDs in the FE Enclosure.

The P502 power supply module powers the LO Clock Receiver module, two Band 4 IRDs, the Water Vapor Radiometer (WVR) antenna amplifier, and cooling system. The P502 will be located in the WVR Enclosure.

The P503 powers the LO Reference Receiver Generator and Distribution module and the four M&C Modules located in the pedestal area of each ngVLA antenna.

4 DC Power Supply System Design

The ngVLA DC Power Supply System design considered two existing designs: those at the Atacama Large Millimeter Array (ALMA) and the Jansky Very Large Array (VLA). Both observatories bring in AC and use commercial off-the-shelf (COTS) parts to convert the AC power to DC power. Both supply DC power to the antenna electronics where each module regulates the DC power to voltages that they can use inside the module.

The two observatories differ when it comes to backup power and the input to the module power supplies. ALMA uses Uninterruptible Power Source (UPS) and feeds the modular power supplies AC power. The VLA uses four 12V lead-acid in series to make up the 48V, which is then fed into the modular power supplies.

Because the ngVLA antenna electronics, environment, and specifications more closely resemble that of the VLA, the ngVLA DC Power Supply system logically follows the VLA design. The ALMA design has had several issues, including operation site altitude and the reliability of the COTS AC-to-DC power supplies. The manufacturer was not helpful pinpointing causes or sources of failures with the module power supplies. The VLA DC Power Supply modules, by contrast, have been highly reliable and experience few failures.

The VLA design was also chosen because it provides multiple stages of regulation. This allows the power going into the antenna electronics to be clean. The ALMA design only has two stages of regulation, one at the power supply module and another inside the antenna electronics. The VLA design has an extra stage of regulation at the AC to 48VDC sub-assembly. Finally, the DC distribution system is more conducive to supporting the system-level RFI emission requirements [AD13].

4.1 DC Power Supply System Block Diagram

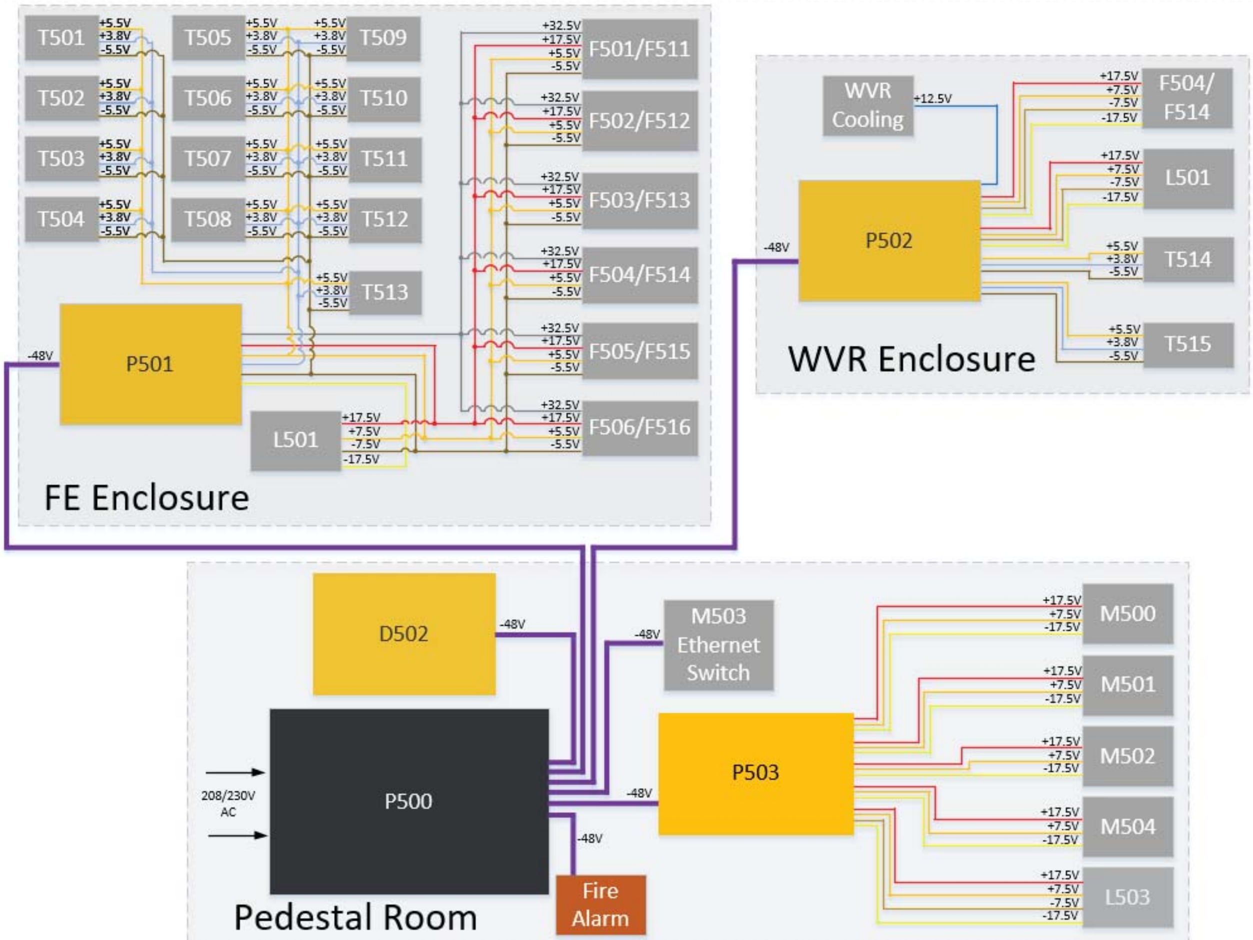


Figure 1 - Block diagram of DC Power Supply system.

4.2 DC Power Supply System Components

4.2.1 P500 Power Supply

The P500 receives 208V 3-phase AC and converts it to –48V DC. The P500 requires 3.2 kW of input power. Lithium batteries will be used as a backup source for the 48V in the event the AC is lost. A battery charger will be used to charge the batteries when AC is available. The batteries and battery charge will be located in the pedestal area of each antenna.

As Figure 1 shows, the P500 feeds 48V into three power supply modules (P501, P502, and P503) that convert the 48V to +32.5V, ±17.5V, +15.5V, ±7.5V, ±5.5V, and +3.8V, depending on the module. The P500 has M&C so it can be shut down for over-current or over-temperature conditions. P500 also powers the fire alarm, Ethernet switch, Digital Back End (DBE), and Data Transmission system (DTS). Figure 2 (next page) shows the P500 block diagram.

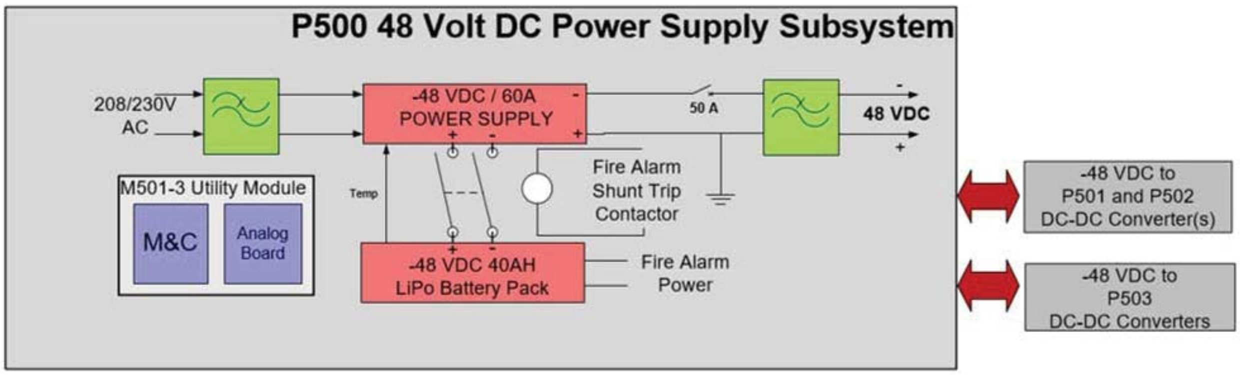


Figure 2 - P500 block diagram.

4.2.2 P501 Power Supply

The P501 power supply module receives –48V @18A from the P500. The P501 uses Vicor DC-DC converter modules to convert the 48V into +3.8V, ±5.5V, ±17.5V, and +32.5V. The P501is used to power the Front End (FE) Low Noise Amplifier (LNA) noise diodes, and bias voltages for Bands 1–6.

The P501 also powers the LO Clock Receiver module and the Integrated Downconverter/Digitizers (IRD) for Bands 1–6. The P501 will be located next to the IRDs in the Front End Enclosure. Figure 3 shows the P501 block diagram.

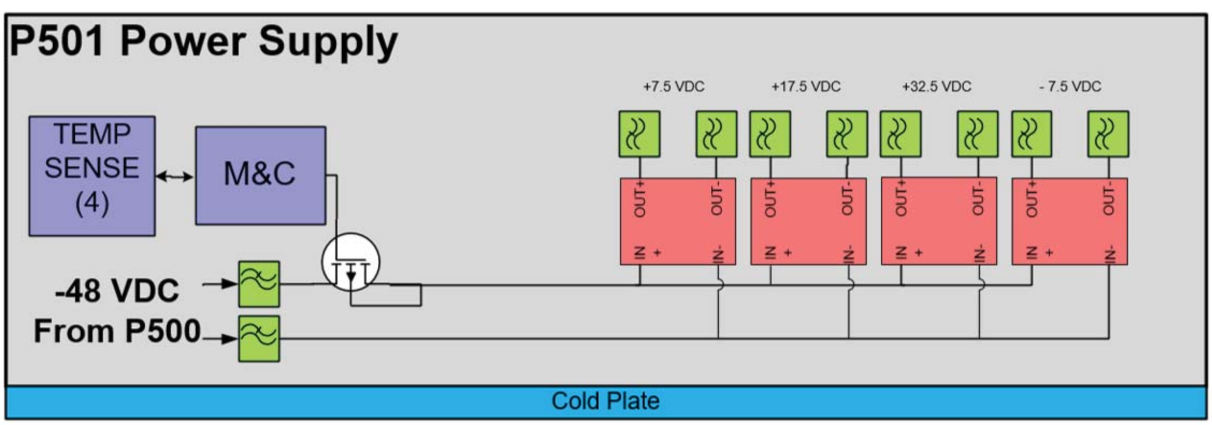


Figure 3 - P501 block diagram.

4.2.3 P502 Power Supply

The P502 power supply module receives –48V @14A from the P500. The P502 uses Vicor DC-DC converter modules to convert the 48V into 3.8V, ±5.5V, +15.5V, ±17.5V, and +32.5V. The P502 power supply module is used to power the LO Clock Receiver, two Band 4 IRDs, the Water Vapor Radiometer (WVR) antenna amplifier, and cooling system. It will be located in the WVR Enclosure. Figure 4 (next page) shows the P502 block diagram.

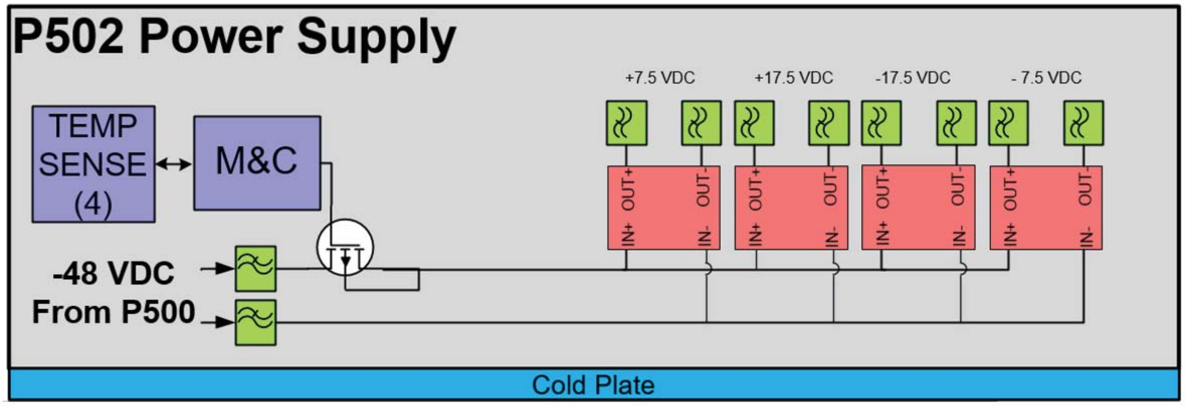


Figure 4 - P502 block diagram.

4.2.4 P503 Power Supply

The P503 power supply module receives –48V @14A from the P500. The P503 uses Vicor DC–DC converter modules to convert the 48V into ±7.5V and ±17.5V. The P503 is used to power the LO Reference Receiver Generator and Distribution module and four Monitor Control modules. The P503 module will be located in the pedestal area of each ngVLA antenna. Figure 5 shows the P503 block diagram.

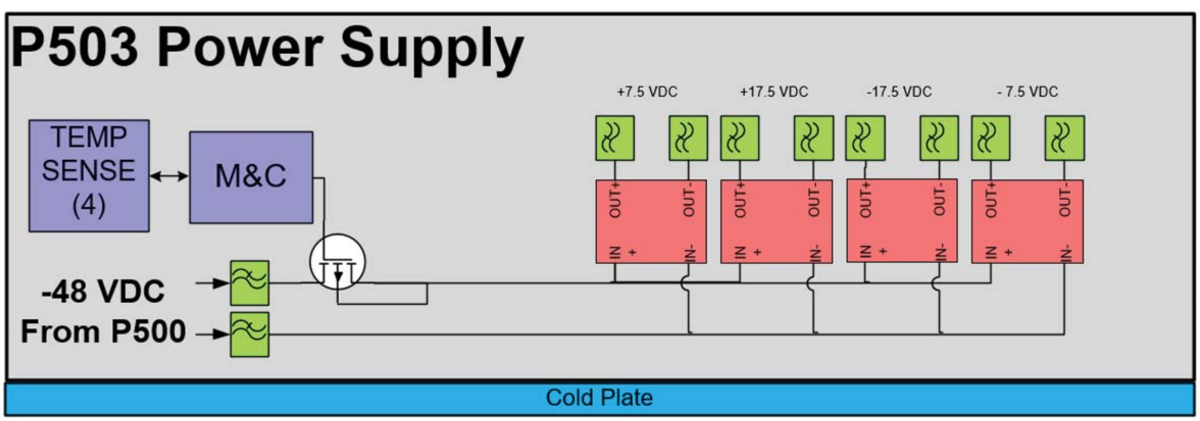


Figure 5 - P503 block diagram.

4.3 DC Power Supply System Interfaces with Other Subsystems

Below are other subsystem requirements from the DC Power Supply system.

4.3.1 Antenna Non-Electronics

4.3.1.1 Antenna AC

The P500 requires 208V 3-phase AC @3.2 kW. The P500 will supply the fire alarm system –48V @2A.

4.3.1.2 Antenna HVAC

The P500 requires cooling for 165W of heat dissipation. The P501 requires cooling for 195W of heat dissipation. The P502 requires cooling for 145W of heat dissipation. The P503 requires cooling for 145W of heat dissipation.

4.3.1.3 WVR Cooling System

The P502 will supply +15.5 V @11.4A to the WVR cooling system, which will then regulate that voltage down to the voltage that it requires.

4.3.2 Digital Back End (DBE)/Data Transmission Systems (DTS)

The whole DBE/DTS requires –48V @10A from the P500. The DBE/DTS system will have its own power system inside that regulates the –48V down to voltages it requires.

4.3.3 Front End (FE)

The Front End consists of six bands. The P501 will supply the FE with +32.5V @0.5A, +17.5V @6A, +7.5V @0.5A, and –7.5V @0.5A for all six bands.

4.3.4 Integrated Downconverter/Digitizers (IRD)

The IRDs consist of 13 modules. Each requires +5.5V @1A, +3.8V @1A and –5.5V @0.1A from P501.

4.3.5 LO Reference Receiver, Generator, and Distributor

4.3.5.1 LO Clock Module

The LO Clock Module is located in the FE Enclosure and in the WVR Enclosure. These modules require +17.5V @2.5A, +5.5V @1.5A, –5.5V @0.25A, and –17.5V @–0.25A from the P501 and P502.

4.3.5.2 LO Reference Receiver, Generator, and Distributor Module

The Reference Receiver, Generator, and Distributor module in the pedestal room requires +17.5V @2.5A, +7.5V @1.5A, –7.5V @0.25A, and –17.5V @0.25A from the P503.

4.3.6 Monitor and Control (M&C)

The monitor and control system requires that a Module Interface Board (MIB) be used inside the P500, P501, P502, and P503 modules.

The P500 will power the Ethernet switch located in the pedestal room with –48V @2A.

The P503 will also power the four M&C modules located in the pedestal room of the antennas. The P503 will supply each M&C module with +17.5V @1 A, +7.5V @2A, and –17.5V @1A.

4.3.7 Water Vapor Radiometer (WVR)

The WVR will use two Band 4 IRDs. The IRDs will only require +5.5V @2A, +3.8V @2A and –5V @0.2A from the P502.

The P502 will also be used to power the amplifiers and other electronics in the WVR antenna. The P502 will supply the antenna with +32.5V @30 mA, +17.5V @30 mA, +5.5V @10 mA, and –5.5 @0.5A.

5 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter Array
DBE	Digital Back End
DTS	Data Transmission System
FE	Front End
HVAC	Heating, Ventilation, and Air Conditioning
IRD	Integrated Downconverter/Digitizers
LNA	Low Noise Amplifier
LO	Local Oscillator
M&C	Monitor and Control
ngVLA	Next Generation VLA
RD	Reference Document
UPS	Uninterruptible Power Source
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

Bins, Modules, and Racks Work Package: Preliminary Technical Requirements

020.30.55.00.00-0001-REQ-A-BINS_MODULES_RACKS_PRELIM_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
D. Gerrard, S. Sturgis, J. Allison	Electronics Div., NRAO	2018-10-26
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-05-03

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.17 16:13:09 -06'00'	Electronics Division, NRAO	2019-07-17
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:34:10 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-17

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:34:26 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-17

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-24	J. Allison	1, 3, 4.1	Initial Draft Version
02	2018-07-09	S. Sturgis	All	Revised and updated
03	2018-09-24	S. Durand	All	Basic edits
04	2018-10-19	J. Allison	All	Misc. edits and corrections
05	2018-10-23	J. Allison	All	Misc. edits and corrections. Addressed RID numbers: IPDSR-594, 592, 531, 530
06	2018-10-26	J. Allison	10	Addressed RID number IPDSR-593
07	2019-05-30	R. Selina	2.1, 3.2, 4	Edits throughout for release. Updated requirements numbering scheme, refined some requirements, etc.

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents and Drawings 6
2.1 Applicable Documents 6
2.2 Reference Documents 6
3 Overview of the Bins, Modules, and Racks Technical Requirements 7
3.1 Document Outline 7
3.2 Project Background 7
3.3 General Bins, Modules, and Racks Description 7
3.4 Summary of Bins, Modules, and Racks Requirements 8
3.4.1 General Functional Specifications 8
3.4.2 Other General Requirements 8
4 Functional and Performance Requirements 9
4.1 RF Shielding 9
4.2 Environmental Conditions 9
4.2.1 Normal Operating Conditions 9
4.2.2 Specific Environmental Requirements 9
4.3 Life Cycle Requirements 9
5 Interface Requirements 10
5.1 Interface between Modules and Bins 10
5.2 Interface between Bins and Rack 10
5.3 Interface between Racks and Antenna 10
5.3.1 Electrical Interface 10
5.3.2 Mechanical Interface 10
5.3.3 HVAC 10
5.4 Interface to the Monitor & Control System 10
6 Safety 11
6.1 Electrical Safety 11
6.2 Handling, Transport, and Storage Safety 11
7 Requirements for Design 11
7.1 Materials, Parts and Processes 11
7.1.1 Fasteners 11
7.1.2 Paints 11
7.1.3 Surface Treatment 11
7.1.4 Name Plates and Product Marking 11
7.1.5 Labels 11
8 Documentation Requirements 12
8.1 Technical Documentation 12
9 Verification and Quality Assurance 12
10 Key Performance Parameters 13
11 Appendix 14
11.1 Abbreviations & Acronyms 14
11.2 Maintenance Definitions 15

11.2.1 Maintenance Approach 15
11.2.2 Periodic Preventive Maintenance 15

1 Introduction

1.1 Purpose

This document aims to present a set of technical requirements for the reference design of the ngVLA Bins, Modules, and Racks work package. Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow-down from the preliminary ngVLA Science Requirements [AD01].

The Science goals 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 science, system and subsystem requirements, are reflected in this draft.

1.2 Scope

The scope of this document is the ngVLA Bins, Modules, and Racks work package. This consists of any modular unit housing electronic components within the Antenna and the bins in which they are mounted.

This requirements document establishes the performance, functional, design, and test requirements applicable to the ngVLA Bins, Modules, and Racks. It also includes interface requirements that must be defined.

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 this Technical Specification shall be considered as a superseding requirement.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD04	ngVLA System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements	020.10.15.10.00-0002-REQ
AD07	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
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

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev / Doc. No.
RD01	Cabinets, Racks, Panels, and Associated Equipment	EIA/ECA-310 Rev. E

3 Overview of the Bins, Modules, and Racks Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA Bins, Modules, and Racks work package. These parameters determine the overall form and performance of the Bins, Modules, and Racks work package.

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 Bins, Modules, and Racks Work Package 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 Bins, Modules, and Racks 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, 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 observatory will be a synthesis radio telescope constituted of reflector antennas of 18 meters diameter and 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 Bins, Modules, and Racks Description

The Bins, Modules, and Racks work package consists of individual modules (LRUs) housed in a number of bins all inside of an EIA standard electronics rack located in the pedestal room of the antenna. The work package may also include a number of modules and bins in other locations as well. Its key function is to modularize the electronics, and make assembly and maintenance of the antenna electronics as simple as possible, while providing adequate RFI shielding for the antenna and any other sensitive equipment.

3.4 Summary of Bins, Modules, and Racks Requirements

The following table summarizes major requirements to give the reader a high-level view of the subsystem. Should a conflict arise between requirements listed here and descriptions in Sections 4–10, the latter shall take precedence.

3.4.1 General Functional Specifications

Parameter	Req. #	Summary of Requirement	Traceability
Ease of Access	BMR0001	Must be simple and quick to access contained components.	SYS2403
Ease of Installation	BMR0002	Must be simple and quick to install and uninstall.	SYS2403
RFI Shielding	BMR0003	Must provide RFI shielding where needed.	SYS2106
Heat Dissipation	BMR0004	Must provide a means of expelling heat where needed.	
Volume	BMR0005	Must be configurable to different volumes of electronic components.	SYS2403
Mass	BMR0006	Must be low enough for a single person to lift and manipulate.	SYS2403

3.4.2 Other General Requirements

Parameter	Req. #	Summary of Requirement	Traceability
Corrosion resistance	BMR0101	Must have adequate corrosion prevention.	SYS2801
Hardware	BMR0102	Metric hardware, whenever possible.	
Standardized Components	BMR0103	Modules must be made up of standardized components requiring little alteration to accommodate different systems' needs.	
Minimize External Connectors	BMR0104	The use of as few external connectors as possible is encouraged.	SYS2106
Shielded Connectors	BMR0105	Any connectors entering/exiting any modules or racks must maintain RFI shielding levels.	SYS2106
Meet Specified General Dimensions	BMR0106	General dimensions of machined parts must fit the tolerances outlined in manufacturing drawing of the parts to ensure everything fits together correctly and mounting properly.	
Meet Specified Surface Flatness and Finish	BMR0107	Surface flatness and finish of machined parts must fit those outlined in manufacturing drawing to ensure surface contact for heat transfer spec. RFI is mitigated properly, and parts are kept safe from corrosion.	

4 Functional and Performance Requirements

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

4.1 RF Shielding

Parameter	Req. #	Value	Traceability
Module RF Shielding	BMR0401	>50 dB from 1–30 GHz	SYS2106
Rack RF Shielding	BMR0402	>80 dB from 1–30 GHz	SYS2106

Module and rack required RF shielding levels are not presently defined, and dependent on emission levels within the enclosures, so starting at a conservative level is prudent.

4.2 Environmental Conditions

4.2.1 Normal Operating Conditions

The modules, bins, and racks are not designed to withstand outside environmental conditions. The cost of an outdoor RFI-shielded rack is expected to be significantly higher compared to an indoor shielded rack. Each module, bin, or rack located outside of the pedestal room will reside inside of a separate, environmentally-sealed enclosure.

4.2.2 Specific Environmental Requirements

Parameter	Req. #	Value	Traceability
Rack Cooling	BMR0501	Must be forced-air cooled	
Bins and Module Cooling	BMR0502	Forced air must be directed to only flow through the bins and past the modules and not in the space between the doors or walls of the rack and the modules/bins.	
Rack air inlet temperature	BMR0503	4 ± 2°C	
Maximum air temperature difference from inlet to exit	BMR0504	10°C	

Any rack with heat generating modules contained within it must be able to be cooled with forced air. Typically this means honeycomb filters top and bottom and forced air flows from bottom to top. The forced air system may be an open or closed system.

4.3 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	BMR0601	The Bins, Modules, and Racks shall be designed to be operated and supported for a period of 20 years.	SYS2701
Lifecycle Optimization	BMR0602	The Bins, Modules, and Racks design shall minimize its lifecycle cost for 20 years of operation.	SYS2702

Lifecycle costs include manufacture, transport, construction/assembly, operation, and decommissioning.

5 Interface Requirements

This section provides information about the interfaces of the Bins, Modules, and Racks. Interface Control Documents (ICDs) are required between the Bins, Modules, and Racks 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 Bins, Modules, and Racks Designer, and approved by ngVLA, as part of the Bins, Modules, and Racks reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface between Modules and Bins

The module shall slide into the bin and be secured in such a manner that it is easy and quick to install or remove with minimal hand tools.

5.2 Interface between Bins and Rack

The bins will mount to the standard EIA rack mounting rails and will conform to EIA rack mount standards [RD01].

5.3 Interface between Racks and Antenna

5.3.1 Electrical Interface

The ICD should describe both the mechanical and electrical specifications of the electrical interfaces.

5.3.2 Mechanical Interface

The rack base will be bolted to the floor, and at least one point at the top of the rack will be anchored to a point on a wall or other secure mounting point.

5.3.3 HVAC

The rack will have an HVAC interface at both the top and bottom, for a closed system. This will effectively prevent the ingress of dust and other contaminants, and allow a much longer service interval.

5.4 Interface to the Monitor and Control System

The rack air inlet and exit temperature should be monitored.

6 Safety

6.1 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard. 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 [AD07] while taking into account the altitude of up to 2500 m above sea level.

6.2 Handling, Transport, and Storage Safety

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

7 Requirements for Design

7.1 Materials, Parts and Processes

7.1.1 Fasteners

Where reasonably possible, all fasteners shall be metric.

7.1.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

7.1.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

7.1.4 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.

7.1.5 Labels

Racks, bins and modules, and all associated electrical interconnects shall be labeled.

8 Documentation Requirements

8.1 Technical Documentation

All documentation related to the Bins, Modules, and Racks shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use both metric and imperial units.
- Drawings will be archived in Adobe PDF format.
- All CAD source files will be provided.
- The CAD system used is AutoDesk Inventor and/or AutoCAD (not preferred).
- The electronic document formats are Microsoft Word and Adobe PDF.

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

9 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.

The following table summarizes the expected verification method for each requirement.

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
BMR0313	Machined Part Dimensions	X		X		
BMR0314	Machined Part Surface Flatness/Finish	X		X		
BMR0401	Module RF Shielding				X	
BMR0402	Rack RF Shielding				X	

Table 1 - Expected requirements verification method.

10 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 are parameters that 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.

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 Bins, Modules, and Racks (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 2. 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. #
Module RF Shielding	BMR0401
Rack RF Shielding	BMR0402

Table 2 - Key performance parameters for monitoring during design.

11 Appendix

11.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
FDR	Final Design Review
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
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
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

11.2 Maintenance Definitions

11.2.1 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. In the context of this subsystem, an LRU is defined as any ARCS module.

LRU exchange shall be possible by 2 trained people within 4 working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the Bins, Modules, and Racks.

A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

11.2.2 Periodic Preventive Maintenance

The ARCS modules require no preventive maintenance. The shielded racks will periodically require replacement of air filters at the HVAC inlet or outlet, where used.

Bins, Modules, and Racks Reference Design Description

020.30.55.00.00-0002-DSN-A-BINS_MODULES_RACKS_REF_DSN

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
D. Gerrard, S. Sturgis, J. Allison	Electronics Div., NRAO	2018-10-23
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-05-04

APPROVALS (Name and Signature)	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer 2019.07.17 16:50:09 -06'00'	Electronics Div., NRAO	2019-07-17
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:58:15 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-17

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.17 16:58:39 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-17

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-24	J. Allison	1-5	Initial draft
02	2018-06-25	S. Durand	All	Small edits
03	2018-07-10	S. Sturgis	All	Revised and updated
04	2018-09-24	S. Durand	All	More small edits
05	2018-10-19	J. Allison	All	Small edits and corrections
06	2018-10-23	J. Allison	All	Small edits and corrections, addressed RID numbers: IPDSR-532 & 591
07	2019-05-30	R. Selina	2, 3, 4	Minor edits for release throughout; struck interface section (duplicate to requirements doc)
A	2019-07-17	A. Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction **4**
1.1 Purpose *4*
1.2 Scope *4*
2 Related Documents and Drawings **4**
2.1 Applicable Documents *4*
2.2 Reference Documents *4*
3 Subsystem Overview **5**
4 Subsystem Design **5**
4.1 Modules *5*
4.2 Bins *6*
4.3 Racks *6*
4.4 Subsystem Components *6*
5 Appendix **10**
5.1 Abbreviations and Acronyms *10*
5.2 ARCS Module Testing Results *11*

1 Introduction

1.1 Purpose

This document provides a description for the Bins, Modules, and Racks subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the Bins, Modules, and Racks subsystem at the Antenna, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems.

It does not include specific technical requirements [see AD01] or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Bins, Modules, and Racks Subsystem Preliminary Requirements	020.30.55.00.00-0001-REQ
AD02	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	ngVLA EMC & RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
AD04	Antenna Electronics Front End Enclosure Block Diagram	020.30.00.00.00-0002-BLK
AD05	Antenna Electronics Pedestal Enclosure Block Diagram	020.30.00.00.00-0003-BLK

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	ALMA Back End IPT Shielded Rack Specification	BEND-57.02.00.00-004-A-SPE
RD02	ARCS Module RFI Test Report	D. Mertely, 2018.

3 Subsystem Overview

The Bins, Modules, and Racks subsystem consists of individual modules (LRUs) housed in a number of bins all inside of an EIA standard electronics rack located in the antenna's pedestal room. The work package may also include a number of modules and bins in locations other than the electronics rack and other than the pedestal room. Its key function is to house the LRUs that make up the antenna electronics, and make assembly and maintenance of the antenna electronics as simple as possible while providing adequate RFI shielding for the antenna and any other sensitive equipment.

4 Subsystem Design

4.1 Modules

The proposed modules for this subsystem are the Advanced RFI Containment System (ARCS) modules that were recently developed by NRAO. There are three primary types of ARCS modules, designated as series 100, 200, and 300. The 100 series modules consist of two high-tolerance machined pieces of aluminum that fit together like a clamshell, leaving a cavity in the middle for mounting electronics. The 200 series modules consist of three pieces, and allow for dual internal cavities that are independently RFI shielded. The 300 series modules are also three-piece modules, but with individually removable side panels that allow access to the internal electronics from either side of the module. The module style to be selected is dependent on the degree of access required for the components within, and the desired mounting layout of said components.

All module types have double-gasket seams around the edge, utilizing specialized RFI gaskets. A series of compression latches compress the gasket, and ensure a high level of RFI shielding is achieved. All modules will have guide blocks that help guide the module into the bin, as well as a front panel that is used to secure the module into the bin via four captive thumbscrews.

The modules are made out of ATP5 aluminum tool plate to prevent warping during machining. This helps ensure that the modules will meet their dimensional specifications so that they may mitigate RFI effectively and fit into their bins with ease. All module pieces will be chromated per MIL-C-5541-CL.III after machining in order to maintain a conductive surface. Each piece of every module also has its own RFI gasket which is attached using electrically conductive adhesive.

All of the individual module pieces can vary in width by half-inch increments, so a large variety of sizes and styles can be achieved in order to optimize space for electrical components. Furthermore, the outer covers may be produced with heatsink fins for heat-generating components, and the interiors can be customized with pockets or ridges to better accommodate mounting of electrical components.

Input/output connections can be made on either the front or rear of the module. Blind mate connections are also possible with the addition of a panel on the rear of the bin, to hold one side of the blind mate connector.

Another benefit of these modules is that there is no designated front, rear, top or bottom of the module. Modules may be inserted into the bin from either the front or the rear, and either right side up or upside down.

The ARCS module concept can be readily adapted for applications where rack or bin mounting is not a requirement or desired. For example, the IRD enclosure is expected to be variant of a 100 series module, but with a form factor of 24" x 20" instead of the standard 8" x 20".

4.2 Bins

Bins provide a convenient and reliable method of organizing groups of modules near one another. The standard ARCS bin is six rack units (6 RU) tall by 20 inches deep, and is designed to fit into a standard EIA 19 inch wide rack. However, bins can be configured for any rack height, width or depth.

There is not a fixed number of modules per bin, because of the varying module widths. To accommodate a mix of module widths, bins are designed for module widths in increments of ½". The bins simply mount to the vertical rails of the rack using #10 machine screws.

4.3 Racks

The racks will be a variant of the ALMA Back End racks [RD01], as they are a proven solution. These racks provide a high level of RFI shielding, using a combination of a welded steel external shell, RFI gaskets, and an RFI-absorbing foam. The rack typically has multiple I/O panel location options for running power and signals in or out of the rack, and honeycomb filters on the top and bottom to allow airflow through the rack for cooling without compromising the RFI shielding. The dimensions and I/O panel locations of the racks will be dependent on the design and available space of the pedestal room in the selected antenna.

4.4 Subsystem Components

Figures 1–4 show examples of different ARCS module configurations.

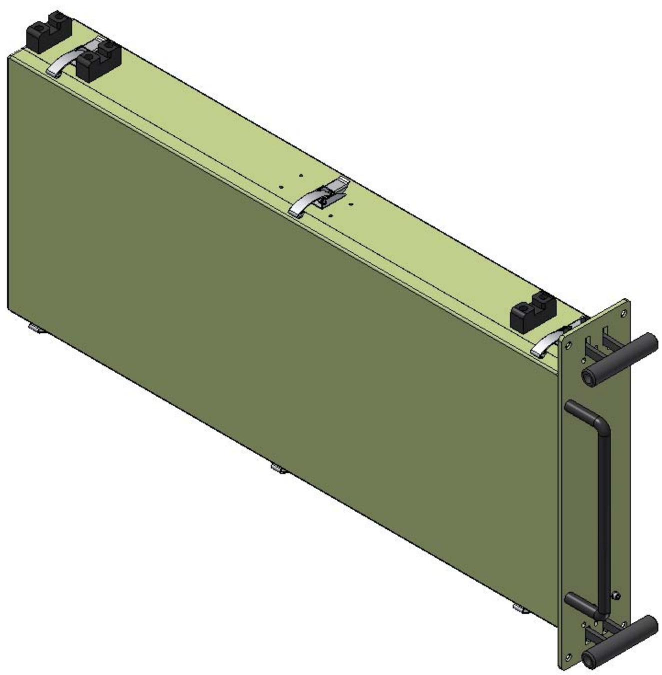


Figure 1 - Series 100 ARCS module.

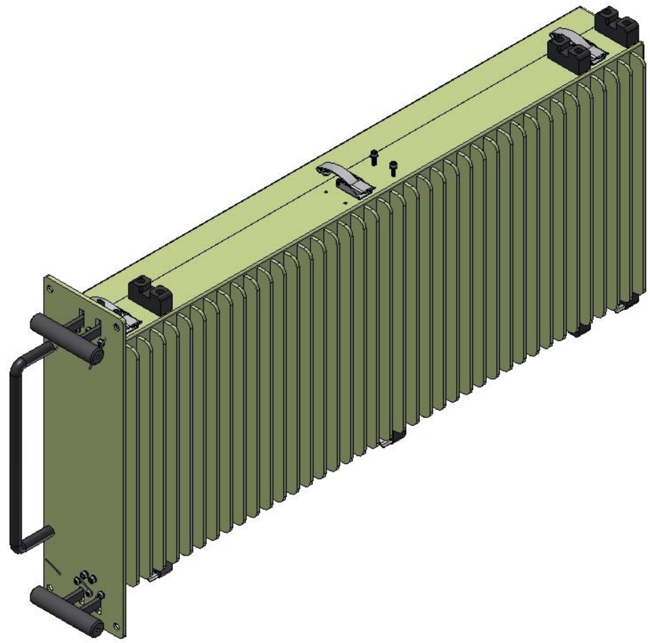


Figure 2 -100 Series ARCS module with integrated heatsink.

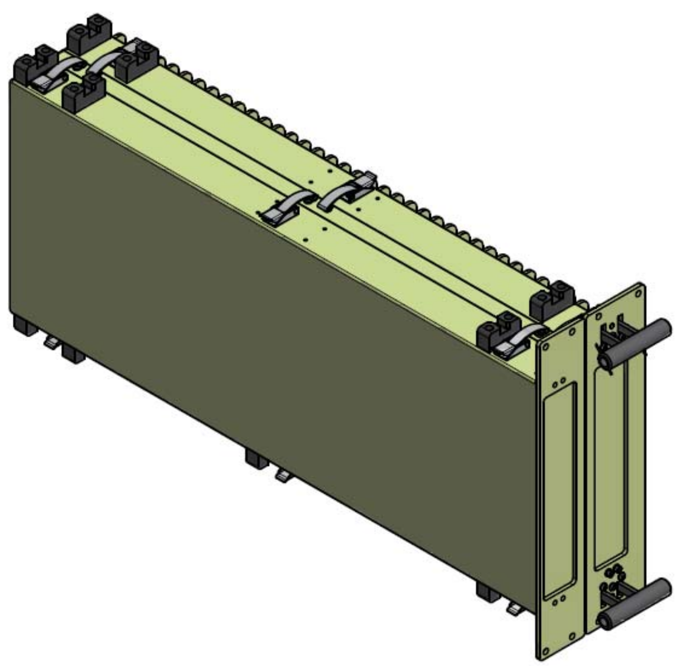


Figure 3 - 200 Series ARCS module (two cavity) with one integrated heatsink.

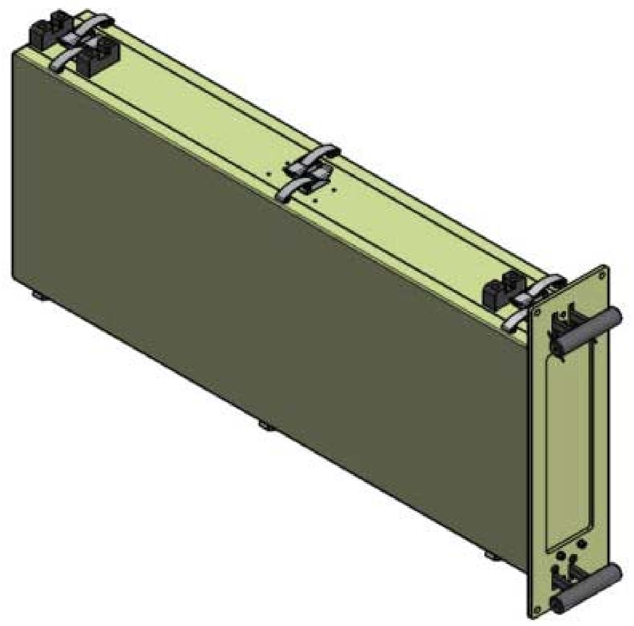


Figure 4 - 300 Series ARCS module (components accessible from either side).

Figure 5 shows an example of modules installed in a bin.

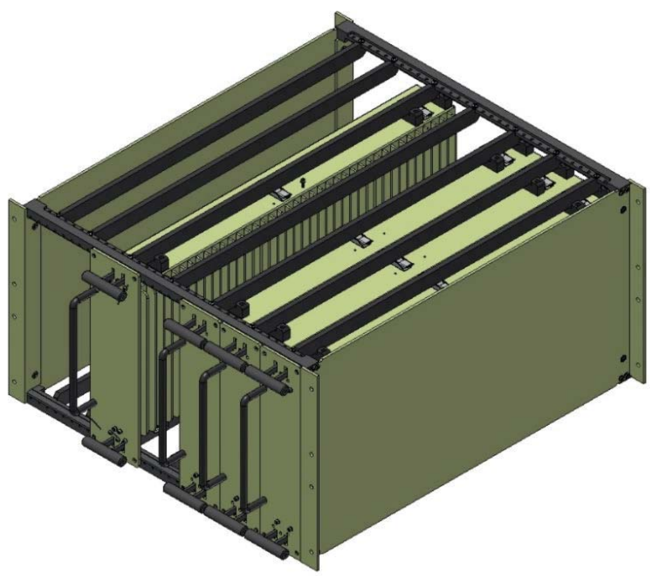


Figure 5 - ARCS modules installed in a bin.

Figure 6 shows an example of the rack used to house the ARCS bin. Note the different possible locations of the I/O panel, on top (and bottom) or the side.

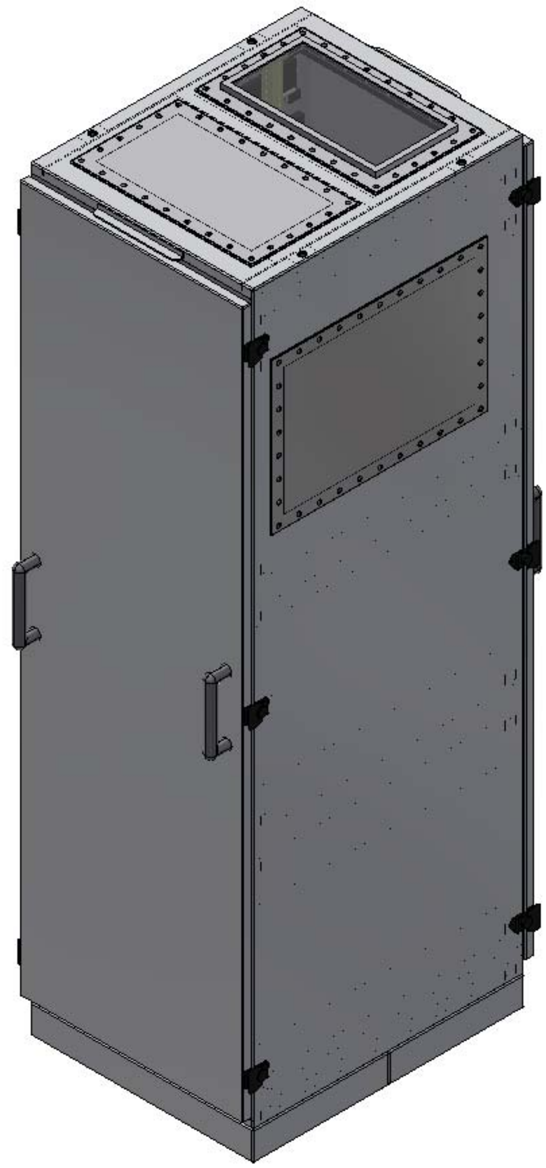


Figure 6 - Shielded rack.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
ARCS	Advanced RFI Containment System
BE	Back End
EIA	Electronics Industries Alliance
FE	Front End
HVAC	Heating, Ventilation and Air Conditioning
ICD	Interface Control Document
IRD	Integrated Receiver Downconverter/Digitizer
LRU	Line Replaceable Unit
ngVLA	Next Generation VLA
RFI	Radio Frequency Interference
RU	Rack Units
UPS	Uninterruptible Power Supply
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

5.2 ARCS Module Testing Results

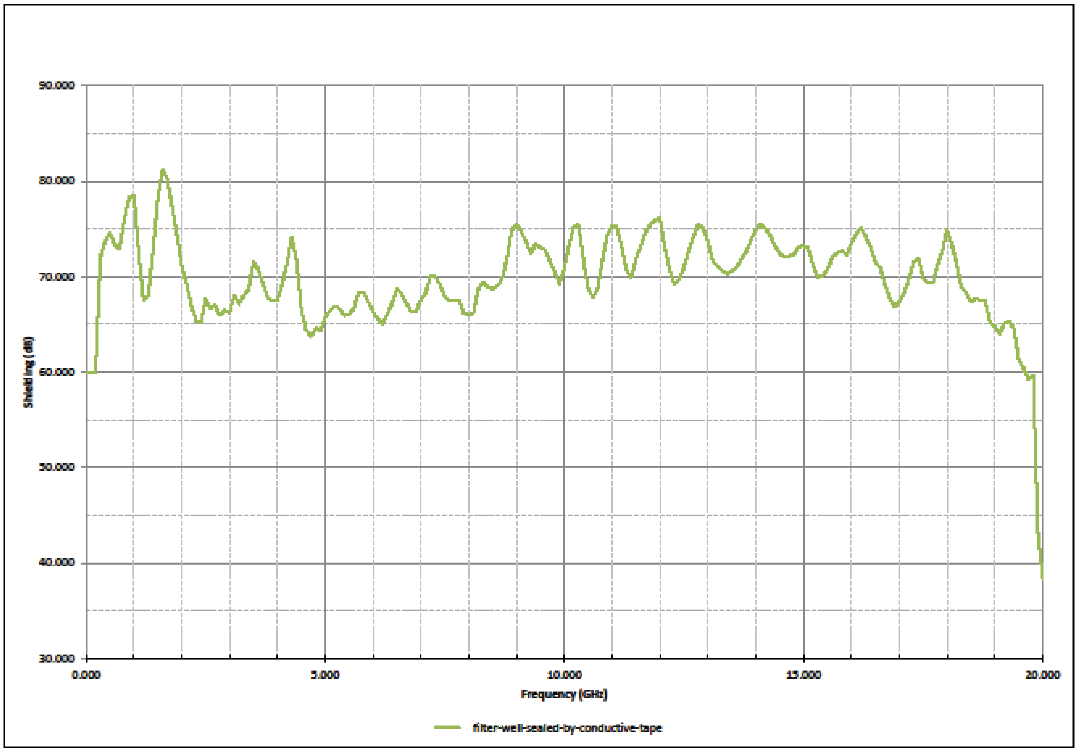


Figure 7 - Preliminary shielding effectiveness of 100 series ARCS module [RD02]. Note: tests were performed in reverb chamber, not anechoic chamber.

Antenna Electronics Environmental Control System: Preliminary Technical Requirements

020.30.60.00.00-0001-REQ-A-ANTENNA_ELECTRONICS_ENVIR_CONTROL_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
S. Sturgis, J. Allison	Electronics Div., NRAO	2019-07-19
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-07-19

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer 2019.07.25 10:54:39 -06'00'	Electronics Div., NRAO	2019-07-25
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:20:21 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-25

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.25 16:20:37 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-25

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-22	J. Allison	1-4	Initial Draft
02	2018-07-12	S. Sturgis	All	Updated and revised doc number, title, all sections.
03	2018-09-02	S. Durand	All	Small edits
05	2018-09-19	S. Durand	All	More Small edits
06	2018-11-09	J. Allison	All	Addressed RID numbers 630 & 631. Added references to Cryogenics, IRD, and WVR specifications documents. Added information about verification & QA
07	2018-11-12	S. Sturgis	All	Minor edits
08	2019-07-19	L. Leyba-Newton	2, 4, 7, 11	Restructured, added clarity, completed sections.
09	2019-07-22	R. Selina	1.1, 2.2, 3.4	Updated functional requirements. Other edits for release.
A	2019-07-25	A. Lear	All	Prepared PDF for approvals & release

Table of Contents

1 Introduction 5
1.1 Purpose 5
1.2 Scope 5
2 Related Documents & Drawings 5
2.1 Applicable Documents 5
2.2 Reference Documents 5
3 Overview of Antenna Electronics Environmental Control System Technical Requirements 6
3.1 Document Outline 6
3.2 Project Background 6
3.3 General Antenna Electronics Environmental Control System Description 6
3.4 Summary: Antenna Electronics Environmental Control System Requirements 7
3.4.1 General Functional Specifications 7
4 Environmental Control System Functional and Performance Requirements 8
4.1 Functional Requirements 8
4.2 Additional Requirements 9
4.2.1 Operating Conditions 9
4.2.2 Survival Conditions 11
4.2.3 Solar Radiation 11
4.2.4 Rain/Water Infiltration 12
4.2.5 Mechanical Shock 12
4.3 Maintenance and Reliability Requirements 12
4.4 Monitor and Control Requirements 12
4.5 Lifecycle Requirements 13
5 Interface Requirements 13
6 Subsystem Requirements 13
7 Safety 14
7.1 General 14
7.2 Safety Design Requirements 14
7.2.1 Electrical Safety 14
7.2.2 Handling, Transport, and Storage Safety 14
8 Requirements for Design 15
8.1 Analyses and Design Requirements 15
8.1.1 Reliability, Availability, Maintainability Analysis 15
8.2 Electromagnetic Compatibility Requirements 15
8.3 Materials, Parts and Processes 15
8.3.1 Fasteners 15
8.3.2 Paints 15
8.3.3 Surface Treatment 15
8.3.4 Name Plates and Product Marking 15
8.3.5 Labels 16
9 Documentation Requirements 17
9.1 Technical Documentation 17

9.2 Software and Software Documentation 17
10 Verification and Quality Assurance 18
11 Key Performance Parameters 20
12 Appendix 21
12.1 Abbreviations and Acronyms 21
12.2 Maintenance Definitions 22
12.2.1 Maintenance Approach 22
12.2.2 Periodic Preventive Maintenance 22

1 Introduction

1.1 Purpose

This document aims to present a set of technical requirements for the reference design of the ngVLA Antenna Electronics Environmental Control System. These parameters determine the overall form and performance of the environmental control of the antenna electronics. Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow down from the preliminary ngVLA Science Requirements [AD01].

1.2 Scope

The scope of this document is the environmental control for the ngVLA antenna electronics. This consists of temperature control of all electronics enclosures as well as protecting electrical components at the antenna from the environment. It includes interface requirements that must be defined. This requirements document establishes the performance, functional, design, and test requirements applicable to the environmental control for the ngVLA antenna electronics.

2 Related Documents & 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 this Technical Specification shall be considered as a superseding requirement.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	ngVLA Electronics Environmental Control System: Reference Design Description	020.30.60.00.00-0002-DSN
AD04	Insulation Coordination for Equipment within Low-Voltage Systems	IEC-60664
AD05	Enclosures for Electrical Equipment (1000 Volts Maximum)	NEMA 250
AD06	System Environmental Specifications	020.10.15.10.00-0001-SPE

2.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	System EMC Compatibility and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ
RD02	ngVLA Cryogenic Subsystem Requirements	020.30.10.00.00.0001-REQ
RD03	ngVLA Integrated Receivers and Downconverters: Preliminary Technical Requirements	020.30.15.00.00-0001-REQ
RD04	ngVLA Water Vapor Radiometer Preliminary Technical Requirements	020.45.00.00.00-0001-REQ
RD05	ngVLA Front End Technical Requirements	020.30.03.01.00-0001-REQ

3 Overview of Antenna Electronics Environmental Control System Technical Requirements

3.1 Document Outline

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 Electronics Environmental Control System.

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. Subsystem requirements appear in Section 6.

Safety requirements applicable to both the design phase and the functional environmental control of the antenna electronics 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 Verification and Test, 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 observatory will be a synthesis radio telescope constituted of reflector antennas of 18 meters diameter and 6 meters diameter, operating in a phased or interferometric mode.

The signal-processing center of the array 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 the state of 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 Antenna Electronics Environmental Control System Description

Antenna electronics are located in various places around the antenna. Primary locations include, but are not limited to, the electronics rack in the pedestal room, front end enclosures on the feed arm, the WVR enclosure along the edge of the primary reflector, and the compressor platform at the top-rear of the pedestal. Environmental control of the antenna electronics involves temperature control of all electronics in these locations as well as protection from water, dust, animals, or other environmental hazards.

The primary temperature control system consists of a heated and cooled liquid loop, most likely glycol, which runs from the compressor at the top-rear of the pedestal to the WVR module and the front end enclosures. Liquid cold plates, made of copper tubing running through an aluminum block which components may be directly mounted to, will cool electronics in both the front end enclosures and the WVR, as well as heat or cool components on the compressor platform. The pedestal room electronics rack will be forced-air-cooled via a commercial air conditioning unit which will likely mount to the side of the rack and be purchased from the rack manufacturer.

Protection from water, dust, animals, or other environmental hazards will be accomplished with custom sealed enclosures for the front end, WVR, and Cryo M&C enclosure. The electronics rack in the pedestal room will be protected from such hazards by the antenna structure.

3.4 Summary: Antenna Electronics Environmental Control System Requirements

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

3.4.1 General Functional Specifications

Parameter	Summary of Requirement	Reference Reqs.
Front End Receiver Enclosure	NEMA 4X [AD05], Cooled per [RD05]	020.30.03.01.00-0001-REQ ngVLA Front End Technical Requirements
Front End Auxiliary Enclosure	NEMA 4X [AD05], Cooled per [RD02]	020.30.10.00.00-0001-REQ ngVLA Cryogenic Subsystem Requirements
WVR Receiver Enclosure	NEMA 4X [AD05], Cooled per [RD04]	020.10.15.10.00-0001-SPE System-Level Environmental Specifications
Compressor Platform	Cooled/heated per [RD02]	020.30.10.00.00-0001-REQ ngVLA Cryogenic Subsystem Requirements
Pedestal Room Rack	Cooled as required	020.10.15.10.00-0001-SPE System-Level Environmental Specifications

4 Environmental Control System Functional and Performance Requirements

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

4.1 Functional Requirements

Parameter	Req. #	Value	Traceability
Front End Enclosure	EEC0100	The environmental control system shall provide a protective enclosure meeting NEMA 4X standards for the front end receivers and ancillary equipment mounted on the feed indexing mechanism.	020.30.03.01.00-0001-REQ Front End Technical Requirements
Front End Auxiliary Enclosure	EEC0101	The environmental control system shall provide a protective enclosure meeting NEMA 4X standards for the vacuum pump and ancillary equipment mounted adjacent to the feed indexing mechanism.	020.30.10.00.00-0001-REQ Cryogenic Subsystem Requirements
WVR Enclosure	EEC0102	The environmental control system shall provide a protective enclosure meeting NEMA 4X standards for the WVR front-end electronics mounted to the feed arm adjacent to the main reflector.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications
Front End Enclosure Thermal Regulation	EEC0103	The front end enclosure shall provide an active heat exchanger service for heat-generating electronics within the enclosure.	020.30.03.01.00-0001-REQ ngVLA Front End Technical Requirements
Front End Auxiliary Enclosure Thermal Regulation	EEC0104	The front end auxiliary enclosure shall provide an active heat exchanger service for heat-generating electronics within the enclosure.	020.30.10.00.00-0001-REQ ngVLA Cryogenic Subsystem Requirements
WVR Enclosure Thermal Regulation	EEC0105	The WVR enclosure shall provide an active heat exchanger service for heat-generating electronics within the enclosure.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications
Compressor Enclosure Thermal Regulation	EEC0106	The environmental control system shall provide an active heat exchanger service for heat-generating electronics within the compressor enclosure.	020.30.10.00.00-0001-REQ ngVLA Cryogenic Subsystem Requirements

Parameter	Req. #	Value	Traceability
Pedestal Room Rack Thermal Regulation	EEC0107	The environmental control system shall provide an active forced-air heat exchanger service for heat-generating electronics in the pedestal room rack.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications

4.2 *Additional Requirements*

Parameter	Req. #	Value	Traceability
Vibration	EEC0152	All Antenna Electronics Environmental Control exposed equipment, including all equipment within the antenna, shall be designed to withstand persistent wind-induced vibration.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0531
Dust	EEC0153	All Antenna Electronics Environmental Control exposed equipment shall be protected against windblown dust, ashes, and grit.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0541
Rodents	EEC0154	All Antenna Electronics Environmental Control exposed equipment 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.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0551

4.2.1 Operating Conditions

Parameter	Req.#	Value	Traceability
Solar Thermal Load	EEC0250	Antenna Electronics Environmental Control equipment shall provide needed environmental conditioning to the antenna electronics while meeting the condition: Exposed to full Sun.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0321
Wind Speed	EEC0251	Antenna Electronics Environmental Control equipment shall provide needed environmental conditioning to the antenna electronics while meeting the condition: $W \leq 15$ m/s average over 10 min. $W \leq 20$ m/s gust.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0322
Outdoor Temperature	EEC0252	Antenna Electronics Environmental Control equipment shall provide needed environmental conditioning to the antenna electronics while meeting the condition: -20 C $\leq T \leq 45$ C	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0323

Parameter	Req.#	Value	Traceability
Outdoor Temperature Rate of Change	EEC0253	Antenna Electronics Environmental Control equipment shall provide needed environmental conditioning to the antenna electronics while meeting the condition: $\Delta T = 3.6^{\circ}C/hr$.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0324
Precipitation	EEC0254	Antenna Electronics Environmental Control equipment shall provide needed environmental conditioning to the antenna electronics while meeting the condition: 5 cm/hr. precipitation. (TBC)	020.10.15.10.00-0001-SPE System-Level Environmental Specifications
Cooling Temp Front End Enclosure	EEC0255	The Front End enclosure shall provide needed environmental conditioning to provide an internal operational temperature range of –15 to 35°C; with a temp gradient of less than 3.6°C/hr.	020.30.15.00.00-0001-REQ
Cooling Temp Front End Auxiliary Enclosure	EEC0256	The Front End Auxiliary enclosure shall provide needed environmental conditioning to provide an internal operational temperature range of 12 to 45°C	020.30.10.00.00.0001-REQ
Cooling Temp-Compressor Platform	EEC0257	Antenna Electronics Environmental Control components shall provide needed environmental conditioning to provide an internal operational temperature range, within the compressor enclosure, of –30 to 45°C	020.30.10.00.00.0001-REQ
Heat Exchanger Service Temperature	EEC0258	The Heat Exchanger Service provided to various locations around the antenna shall maintain an operational temperature >28 C; with a temp grad. Of less than 0.1°C/hr.	020.45.00.00.00-0001-REQ

This section describes the operating conditions under which the environmental control system is expected to meet its full specification. This environmental definition is consistent with the limit to the operating conditions in [AD06].

4.2.2 Survival Conditions

Parameter	Constraints	Value	
Wind	EEC0350	Antenna Electronics Environmental Control equipment shall survive wind speeds of 0 m/s ≤ W ≤ 50 m/s average	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0341
Temperature	EEC0351	Antenna Electronics Environmental Control equipment and the electronics they house shall survive outdoor temperatures of –30 C ≤ T ≤ 50 C	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0342
Radial Ice	EEC0352	Antenna Electronics Environmental Control equipment and the electronics they house shall survive radial ice of 2.5 cm	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0343
Snow Load – Equipment	EEC0354	Antenna Electronics Environmental Control equipment and the electronics they house shall survive snow loads of 100 kg/m^2 on horizontal surfaces.	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0345
Hail Stones	EEC0355	Antenna Electronics Environmental Control equipment and the electronics they house shall survive hail stones of 2.0 cm diameter	020.10.15.10.00-0001-SPE System-Level Environmental Specifications ENV0346

The survival conditions describe the environment that the antenna and all outside structures should be able to withstand without damage when placed in its least-vulnerable state. For the antenna, the designer will specify the orientation that will result in minimum stress to the structure at the maximum wind speed and maximum snow and ice loading. Systems housed within or on the antenna (including the environmental control system) shall assume this orientation.

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.

4.2.3 Solar Radiation

Parameter	Req. #	Value	Traceability
Solar Flux	EEC0360	All environmental control equipment exposed to outside environment shall be designed to allow normal operations given the condition: a maximum diurnal solar flux of 1200 W/m^2 from 0.3–60 µm.	020.10.15.10.00-0001-SPE ENV0561
UV Radiation	EEC0361	All environmental control equipment exposed to outside environment shall be designed to allow normal operations, over the full operating life of the array, given the condition: a maximum diurnal UV radiated flux of 100W/m^2 from 280–400 nm.	020.10.15.10.00-0001-SPE ENV0562

4.2.4 Rain/Water Infiltration

Parameter	Req. #	Value	Traceability
Rain/Water Infiltration	EEC0450	All environmental control exposed equipment shall be designed to withstand rainfall intensity up to 10 cm/hr., with droplets sized 0.5 to 4.5mm, at wind velocity of 18 m/s from the vertical to horizontal direction, while protecting any housed equipment.	020.10.15.10.00-0001-SPE ENV0571

4.2.5 Mechanical Shock

Parameter	Req. #	Value	Traceability
Transportation Environment	EEC0500	All environmental control equipment shall be designed to withstand typical loads and environments encountered during transportation as part of assembly or maintenance.	020.10.15.10.00-0001-SPE ENV0581
Mechanical Shocks	EEC0501	All environmental control equipment shall be designed to survive mechanical shock levels from handling as defined in Table 1 of AD06.	020.10.15.10.00-0001-SPE ENV0582

4.3 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Mean Time Between Failures	EEC0550	The Electronics Environmental Enclosures shall be designed to have a MTBF ≥ TBD hrs.	020.10.15.10.00-0003-REQ SYS2302

The maintenance and reliability requirements are in support of high-level requirements that limit the total operating cost of the array.

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. "Failure" will be defined as a condition which places the system outside of its performance specifications or into an unsafe state, requiring repair.

4.4 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Self-Monitoring	EEC0600	The Electronics Environmental Enclosures shall measure, report, and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures.	020.10.15.10.00-0003-REQ SYS2701

The expectation with self-monitoring is that the monitor and control system expose lower-level sensors to the monitor and control system when queried. The cadence of access is flexible, and is 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 Electronics Environmental Control System with a summary output on the interface.

Other features of the M&C interface are to be specified in the Monitor and Control ICD.

4.5 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	EEC0650	The Electronics Environmental Enclosures shall be designed to be operated and supported for a period of 20 years.	020.10.15.10.00-0003-REQ SYS2801
Lifecycle Optimization	EEC0651	The Electronics Environmental Enclosures design shall minimize its lifecycle cost for 20 years of operation.	020.10.15.10.00-0003-REQ SYS2802

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning.

5 Interface Requirements

This section provides information about the interfaces of the Antenna Electronics Environmental Control System. Interface Control Documents (ICDs) are required between the Antenna Electronics Environmental Control system 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 Electronics Environmental Control system designer, and approved by ngVLA, as part of the Antenna Electronics Environmental Control system reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

6 Subsystem Requirements

Derivation of any subsystem requirements will be included as part of the Antenna Electronics Environmental Control system conceptual design efforts, and updated throughout the design. Post CoDR, the subsystem requirements will only be updated through formal project change control processes.

7 Safety

7.1 General

7.2 Safety Design Requirements

7.2.1 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard.

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 while taking into account the altitude of up to 2500 m above sea level.

7.2.2 Handling, Transport, and Storage Safety

The design of the Antenna Electronics Environmental Control system shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation. A safety hazard analysis shall be completed prior to the system CoDR.

8 Requirements for Design

8.1 Analyses and Design Requirements

8.1.1 Reliability, Availability, Maintainability Analysis

A Reliability, Availability, Maintainability analysis shall be performed in order to locate weak design points and to 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 may be used, 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.

The ngVLA equipment will typically 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), the Mean Time To Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

8.2 Electromagnetic Compatibility Requirements

The ngVLA Antenna Electronics Environmental Control System elements shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).

8.3 Materials, Parts and Processes

8.3.1 Fasteners

All fasteners shall be metric where reasonably possible.

8.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

8.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

8.3.4 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 any Line Replaceable Units (LRUs; see Section 12.2), it is highly desirable that the serial number of the LRU be ascertainable over the monitor and control interface (see Section 4.4).

8.3.5 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled using a marking based on barcodes.

9 Documentation Requirements

9.1 Technical Documentation

All documentation related to the antenna electronics environmental control system shall meet the following requirements:

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use dual metric and imperial 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 CAD system used is AutoDesk Inventor and/or AutoCAD (discouraged).

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

9.2 Software and Software Documentation

The Antenna Electronics Environmental Control System 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 on-line 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. The following table summarizes the expected verification method for each requirement.

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
EEC0100	Front End Enclosure	X				
EEC0101	Front End Auxiliary Enclosure	X				
EEC0102	WVR Enclosure	X				
EEC0103	Front End Enclosure Thermal Regulation	X				
EEC0104	Front End Auxiliary Enclosure Thermal Regulation	X				
EEC0105	WVR Enclosure Thermal Regulation	X				
EEC0106	Compressor Enclosure Thermal Regulation	X				
EEC0107	Pedestal Room Rack Thermal Regulation	X				
EEC0152	Vibration	X				
EEC0153	Dust	X				
EEC0154	Rodents	X				
EEC0250	Solar Thermal Load		X			
EEC0251	Wind Speed	X				
EEC0252	Outdoor Temperature		X			
EEC0253	Outdoor Temperature Rate of Change		X			
EEC0254	Precipitation	X				
EEC0255	Cooling Temp Front End Enclosure		X			
EEC0256	Cooling Temp Front End Auxiliary Enclosure		X			
EEC0257	Cooling Temp-Compressor Platform		X			
EEC0258	Heat Exchanger Service Temperature		X		X	X

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
EEC0350	Wind	X				
EEC0351	Temperature	X				
EEC0352	Radial Ice	X	X			
EEC0354	Snow Load – Equipment		X			
EEC0355	Hail Stones		X			
EEC0360	Solar Flux		X			
EEC0361	UV Radiation		X			
EEC0450	Rain Infiltration				X	
EEC0500	Transportation Environment		X			
EEC0501	Mechanical Shocks		X			
EEC0550	Mean Time Between Failures		X			
EEC0600	Self-Monitoring			X		
EEC0650	Design Life	X				
EEC0651	Life Cycle Optimization		X			

Table 1 - 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 are parameters that have a large influence on the eventual effectiveness of the facility, and are useful high-level metrics for trade-off decisions.

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 Electronics Environmental Control System (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. #
Front End Receiver Enclosure Temp. Reg.	EEC0255
Heat Exchanger Service Temperature Reg.	EEC0258
Mean Time Between Failures	EEC0550

Table 2 - Key Performance Parameters for monitoring during design.

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CoDR	Conceptual Design Review
CFD	Computational Fluid Dynamics
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
EMP	Electro-Magnetic Pulse
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
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
SAC	Science Advisory Council
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

12.2 Maintenance Definitions

12.2.1 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 easiness of handling, etc.) by maintenance staff of technician level.

LRU exchange shall be possible by two trained people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the Electronics Environmental Enclosures.

A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

LRUs shall be defined by the Antenna Electronics Environmental Control System designer, depending on the design. The LRUs will be maintained by the ngVLA project (with or without industrial support).

12.2.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to keep the Antenna Electronics Environmental Control System operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

Antenna Electronics Environmental Control System Reference Design Description

020.30.60.00.00-0002-DSN-A-ENVIR_CONTROL_REF_DESIGN

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
D. Gerrard, S. Sturgis, and J. Allison	Electronics Div., NRAO	2018-11-12
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	2019-05-04

APPROVALS (Name and Signature)	**ORGANIZATION**	**DATE**
R. Selina, Project Engineer — R. Selina 2019.07.23 12:40:36 -06'00'	Electronics Div., NRAO	2019-07-23
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.23 14:02:11 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-23

RELEASED BY (Name and Signature)	**ORGANIZATION**	**DATE**
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.23 14:02:27 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-23

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-05-22	J. Allison	1-4	Initial Draft
02	2018-07-10	J. Allison	5	Added design descriptions
03	2018-07-12	S. Sturgis	All	Updated and revised all sections
04	2018-09-21	S. Sturgis	All	Updates throughout to better reflect the current design
05	2018-09-21	S. Durand	All	Small Edits
06	2018-10-09	J. Allison	4, 5	Addressed RID numbers: IPDSR-10, IPDSR-11, IPDSR-12, IPDSR-15, IPDSR-16
07	2018-10-10	J. Allison	4, 5	Addressed RID numbers: IPDSR-14, IPDSR-17
08	2018-10-23	J. Allison	4	Addressed RID number IPDSR-13
09	2018-10-26	J. Allison	5	Addressed RID number IPDSR-1
10	2018-11-07	J. Allison	5	Updated information pertaining to Cryogenics M&C module
11	2018-11-09	J. Allison	5	Replaced text explaining temperature control requirements with a table, added reference documents
12	2018-11-12	S. Sturgis	All	Small edits and clarifications
13	2019-05-30	R. Selina	2, 4.2	Minor edits for release.
A	2019-07-23	A. Lear	All	Prepared PDF for approvals and release

Table of Contents

1 Introduction 4
1.1 Purpose 4
1.2 Scope 4
2 Related Documents and Drawings 4
2.1 Applicable Documents 4
2.2 Reference Documents 4
3 Antenna Electronics Environmental Control System Overview 5
4 Antenna Electronics Environmental Control System Design 6
4.1 Temperature Control Components 7
4.1.1 Liquid Loop Chiller 7
4.1.2 Liquid Loop Heater 7
4.1.3 Liquid Hot/Cold Plate 8
4.1.4 Air Handler 8
4.1.5 Receiver Enclosure Heater 8
4.2 Hazard Control Components 8
4.2.1 Front End Receiver Enclosure 8
4.2.2 Front End Auxiliary Enclosure 9
4.2.3 WVR Enclosure 10
4.2.4 Compressor Platform/Enclosure 10
4.2.5 Pedestal Room Rack 10
4.3 Interfaces with Other Subsystems 11
5 Appendix 12
5.1 Acronyms and Abbreviations 12

1 Introduction

1.1 Purpose

This document provides a description for the Antenna Electronics Environmental Control system reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the Antenna Electronics Environmental Control system, as part of the ngVLA Reference Design. It includes the system's design, how it functions, and interfaces with the necessary hardware and software systems.

It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	V1.0, 3/30/2017
AD02	ngVLA Environmental Specifications	020.10.15.10.00-0001-SPE
AD03	ngVLA Antenna Electronics Environmental Control System: Preliminary Technical Requirements	020.30.60.00.00-0001-REQ

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	ngVLA Cryogenic Subsystem Requirements	020.30.10.00.00.0001-REQ
RD02	ngVLA Integrated Receivers and Downconverters: Preliminary Technical Specifications/Requirements	020.30.15.00.00-0001-REQ
RD03	ngVLA Water Vapor Radiometer Preliminary Technical Requirements	020.45.00.00.00-0001-REQ

3 Antenna Electronics Environmental Control System Overview

The antenna electronics are located in various places around the antenna. Primary locations include but are not limited to the electronics rack in the pedestal room, the Receiver and Auxiliary Enclosures on the feed arm, the WVR enclosure near the base of the feed arm, and the compressor platform/enclosure at the top rear of the pedestal. Environmental control of the antenna electronics consists of temperature control of all the electronics in these locations as well as protection from water, dust, animals, or other environmental hazards.

There are two temperature control systems for the antenna electronics: a hot/cold liquid loop above the azimuth axis and a traditional air-cooling unit in the pedestal room. The first consists of a hot/cold liquid loop, most likely glycol, which runs from a chiller unit at the top-rear of the pedestal to the WVR Enclosure, and the front end Receiver and Auxiliary Enclosures. At each location a local liquid hot/cold plate that consists of copper tubing running through an aluminum block, which components may be directly mounted to, will cool components in both the front end enclosures and the WVR enclosure, as well as on the compressor platform/enclosure.

The pedestal room electronics rack will be forced-air-cooled via a local air handler unit to force cold air through the rack from bottom to top. This system will likely be closed loop so that it does not have to cool the entire pedestal room.

Protection from water, dust, animals, or other environmental hazards will be provided by custom designed Front End Receiver, Auxiliary, WVR, and compressor platform enclosures as necessary, and an electronics rack in the pedestal room.

4 Antenna Electronics Environmental Control System Design

There are three main parts to the Antenna Electronics Environmental Control system: the hot/cold liquid loop, the cold air blower, and the environmental enclosures. The hot/cold liquid loop was chosen because it is much easier to move heat around the antenna via a dense liquid than it is via air.

The cold air blower was chosen because the modules in the electronics rack require air-cooling, and it was undesirable to run a cold liquid line through the azimuth wrap/axis.

The temperature regulation requirements are tabulated by component and location below:

Location	Component	Operational Temp Range [C]	Temp Grad [C/hr]	Heat Dissipation [W]
FE Receiver Enclosure	IRD Module	–15 to 35 [RD02]	3.6 [RD02]	115
	P501 Module	N/A	N/A	195
FE Auxiliary Enclosure	Vacuum Pump	12 to 45 [RD01]	N/A	TBD
Compressor Platform	Helium Compressor	–30 to 45 [RD01]	N/A	TBD
	Cryo M&C Cold Plate	TBD	N/A	200
	Glycol Chiller	TBD	N/A	TBD
	Cryo M&C Module	TBD	N/A	TBD
WVR Receiver Enclosure	Component Cold Plate	>28	0.02	20 [RD03]
	P502 Module	N/A	N/A	145
Back End Rack	D501 Module	N/A	N/A	TBD
	F518 Module	N/A	N/A	100
	M500 Module	N/A	N/A	75
	M501 Module	N/A	N/A	75
	P500 Module	N/A	N/A	165
	P503 Module	N/A	N/A	145

These are preliminary numbers which will likely change during the development of the conceptual design

4.1 Temperature Control Components

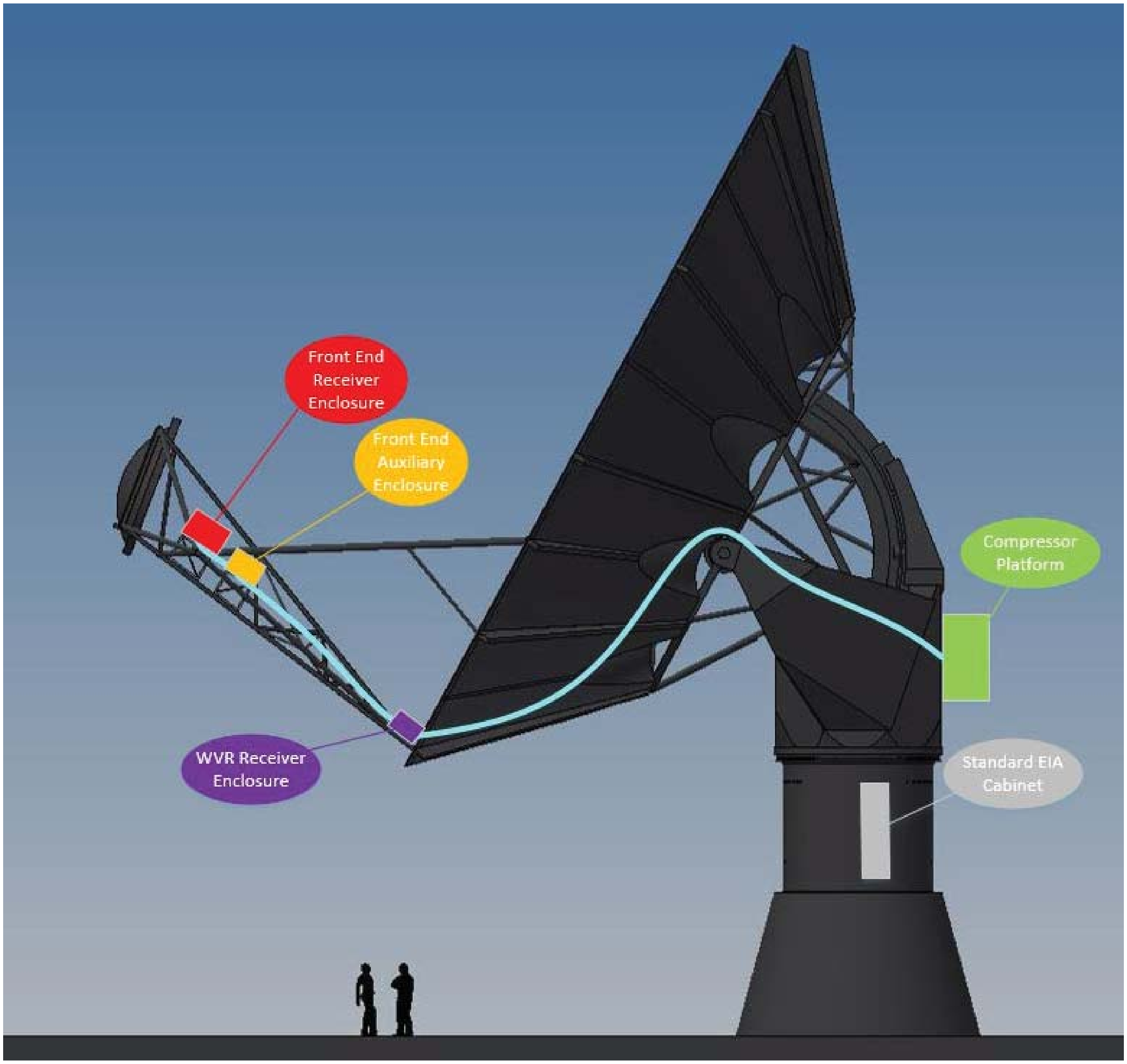


Figure 1 - Locations of antenna electronics environmental control system components.

4.1.1 Liquid Loop Chiller

There will be an air-cooled chiller unit to cool the liquid (glycol) located on the compressor platform/enclosure. The chiller shall be capable of delivering +/-1 degree C glycol to all required components.

4.1.2 Liquid Loop Heater

The glycol chiller shall be capable of both cooling and heating of the glycol.

4.1.3 Liquid Hot/Cold Plate

There will be multiple liquid hot/cold plates located in the front end receiver enclosure to cool the IRD enclosure, the P501 Module, and the general environment of the enclosure as well as any other components that may require cooling. The IRD module in the receiver enclosure will require a high level of precise temperature control (0.1°C/20min), which is more precise than the chiller can provide. The higher precision will be achieved with locally located thermoelectric modules.

There will be a liquid hot/cold plate in the WVR receiver enclosure. The temperature control in the WVR enclosure will require a high level of precise temperature control (0.05°C/hour), which is more precise than the chiller can provide. The higher precision will be achieved with locally located thermoelectric modules.

There will be multiple liquid hot/cold plates located in the auxiliary front end enclosure for cooling components, the full list of which is TBD. The temperature control in the auxiliary enclosure will only require an average level of temperature control (+/-1°C/hour) and will be achieved with the chilled glycol.

There will be a liquid hot/cold plate on the compressor platform for heating or cooling the M&C module. The temperature control for the Cryo M&C module will only require an average level of temperature control (+/-1°C/hour) and will be achieved with the chilled glycol.

4.1.4 Air Handler

There will be an air handler unit located in the pedestal room to force air through the electronics rack. This is anticipated to be a closed loop system so that the air handler does not cool the entire pedestal room but only the electronics rack and any associated equipment. Furthermore, the air handler's heat exchanger may require venting to outside of the pedestal room, depending on how well the room is sealed/insulated. The pedestal room electronics rack will only require an average level of temperature control (+/-1°C/hour).

4.1.5 Receiver Enclosure Heater

To combat condensation on the front of the receiver windows, there will be heaters located on the front of the environmental receiver enclosure in such a way as to not interfere with the receivers operation.

4.2 Hazard Control Components

4.2.1 Front End Receiver Enclosure

The front end electronics located on the feed arm of the antenna will be housed in environmentally sealed enclosures to protect them from water and debris. The Receiver Enclosure will house Dewars A & B, the IRD Enclosure, the P501 Module, and the M&C for both Dewars and will be made up of a welded aluminum frame with removable panels on all sides so that the housed components may be easily accessed for maintenance.

The removable panels will have lockable push-to-close latches and will be located on all sides of the enclosure except for the bottom and the side facing the secondary reflector. The enclosure will have one fixed plate on the rear side where permanent connections to other systems will be located. This will help minimize external connectors and simplify the installation and removal of housed +. The removable panels will be made of an aluminum composite panel, with thin sheets of aluminum on either side of corrugated plastic. Their edges will be lined with aluminum U-channels which will stiffen the entire panel. Each panel will also have a layer of insulation on the inside to maintain temperature inside of the enclosure. The frames will have environmental seals where all removable panels are installed to protect the components from water, dust, and debris. This enclosure is designed to only protect from environmental hazards. All housed components requiring RFI shielding will have their own RFI tight packaging inside of this enclosure.

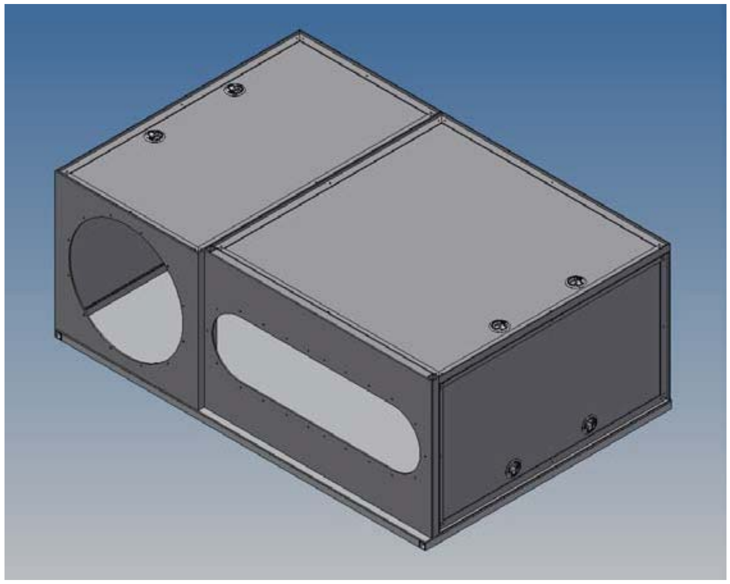


Figure 2 - Front End receiver enclosure.

4.2.2 Front End Auxiliary Enclosure

The Auxiliary Enclosure will be located on the feed arm near to the Receiver Enclosure and will be based on the same design as the Receiver enclosure.

The Auxiliary Enclosure will house any equipment the receivers need to function that doesn't need to be co-located with the receivers. Having this enclosure allows us to minimize the amount of mass being shifted around at the end of the antenna arm.

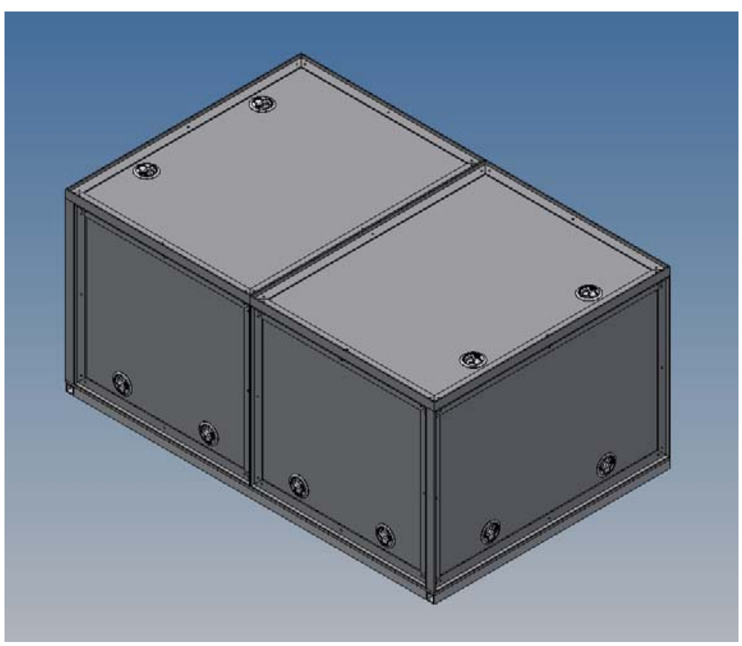


Figure 3 - Front End auxiliary enclosure.

4.2.3 WVR Enclosure

The WVR Enclosure will likely be a welded box located somewhere along the edge of the antenna's main reflector, possibly near to the base of the feed arm. The exact location is still to be determined, based on physical interference between surrounding antennas and signal interference from the structure of the host antenna.

4.2.4 Compressor Platform/Enclosure

The Compressor Platform/Enclosure is located near the top rear of the pedestal and holds the cryogenic helium compressor, the liquid glycol chiller and heater, and an RFI-tight cryogenics M&C module. Depending on the helium compressor's environmental requirements, this may be more of a vented enclosure than an open platform. If built as an enclosure it will be similar in design to the Front End Auxiliary Enclosure.

4.2.5 Pedestal Room Rack

The Pedestal room rack (provide by the Bins, Modules & Racks work package) will be located in the pedestal room and will house all of the modules for the Antenna Electronics that are not housed in the front end, WVR, or compressor enclosure. The current plan is to use a single 19inch rack, but depending on the size of the pedestal room and the number of modules housed this may be expanded to two smaller racks. Smaller racks may be shorter, shallower or both. The standard sized rack is the preferred option. The modules inside of the rack will be cooled using a closed loop forced air system (provided as part of this Antenna Electronics Environmental Control work package) with the air entering the bottom of the rack, being directed past the heatsinks on the modules, and then being recirculated out of the top of the rack and back to the air handler unit.

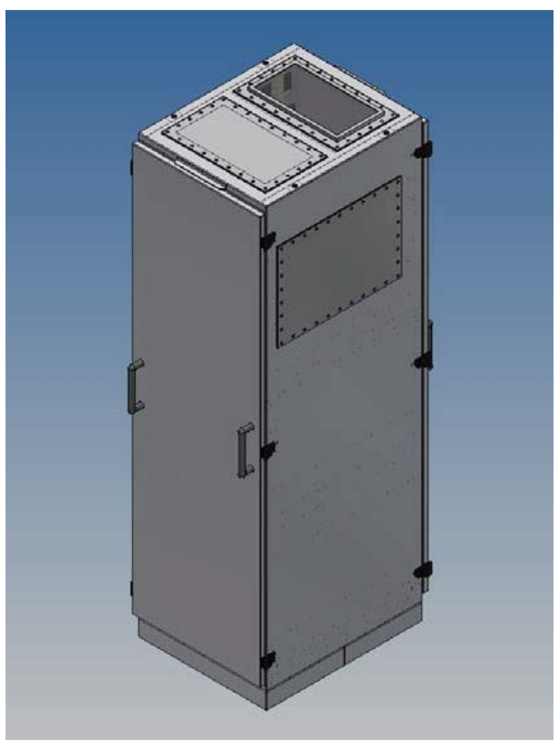


Figure 3 - Pedestal room rack.

4.3 Interfaces with Other Subsystems

The Environmental Control system will have interfaces as follows:

- Pedestal room
  - ICD between air handler and electronics rack
  - ICD between air handler and antenna
- Compressor platform/enclosure
  - ICD between enclosure and antenna
  - ICD between enclosure and cryogenic compressor
  - ICD between enclosure and glycol chiller
- WVR
  - ICD between environmental enclosure and antenna
  - ICD between environmental control system and WVR subsystem
- Auxiliary front end enclosure
  - ICD between auxiliary front end enclosure and antenna
  - ICD between auxiliary front end enclosure and TBD equipment housed within it
- Receiver Front end enclosure
  - ICD between receiver front end enclosure and antenna
  - ICD between receiver front end enclosure and Dewar A LRU
  - ICD between receiver front end enclosure and Dewar B LRU
  - ICD between receiver front end enclosure and P501 Module
  - ICD between receiver front end enclosure and TBD equipment housed within it

5 Appendix

5.1 Acronyms and Abbreviations

Acronym	Description
AD	Applicable Document
DBE	Digital Back End
DTS	Data Transmission System
IF	Intermediate Frequency
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
PLL	Phase Locked Loop
RD	Reference Document
RF	Radio Frequency
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

Independent Phase Calibration System: Preliminary Requirements

020.45.00.00.00-0001-REQ-A-INDEP_PHASE_CALIBRATION_PRELIM_REQS

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
A. Erickson	Electronics Div., NRAO	04-30-2019
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	05-04-2019

APPROVALS (Name and Signature)	ORGANIZATION	DATE
R. Selina, Project Engineer — R. Selina 2019.07.26 13:26:22 -06'00'	Electronics Div., NRAO	2019-07-26
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.26 19:12:26 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-26

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director — Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.26 19:12:43 -06'00'	Asst. Director, NM-Operations, NRAO	2019-07-26

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-09-27	Erickson	All	Final 01
02	2018-12-20	Erickson	All	Address RIDs
03	2019-04-30	Erickson	All	Final review
04	2019-05-30	Selina	2.1, 4, 11	Minor edits for release. Updated traceability.
A	2019-07-26	Lear	All	Prepared PDF for signatures and release

Table of Contents

1 Introduction ... 5
1.1 Purpose ... 5
1.2 Scope ... 5
2 Related Documents and Drawings ... 5
2.1 Applicable Documents ... 5
2.2 Reference Documents ... 6
3 Overview of the Independent Phase Calibration System Technical Requirements ... 7
3.1 Document Outline ... 7
3.2 Project Background ... 7
3.3 General Description ... 8
3.4 Summary of WVR System Requirements ... 8
3.4.1 General Technical Requirements ... 8
3.4.2 Other General Requirements ... 9
4 Functional and Performance Requirements ... 11
4.1 Performance Requirements ... 11
4.2 Spurious Signals/Radio Frequency Interference Generation ... 11
4.3 Environmental Conditions ... 11
4.4 Maintenance and Reliability Requirements ... 11
4.5 Monitor and Control Requirements ... 12
4.6 Lifecycle Requirements ... 12
5 Interface Requirements ... 13
5.1 Interface to the Antenna Liquid Cooling System ... 13
5.2 Interface to the Monitor and Control Network ... 13
5.3 Interface to the Antenna Mechanical Structure ... 13
5.4 Interface to the Pedestal Room Rack Cooling System ... 13
5.5 Interface to the Pedestal Room Rack Power System ... 13
6 Subsystem Requirements ... 14
7 Safety ... 14
7.1 Mechanical Safety ... 14
7.2 Electrical Safety ... 14
7.3 Handling, Transport, and Storage Safety ... 14
8 Requirements for Design ... 15
8.1 Analyses and Design Requirements ... 15
8.1.1 Reliability Availability Maintainability Analysis ... 15
8.2 Electromagnetic Compatibility Requirements ... 15
8.3 Materials, Parts, and Processes ... 15
8.3.1 Fasteners ... 15
8.3.2 Paints ... 15
8.3.3 Surface Treatment ... 15
8.3.4 Name Plates and Product Marking ... 15
8.3.5 Labels ... 16
9 Documentation Requirements ... 16
9.1 Technical Documentation ... 16
9.2 Software and Software Documentation ... 16

10 Verification and Quality Assurance 17
11 Key Performance Parameters 18
12 Appendix 19
12.1 Abbreviations and Acronyms 19
12.2 Maintenance Definitions 20
12.2.1 Maintenance Approach 20
12.2.2 Periodic Preventive Maintenance 20

1 Introduction

1.1 Purpose

This document aims to present a set of technical requirements for the reference design of the ngVLA Independent Phase Calibration system.

Many requirements flow down from the preliminary ngVLA System Requirements [AD02], which in turn flow-down from the preliminary ngVLA Science Requirements [AD01].

The Science goals 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 represents a preliminary analysis of these use cases, and the flow down recursively to the science, system and subsystem requirements.

1.2 Scope

The scope of this document is the ngVLA Independent Phase Calibration system. It includes interface requirements that must be defined.

This requirements document establishes the performance, functional, design, and test requirements applicable to the ngVLA Independent Phase Calibration system.

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 this Technical Specification shall be considered as a superseding requirement.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Protection Against Electric Shock—Common Aspects for Installation and Equipment	IEC 61140:2016
AD07	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD08	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
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	Monitor & Control Hardware Interface Layer: Preliminary Requirements	020.30.45.00.00-0002-REQ

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	Fast Switching Calibration at the ngVLA Site	ngVLA Memo No. 1
RD02	Calibration Strategies for the ngVLA	ngVLA Memo No. 2
RD03	The Concept of a Reference Array for the ngVLA	ngVLA Memo No. 4
RD04	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10
RD05	Results of Water Vapor Radiometry Tests at the VLA	EVLA Memo No. 73
RD06	A Study of the Compact Water Vapor Radiometer for Phase Calibration of the Karl G. Jansky Very Large Array	EVLA Memo No. 203

3 Overview of the Independent Phase Calibration System Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA Independent Phase Calibration system. These parameters determine this system's overall form and performance.

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 Independent Phase Calibration system 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 Independent Phase Calibration system 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, 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 facility will operate as a proposal-driven instrument with Principal Investigator (PI)-led proposals determining the science program. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher-level data products (typically image cubes). Data and quality assured data products will be available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

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.

Array operations will be conducted from both the VLA site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a metropolitan area and will serve as the base for science operations and support staff, software operations, and related administration. Research and development activities will be split among these centers as appropriate.

3.3 General Description

The independent phase calibration system consists of a water vapor radiometer (WVR) that measures atmospheric water vapor concentration in the antenna main beam. This data can be used to provide continuous phase calibration between calibrator source measurements.

The WVR has its own antenna: a fixed dish one meter in diameter mounted below the main dish. A WVR receiver module sits at the offset Gregorian focus of this antenna, and receives, amplifies, downconverts, and digitizes a band from 18–30 GHz. The receiver is temperature stabilized by a thermally regulated plate on which the electronics are mounted. The whole unit is thermally stabilized by the antenna liquid cooling system with a Peltier thermoelectric device for fine temperature regulation. Power is delivered to the receiver module and to a feed heater located in front of the module from the –48V antenna power supply via a junction box near the receiver module.

Digitized data is sent over dedicated fiber to a high-speed FPGA-based processing module in the pedestal room electronics rack. The low-speed processed data is injected onto the antenna monitor and control data stream for inclusion in the science data package. The processing module is powered and cooled by standard rack power and cooling air.

3.4 Summary of WVR System Requirements

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

3.4.1 General Technical Requirements

Parameter	Summary of Requirement	Reference Reqs.
Precipitable water vapor relative measurement	35μm	WVR0001
Measurement interval	≤1s	WVR0002
Beam diameter	≤18m at 2km	WVR0003
Pointing offset from main beam	≤0.7deg	WVR0004
Digitized bandwidth	18–26GHz	WVR0005
Receiver temperature stability	≤2.5mK over 20 minutes	WVR0006
Receiver components temperature	30C +/– 2C	WVR0007
Channel count (minimum)	32	WVR0008

- **Precipitable water vapor relative measurement**: See VLA Memo 203 [RD06] for derivation.
- **Measurement interval**: Expected wind speeds at the altitude at which most precipitable water vapor (PWV) is expected from the relationship between WVR spacing and frequency of measurement. For 100m WVR antenna spacing, 10m/s wind speeds imply a 10s integration time. A factor of ten is incorporated to allow averaging and to give buffer room for faster wind speeds.
- **Beam diameter**: The WVR beam should sample the main beam at all altitudes where PWVR is present, but must sample the main beam accurately where the primary region of turbulent PWVR is known to exist at 2km above ground level (AGL).

- **Pointing offset from main beam**: As above, the WVR beam must sample the main beam. The pointing offset limits the beam offset to a reasonable amount at 2km AGL.
- **Digitized bandwidth**: The broad water vapor spectral line centered near 22GHz must be sampled entirely. Additionally, one must separate it from the superimposed liquid water emission and the O_2 line emission.
- **Receiver temperature stability**: The PWVR measurement forces a very tight gain stability specification, which in turn requires that the components be held to a very tight temperature range.
- **Receiver components temperature**: The absolute temperature of the components—more specifically, the connecting wires—is chosen to minimize the effects on the RF signal from thermally-induced changes in the properties of Teflon and related insulation materials.
- **Channel count**: High channel count allows excision of expected RFI to be performed without significantly impacting measurement accuracy.

3.4.2 Other General Requirements

Parameter	**Req. #**	**Summary of Requirement**	**Reference Reqs.**
Design Life	WVR1001	Design for an expected operational life no less than 20 years, excluding the batteries	SYS2701
Maintenance Interval	WVR1002	Preventive maintenance interval of no shorter than 2 years, with a goal of 4 years.	SYS2401
Mean Time Between Failures (MTBF)	WVR1003	Antenna electronics has MTBF of 35,040 hours each.	SYS2402
Modularization	WVR1004	Line Replaceable Units (LRU) to facilitate site maintenance	SYS2403
Altitude Range	WVR1005	Sea level to 2500 meters	ENV0351
Lightning Protection	WVR1006	Protect against Lightning Electromagnetic Impulse	ENV0512
Equipment Protection Against Dust	WVR1007	Exposed equipment shall be protected against windblown dust, ashes, and grit	ENV0541
Rodent Protection	WVR1008	Exposed equipment shall be designed to prevent rodent damage	ENV0551
Transportation Environment	WVR1009	Designed to withstand typical loads and environments encountered during transportation	ENV0581
Mechanical Shock	WVR1010	Designed to survive mechanical shock levels	ENV0582
Equipment Shielding	WVR1011	All equipment shall be shielded and have it AC power line and communication lines filtered at the chassis	ENC0327
EMC Test Frequencies	WVR1012	RFI suppression shall extend from 50 MHz to 12 GHz	EMC0328
Hazzard Analysis	WVR1013	Hazard analysis shall be performed for all high-power systems. Include lock-outs for service by technicians	SYS2703

Parameter	Req. #	Summary of Requirement	Reference Reqs.
Precision Operation Temperature Conditions	WVR1014	–15°C ≤ T ≤ 25° C	ENV0313
Precision Operation Temperature Rate of Change Conditions	WVR1015	1.8°C/Hour	ENV0314
Limits to Operating Conditions	WVR1016	–20°C ≤ T ≤ 45°C	ENV0332
Survival Temperature Conditions	WVR1017	–30°C ≤ T ≤ 50°C	ENV0342
Storage Requirements	WVR1018	–65°C ≤ T ≤ 125°C	

4 Functional and Performance Requirements

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

4.1 Performance Requirements

Parameter	Req. #	Summary of Requirement	Traceability
System temperature (T_{sys})	WVR0009	300 K	SYS1504
T_{sys} measurement accuracy	WVR0010	20 mK	SYS1504
T_{sys} drift over 1 minute	WVR0011	5 K	SYS1504
T_{cal}/T_{sys}	WVR0012	10 %	SYS1504
Gain drift with temperature	WVR0013	0.66 %/C	SYS1504

- **T_{sys}**: The WVR is non-cryogenic; ambient T_{sys} allows WVR data recovery.
- **T_{sys} measurement accuracy**: Calibration requires accurate measurement of T_{sys}.
- **T_{sys} 1-minute drift**: Between calibrator fixes, T_{sys} must be held to close tolerance to allow accurate measurement of changes in PWVR signal.
- **T_{cal}/T_{sys}**: Lab calibration must be maintained at or below a fixed fraction of T_{sys}.
- **Gain drift with temperature**: Highly accurate temperature control of amplifiers reduces variations in amplitude with temperature. As temperature variation can never be reduced to zero, amplifiers must meet a requirement for gain drift with temperature to maintain adequate SNR.

4.2 Spurious Signals/Radio Frequency Interference Generation

Processor, receiver, and other WVR-specific modules shall be verified to comply with ngVLA RFI emissions standards as specified in 020.10.15.10.00-0002-REQ.

4.3 Environmental Conditions

The WVR receiver component must meet both Normal and Precision Environmental conditions as defined in 020.10.15.10.00-0001-SPE.

4.4 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Mean Time Between Failures	WVR0101	MTBF ≥ 2000 hrs.	SYS2302

The maintenance and reliability requirements are in support of high-level requirements that limit the total operating cost of the array.

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. “Failure” will be defined as a condition which places the system outside of its performance specifications or into an unsafe state, requiring repair.

4.5 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Self-Monitoring	WVR0201	The Independent Phase Calibration system 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

All WVR modules will provide monitor points per the ngVLA Monitor and Control protocol [AD13] at the necessary intervals. Control points will be documented and tested to comply with the ngVLA Monitor and Control protocol.

4.6 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	WVR0301	The Independent Phase Calibration system shall be designed to be operated and supported for a period of 20 years.	SYS2801
Lifecycle Optimization	WVR0302	The Independent Phase Calibration system design shall minimize its lifecycle cost for 20 years of operation.	SYS2802

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning.

5 Interface Requirements

This section provides information about the interfaces of the Independent Phase Calibration system. Interface Control Documents (ICDs) are required between the Independent Phase Calibration system 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 Independent Phase Calibration system Designer, and approved by ngVLA, as part of the Independent Phase Calibration system reference and conceptual design efforts, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Antenna Liquid Cooling System

The Receiver Cooling Plate shall interface with the antenna liquid cooling system via standard fittings as specified by the ALC specification. Protection to the liquid cooling lines shall be applied per the same specification.

5.2 Interface to the Monitor and Control Network

Interface to the Monitor and Control system shall be per the ngVLA M&C specification for each WVR component. It should be noted that WVR output data will also be transmitted on the M&C network as a standard monitor point.

5.3 Interface to the Antenna Mechanical Structure

Mechanical connection of the WVR components to the antenna structure shall be evaluated under the auspices of antenna designers and engineers to ensure that safety and performance specifications are met for both the mounted module and the structure to which it is attached. Preventive maintenance and inspection items shall be specified for each mounting structure.

5.4 Interface to the Pedestal Room Rack Cooling System

WVR processor module cooling requirements shall be compatible with pedestal room rack cooling systems.

5.5 Interface to the Pedestal Room Rack Power System

WVR processor module power requirements shall be compatible with pedestal rack power systems.

6 Subsystem Requirements

Derivation of any subsystem requirements shall be included as part of the Independent Phase Calibration system reference and conceptual design efforts, and updated throughout the design. Post CDR/FDR, the Subsystem requirements shall only be updated through formal project change control processes, which will include the designer, manufacturer, and NRAO.

7 Safety

7.1 Mechanical Safety

Mechanical safety assessment will be based on a Safety Hazard Analysis.

7.2 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard.

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 [AD07] while taking into account the altitude of up to 2500 m above sea level.

7.3 Handling, Transport, and Storage Safety

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

8 Requirements for Design

8.1 Analyses and Design Requirements

8.1.1 Reliability Availability Maintainability Analysis

A Reliability, Availability Maintainability analysis shall be performed in order to locate weak design points and to 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] may be used, 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.

The ngVLA equipment will typically 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), the Mean Time To Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

8.2 Electromagnetic Compatibility Requirements

The ngVLA Independent Phase Calibration system element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility). See EMC specification EMC0328.

8.3 Materials, Parts, and Processes

8.3.1 Fasteners

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

8.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

8.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

8.3.4 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 (LRU, see Section 12.2), it is highly desirable that the serial number of the LRU be ascertainable over the Monitor and Control interface (see Section 5.2).

8.3.5 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled using a system of marking based on barcodes.

9 Documentation Requirements

9.1 Technical Documentation

All documentation related to the Independent Phase Calibration system 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 CAD system used is AutoDesk Inventor and/or AutoCAD.

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

9.2 Software and Software Documentation

The Independent Phase Calibration system 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 on-line 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.

The following table summarizes the expected verification method for each requirement.

Req. #	Parameter/Requirement	D	A	I	FAT	SAT
WVR001	Precipitable water vapor relative measurement		X			X
WVR002	Measurement interval			X	X	
WVR003	Beam diameter		X			X
WVR004	Pointing offset from main beam					X
WVR005	Digitized bandwidth		X	X	X	
WVR006	Receiver temperature stability		X		X	X
WVR007	Receiver components temperature		X		X	X
WVR008	Channel count	X		X		
WVR009	System temperature (T_{sys})		X		X	X
WVR010	T_{sys} measurement accuracy		X		X	X
WVR011	T_{sys} drift over 1 minute		X		X	X
WVR012	T_{cal}/T_{sys}		X		X	
WVR013	Gain drift with temperature		X		X	

Table 1 - 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 are parameters that 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.

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 Independent Phase Calibration system (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. #
Precipitable water vapor relative measurement	WVR001
Pointing offset from main beam	WVR004
Receiver temperature stability	WVR006

Table 2 - Key Performance Parameters for monitoring during design.

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
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 & 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

12.2 Maintenance Definitions

12.2.1 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 two trained people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the Independent Phase Calibration system.

A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

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

12.2.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to keep the Independent Phase Calibration system operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

Water Vapor Radiometer Design Description

020.45.00.00.00-0002-DSN-A-WATER_VAPOR_RADIOMETER_DSN_DESCR

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
A. Erickson	Electronics Div., NRAO	04-30-2019
S. Durand, Antenna Electronics IPT Lead	Electronics Div., NRAO	05-02-2019

APPROVALS	ORGANIZATION	DATE
R. Selina, Project Engineer R. Selina 2019.07.26 13:25:49 -06'00'	Electronics Division, NRAO	2019-07-26
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.26 19:14:56 -06'00'	Asst. Director, NM-Ops, NRAO	2019-07-26

RELEASED BY (Name and Signature)	ORGANIZATION	DATE
M. McKinnon, Project Director Mark McKinnon Digitally signed by Mark McKinnon Date: 2019.07.26 19:15:14 -06'00'	Asst. Director, NM-Ops, NRAO	2019-07-26

Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	2018-02-12	Ford	All	Initial draft, feedback on Section 3 & 4
0.2	2018-05-01	Erickson	All	Content
1.0	2018-09-26	Erickson	All	Final
2.0	2019-04-30	Erickson	All	Minor revisions to prepare for IPT Lead review
3.0	2019-05-31	Selina	3.1, 3.3	Minor edits for release.
A	2019-07-26	Lear	All	Prepared PDF for signatures and release

Table of Contents

1 Introduction ... 4
1.1 Purpose ... 4
1.2 Scope ... 4
2 Related Documents and Drawings ... 4
2.1 Applicable Documents ... 4
2.2 Reference Documents ... 4
3 Subsystem Overview ... 5
3.1 Motivation ... 5
3.2 Operation ... 5
3.3 Construction ... 5
4 Subsystem Design ... 7
4.1 Subsystem Block Diagram ... 7
4.2 Subsystem Components ... 7
4.2.1 Antenna ... 7
4.2.2 Receiver Module ... 8
4.2.3 WVR Junction Box ... 9
4.2.4 Alignment Wedge ... 9
4.2.5 Cooling Plate ... 9
4.2.6 Feed ... 10
4.2.7 Feed Heater ... 10
4.2.8 Front End ... 10
4.2.9 Integrated Receiver/Digitizer ... 10
4.2.10 Monitor and Control ... 10
4.2.11 Thermal Stabilizer ... 10
4.2.12 Processing Module ... 11
4.2.13 Firmware ... 11
4.3 WVR Locations ... 11
4.4 Interfaces with other Subsystems ... 11
4.4.1 Antenna Feed Arm Truss ... 11
4.4.2 Antenna Liquid Cooling ... 11
4.4.3 Antenna Air Cooling ... 11
4.4.4 Local Oscillator ... 11
4.4.5 Time ... 11
4.4.6 Monitor and Control ... 12
4.4.7 Power ... 12
5 Appendix ... 13
5.1 Abbreviations and Acronyms ... 13

1 Introduction

1.1 Purpose

This document provides a description for the Water Vapor Radiometer (WVR) subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the WVR Subsystem, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev / Doc. No.
AD00	ngVLA WVR Subsystem Preliminary Requirements	020.45.00.00.00-0001-REQ
AD01	Fast Switching Calibration at the ngVLA Site	ngVLA Memo No. 1
AD02	Calibration Strategies for the ngVLA	ngVLA Memo No. 2
AD03	The Concept of A Reference Array for the ngVLA	ngVLA Memo No. 4
AD04	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10
AD05	Results of Water Vapor Radiometry Tests at the VLA	EVLA Memo No. 73
AD06	A Study of the Compact Water Vapor Radiometer for Phase Calibration of the Karl G. Jansky Very Large Array	EVLA Memo No. 203

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev / Doc. No.
RD01	Fast Switching Calibration at the ngVLA Site	ngVLA Memo No. 1

3 Subsystem Overview

3.1 Motivation

Relative phase across a pair of antennas (a baseline) is a key measurable of synthesis arrays. Noise in this signal is contributed by the electronics and by the atmosphere. Water vapor is the largest contributor to atmospheric phase noise. One way to reduce the influence of atmospheric phase noise is to slew all antennas to a calibrator source periodically throughout a science observation in order to calculate the atmospheric phase noise contribution so that it may be subtracted from the science data. This is called fast switching, as the switching interval is much smaller than the science observation.

For a given period in which science may be performed, fast switching reduces the available time-on-sky for the science data by the time necessary to slew to calibrator, observe the calibrator, and slew back to science. Worse, the switching interval decreases as observation frequency increases and also as atmospheric stability decreases. At the highest ngVLA observation frequencies and under normal atmospheric conditions, switching would occur at 30-second intervals [RD01].

It is the goal of the WVR to allow a dramatic increase in this switching interval, as well as reduce any residual atmospheric phase perturbations that corrupt the astronomical data between calibrator observations.

3.2 Operation

The WVR constantly observes an atmospheric water vapor emission line centered at 22 GHz in order to track changes in the column density of water vapor in the WVR beam. Before the observation, a calibrator is observed (as in switching) to establish an absolute phase offset between antennas and WVR-estimated column density is noted. By monitoring changes in the water vapor column density throughout an observation, estimates of change in phase can be applied to the science data. Periodically—but with a much larger interval than that of fast switching—the calibrator can be re-observed to re-establish absolute phase offset.

3.3 Construction

The WVR consists of a 1.2-meter antenna mounted to the main feed arm as shown in Figure 1 and Figure 2, in which the WVR dish is colored red.

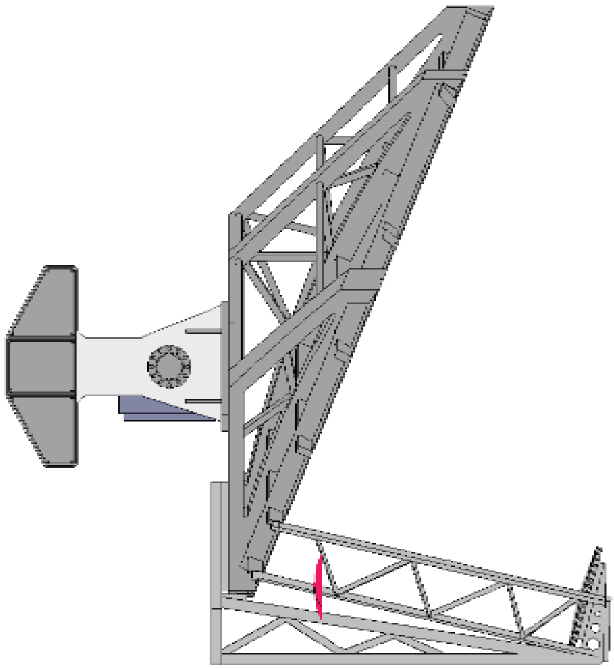


Figure 1 - Main and WVR dishes, side view. Antenna design shown is diagrammatic only.

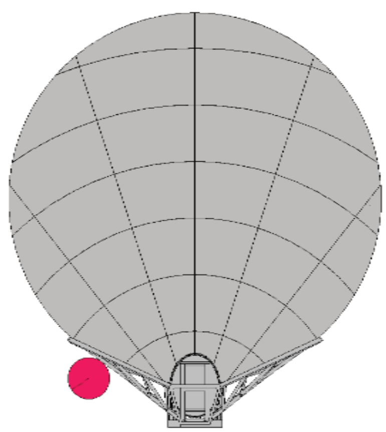


Figure 2 - Main and WVR dishes, front view. Antenna design shown is diagrammatic only.

The fixed WVR beam is aligned parallel to the main antenna beam. The WVR antenna architecture is Offset Prime Focus. The feed, receivers, digitizers, and support electronics are located in a module mounted to the main feed arm at the offset focal point. A mounting plate connected to the antenna's liquid cooling system provides a heat reservoir. Front End and receiver and digitizer electronics are thermally stabilized using Peltier heat pumps. A band from 18–32 GHz is digitized in the receiver module and digital data is streamed via fiber to the WVR processor in the pedestal room. Low-data-rate output is emitted into the Monitor and Control data stream.

4 Subsystem Design

4.1 Subsystem Block Diagram

Figure 3 shows the basic layout for the WVR subsystem.

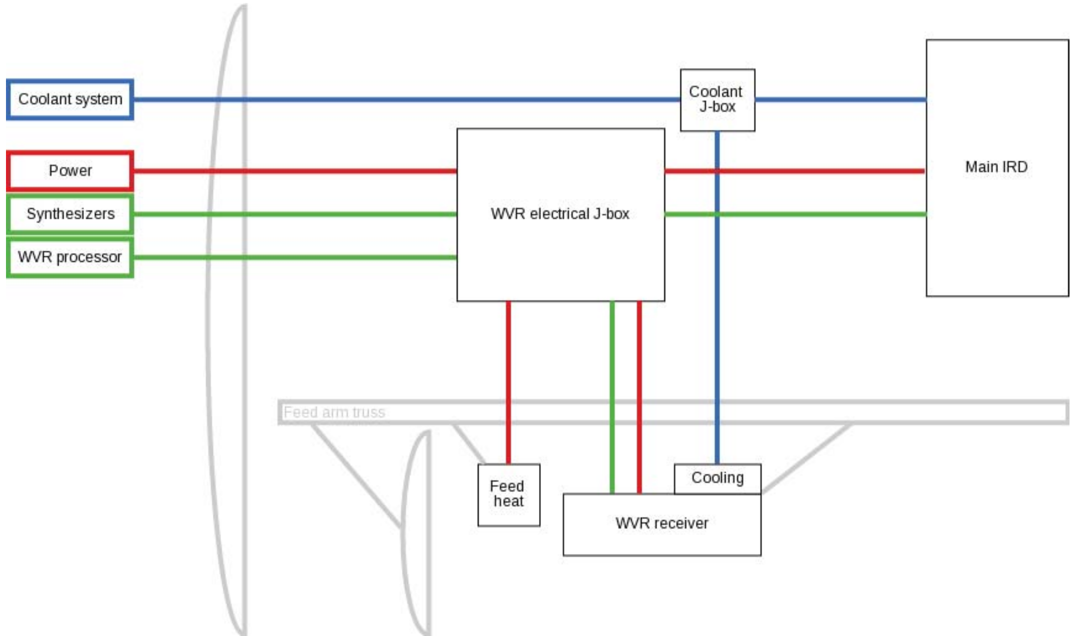


Figure 3 - WVR subsystem overview and interfaces.

4.2 Subsystem Components

4.2.1 Antenna

The antenna is a 1.2 by 1.4 m parabolic dish designed for offset prime focus use, built by General Dynamics and targeted at the Very Small Aperture Terminal (VSAT) customer base. It is constructed of glass fiber reinforced polyester and is rated for a working wind load of 50 mph and survival to 125 mph. Note that the WVR antenna is not acting as a power collector, but rather as a view-limiting device to ensure that atmospheric conditions in the main antenna beam are accurately sampled. The minimum size of the antenna was calculated to achieve a WVR beam diameter at 22 GHz that is close to the beam diameter of the main antenna beam at 2 km altitude, under which most water vapor turbulence has been observed.

The antenna is mounted via truss to the starboard side of the main antenna truss. The WVR side of the truss supports a connection plate, to which an antenna mounting plate is attached via three adjustment bolts. The antenna mounts directly to the antenna mounting plate. Fine adjustment of antenna pointing is provided by the three adjustment bolts. Adjustment is expected to be performed only during installation and major maintenance. Pointing adjustment will be performed by using a software pointing calibration routine to center the main beam on a geostationary satellite with a K-band downlink, then manually adjusting the adjustment bolts on the antenna mounting plate to maximize WVR receiver output. Adjustment bolts are locked with locking nuts and safety wire to prevent motion.

4.2.2 Receiver Module

Figure 4 shows the basic WVR receiver module design.

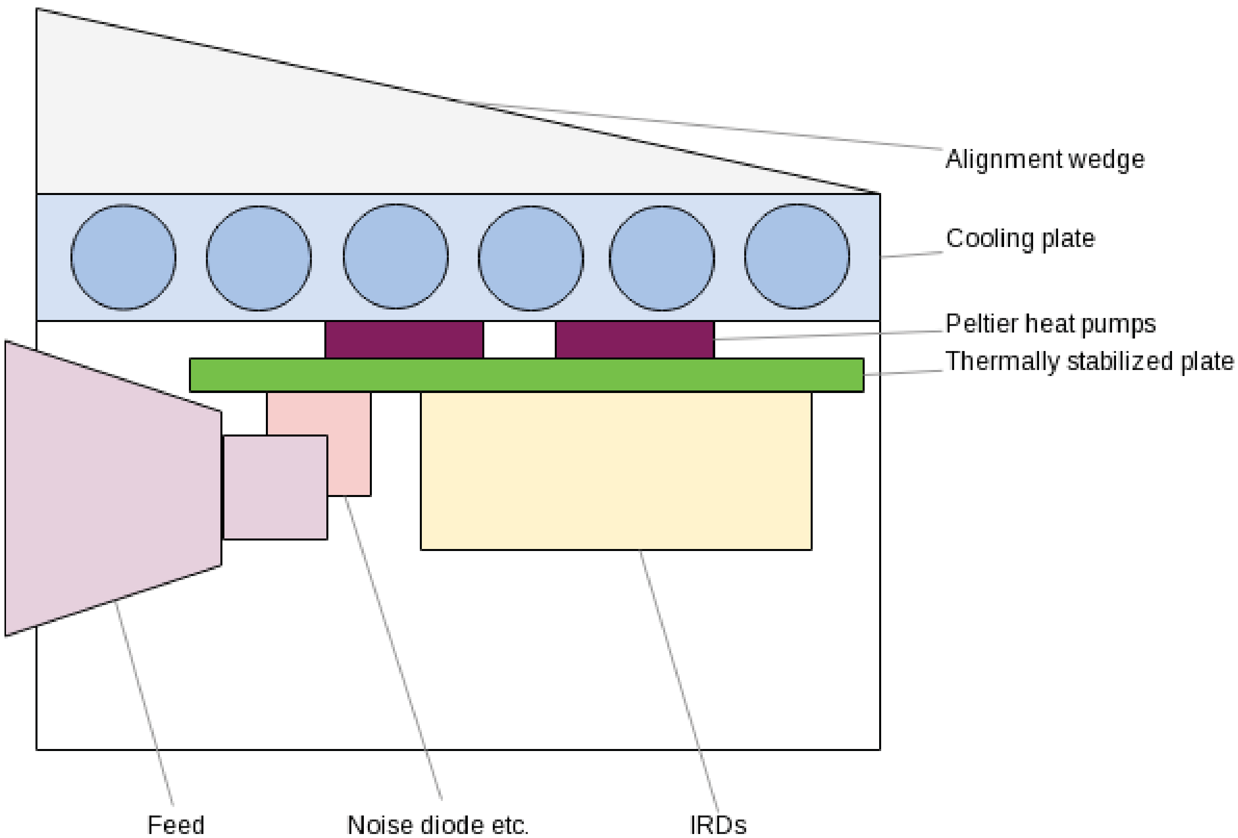


Figure 4 - WVR receiver module layout.

The module contains the feed, receiver, and all digitizing and processing electronics for the WVR. It is an aluminum enclosure with both weather and RFI gasket seals, and a sealed armor cable to protect power and data connections. The module mounts via cooling plate and offset wedge to the main feed arm truss at the correct point to place the feed phase center at the focal point of the WVR antenna.

Inside the module (Figure 5), RFI-tight compartments separate the feed, LNA, switched-power system, and receivers from the power supplies and thermal control boards. All RF components are mounted to a thermally stable plate that is kept at 30.00°C +/– 0.01°C by a control system driving Peltier-effect heat pumps. The heat pumps are thermally connected to the module wall that is thermally connected to the antenna cooling system. Thermal insulation around the thermal plate reduces thermal transfer from the enclosure walls, and an external heat shield reduces solar heating on the exposed module walls.

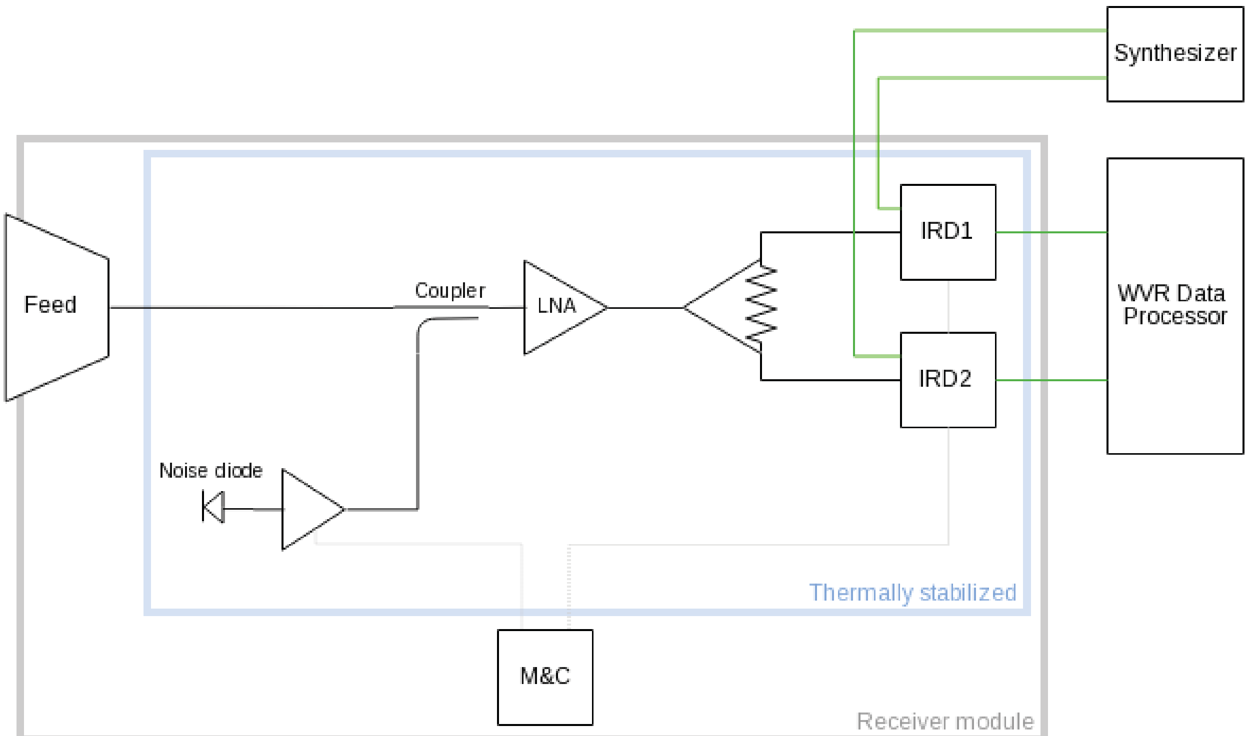


Figure 5 - WVR receiver module schematic.

4.2.3 WVR Junction Box

WVR power and fiber are connected at the WVR junction box located inside the main feed arm truss along the electrical conduit leading from the Pedestal Room to the IRD module. The junction box is a commercial weather-sealed electrical box specified for all-angle exposure. Sealed armor cable is used to convey –48 V power and M&C fiber to the WVR.

4.2.4 Alignment Wedge

A manually adjustable hinged wedge is mounted to the main antenna feed arm truss, and provides the mounting point for the cooling plate and WVR electronics module. The wedge provides the necessary feed angle relative to the WVR antenna in order to allow adjustment of the WVR beam to be parallel to the main antenna beam. The wedge contains a fine-adjustment mechanism to allow the feed angle to be precisely aligned during the WVR pointing/alignment procedure performed during installation and major maintenance. Adjustment bolts are locked after alignment with safety wire.

4.2.5 Cooling Plate

The WVR cooling plate is similar to the main IRD module cooling plate. Fluid cooled by refrigerators on the antenna pedestal is circulated through lines leading to the cooling plate, through channels in the cooling plate, and back to the pedestal room. Coolant temperature is maintained at 20°C +/– 5°C by a control system in the pedestal room. The WVR cooling plate contains channels for circulating fluid, and is removable for maintenance. Mounting holes allow attachment to the alignment wedge on one side and of the electronics module on the other.

Thermal transfer to the module is facilitated by flat-machined surfaces and silicone thermal-transfer gasket. Fluid connections are high-reliability drip-free quick-connects and fluid lines are nitrile-based hydraulic hoses protected by steel armor cable.

4.2.6 Feed

The wide-band feed is an mWave FPP1-222-S linear feed for K band 18.0–26.5 GHz. It is flange-mounted to the aft end of the receiver module with RFI and environmental gaskets. The feed terminates in an SMA-K female connector, and is protected from ultraviolet radiation and physical damage by a PTFE window.

4.2.7 Feed Heater

A radiant feed heater coil is mounted to the main feed arm aft of the feed and facing it. Power connections to the feed heater are supplied from the WVR junction box. Current is supplied to the heater through a solid-state relay in the WVR junction box which is controlled by the WVR processing module in the pedestal room. Feed heat is commanded by the antenna supervisor, which determines if conditions are necessary for feed heat based on weather data, feed temperature, and WVR data output. The supplied heat is sufficient to clear condensation from the window without damaging the window material.

4.2.8 Front End

A single polarization is taken from the K-band feed. A switched noise diode source is coupled to the feed signal, and a low-noise amplifier provides initial gain. A power divider provides the signal to the two Integrated Receiver/Digitizer modules, which amplify and filter, downconvert, and digitize the signals.

4.2.9 Integrated Receiver/Digitizer

The NRAO CDL has developed an Integrated Receiver/Digitizer (IRD) module to be used for ngVLA. The WVR will use two IRD modules, each of which consists of two independent receivers and digitizers. In total, four subbands covering K band will be sampled, with 32 100 MHz channels for each subband being produced by the WVR processing module.

To ensure precise calibration, one channel of each subband will overlap one channel of the neighboring subbands. The IRD digitizers will be configured to provide 8-bit samples to better handle RFI, an increase in which is expected over the array lifetime. Data is streamed over a custom transmit-only fiber link using QSFP28 transceivers directly to the processing module in the pedestal room.

4.2.10 Monitor and Control

Monitor and control in the receiver module is provided by a standard ngVLA M&C board. The board is connected to the M&C fiber network and provides control over the IRDs, switching diode, feed heaters, and all other electronics. All sensors, including feed and cold plate temperatures, system voltages, and system currents, are read by the M&C board and reported to the M&C network. The antenna supervisor software in the pedestal room analyzes conditions in the WVR and elsewhere and provides control over WVR power-up, operation, and safe shutdown.

4.2.11 Thermal Stabilizer

To determine water vapor column density, the amplitude of each spectral channel must be determined with an accuracy of about one part in 10,000. Fluctuations in gain and other parameters of the Front End electronics make this specification impossible to meet unless thermal stability is maintained to within about 0.01°C. To achieve this stability, the RF components and the digitizers are mounted to a thermal mass—the "cold plate"—which is maintained at a specified temperature to that accuracy.

The cold plate is manufactured out of 6063 aluminum, picked for its superior thermal conductivity. Through aluminum load plates, the cold plate is thermally connected to Peltier effect devices, which can pump heat through themselves in either direction based on supplied electrical current. The Peltier devices are thermally connected to the enclosure, then to the antenna cooling plate. The cold plate has thermal sensors mounted to it. The processor on the Monitor and Control board (details below) implements a control system to maintain the cold plate at the specified temperature.

4.2.12 Processing Module

The processing module is a Dell PowerEdge C4130 1U rack-mount server located in the pedestal room electronics rack, hosting a Bittware XUSP3S processing card. Four QSFP28 modules accept fiber data from the WVR receiver module. This server is also the host for the antenna supervisor processing board. RFI Shielding is provided by the pedestal rack.

4.2.13 Firmware

Data from the two IRDs is received via the QSFP link and read by the FPGA logic. A 32-channel polyphase filter (PPF) channelizes the data from the four subbands. Integration of 100–1000 ms is performed per-channel. Detection algorithms flag channels affected by RFI. Calibration routines join the subbands and normalize the bandpass. An ARM processor soft-core is then triggered to process the channel data to determine the water vapor column density in the WVR beam, and the data is emitted onto the M&C network. The processor board also networks M&C data for itself, IRDs, temperature controller, power supplies, and all other electronics in the module.

4.3 WVR Locations

All 18-meter antennas in the array will be equipped with a WVR.

4.4 Interfaces with other Subsystems

4.4.1 Antenna Feed Arm Truss

The antenna will mount to the feed arm truss, and therefore must induce no undue loads from wind or thermal stress.

4.4.2 Antenna Liquid Cooling

The WVR receiver will use 20 W of cooling from the antenna cooling system, and will require one line each for outbound and return cooling fluid.

4.4.3 Antenna Air Cooling

The WVR processor will use 100 W of cooling, supplied by the common rack cooling air.

4.4.4 Local Oscillator

Four LO clocks are provided to the WVR electronics module via fiber from clock synthesizers in the pedestal room.

4.4.5 Time

Accurate observation time will be provided to the data processing module by the array's Time Distribution System.

4.4.6 Monitor and Control

The WVR processor will use 100 kB/s on the M&C Ethernet over a single fiber connection.

4.4.7 Power

The WVR receiver will consume 20 W of power from the antenna supply. The WVR processor will use 100 W of power from the common pedestal rack supply.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDL	Central Development Laboratory, NRAO
DBE	Digital Back End
DTS	Data Transmission System
IF	Intermediate Frequency
LNA	Low-Noise Amplifier
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
PLL	Phase Locked Loop
PFB	Polyphase Filter Bank
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer