ngVLA 6m Antenna Concept Design Document

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

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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.

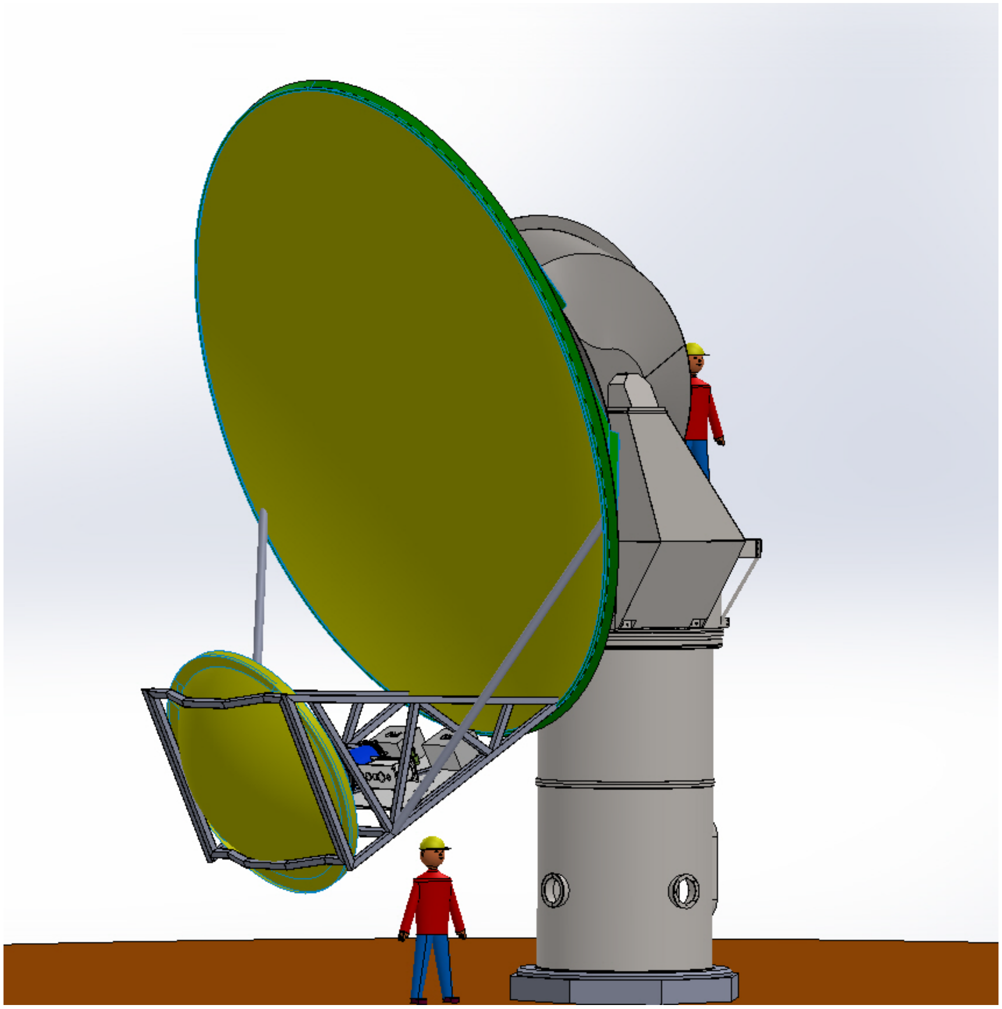

Figure 1 NRC ngVLA 6m Antenna Design Concept

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.

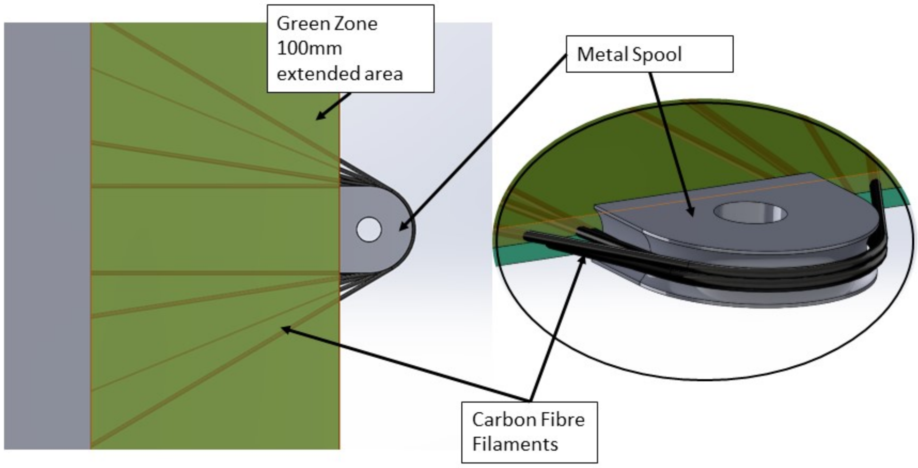

Figure 2 Primary surface edge adjuster tab concept

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.

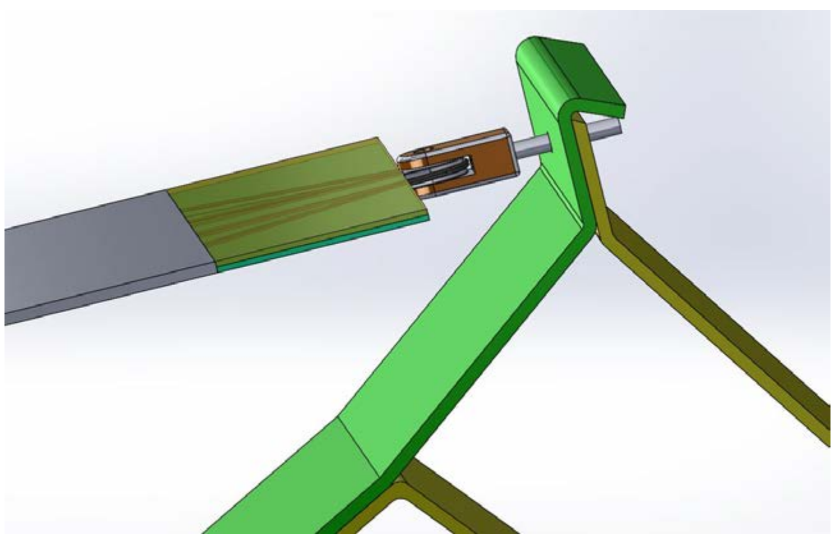

Figure 3 Primary surface edge adjuster with oBUS

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.

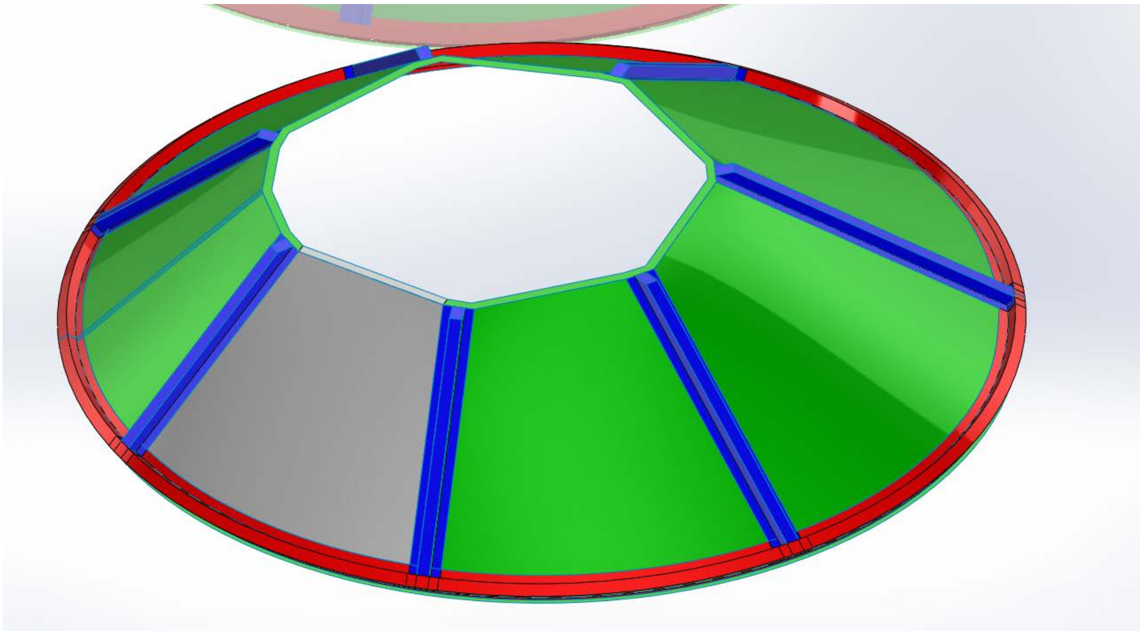

Figure 5 oBUS components in colour

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.

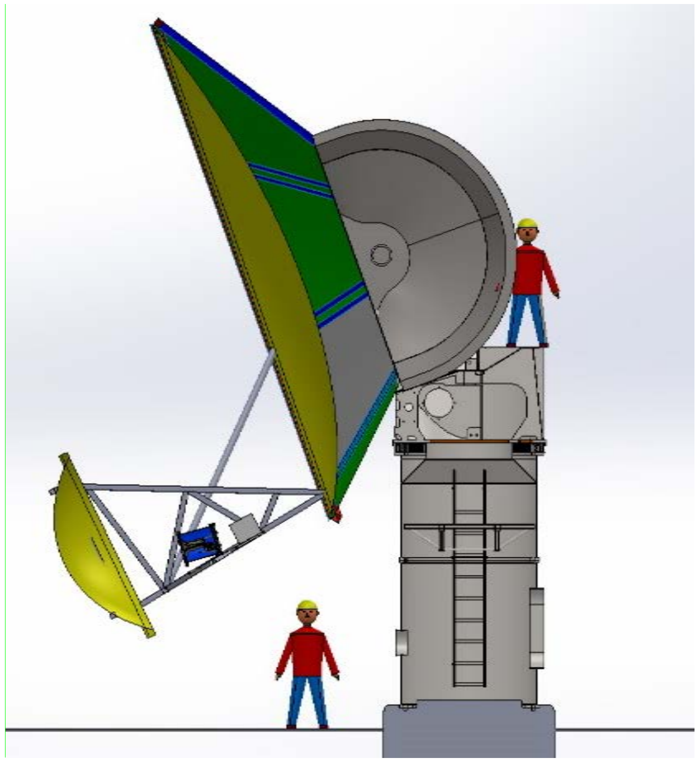

Figure 6 Cross Section of Antenna at Low (12°) Elevation Angle

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.

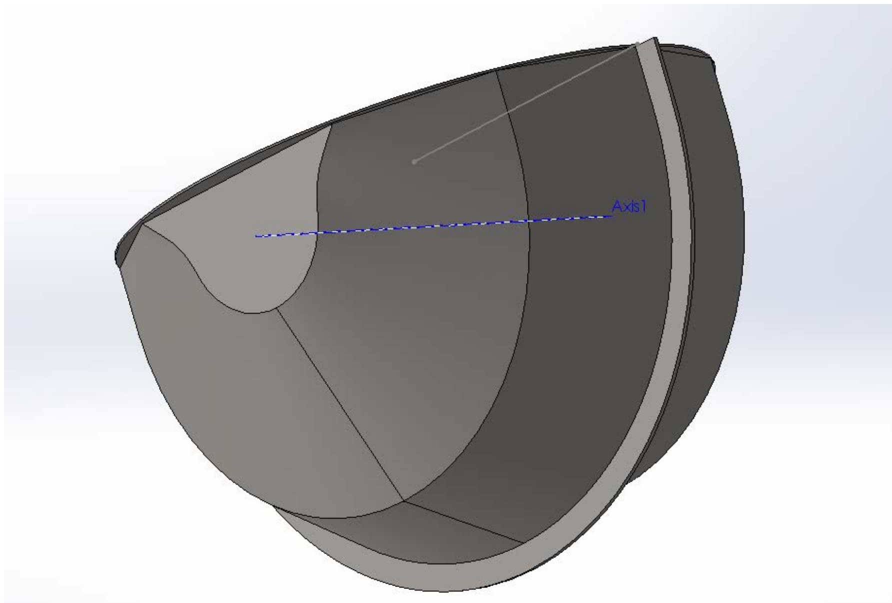

Figure 7 6m iBUS structure

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.

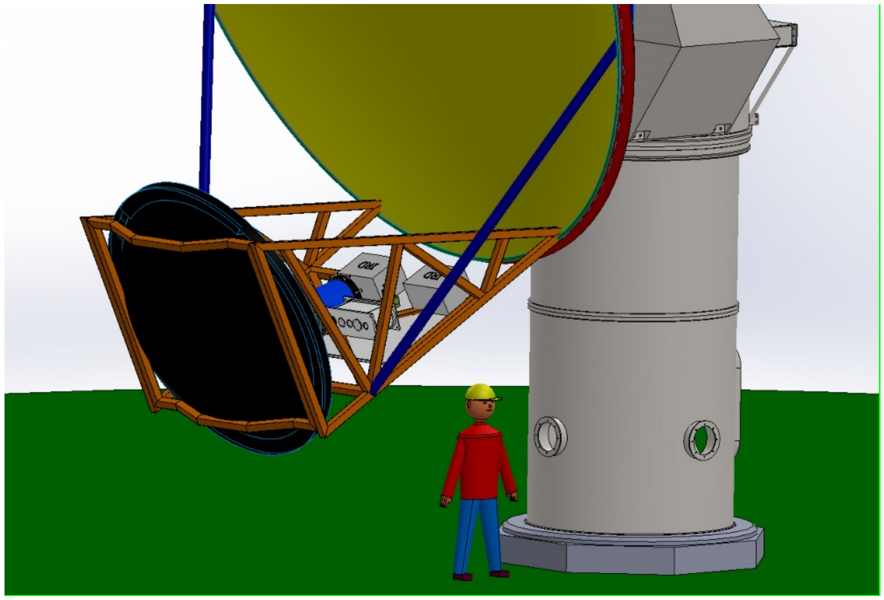

Figure 8 6m Secondary Support Structure.

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.

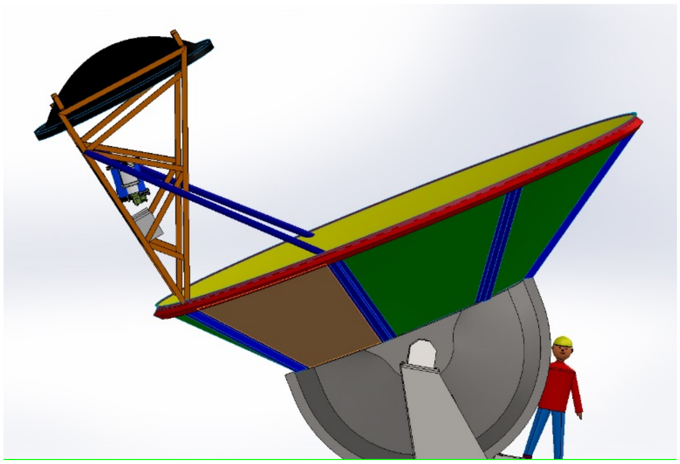

Figure 9 Stiffening Ribs on Primary Reflector to Support Secondary Support Structure

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.

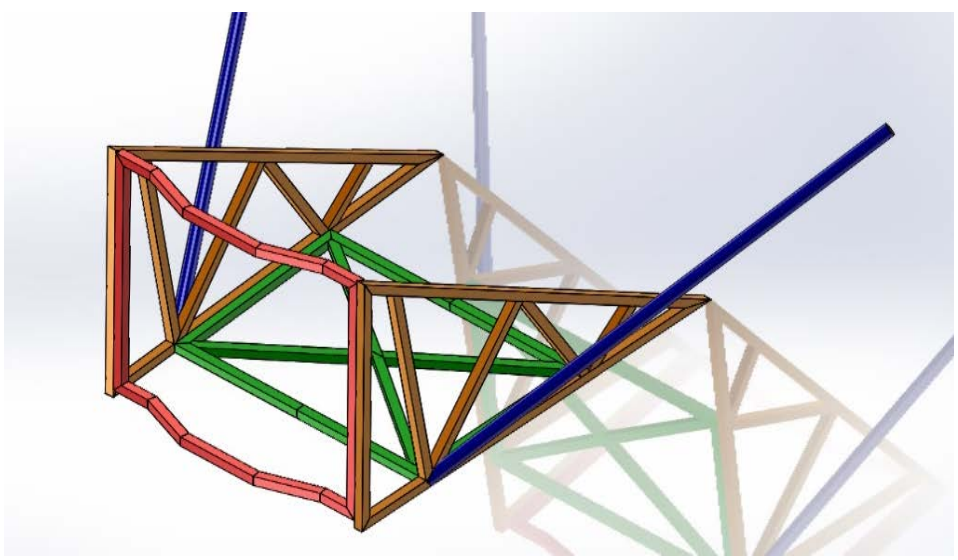

Figure 10 Secondary and Feed Support Structure for 6m dish

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.

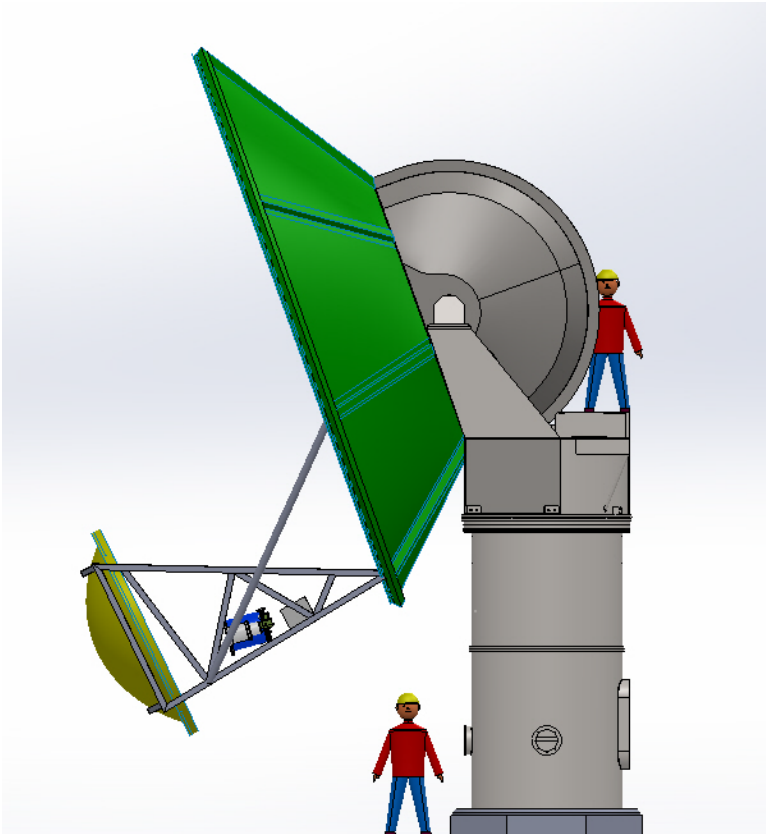

Figure 11 Complete 6m telescope with mount

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.

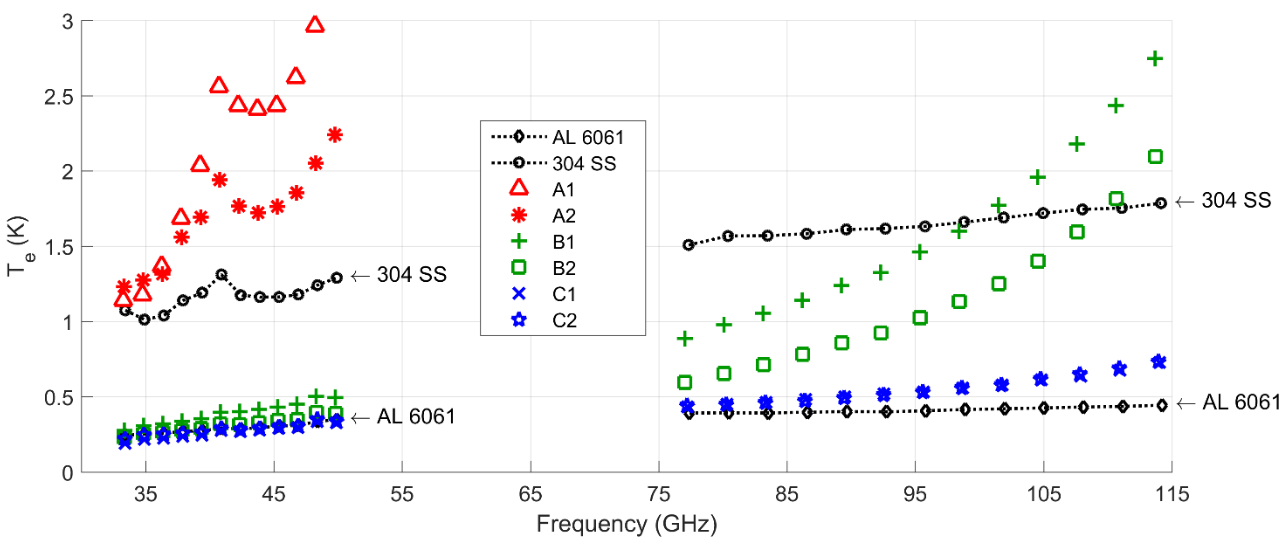

Figure 12 Reflector Surface Noise Measurement Results

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.

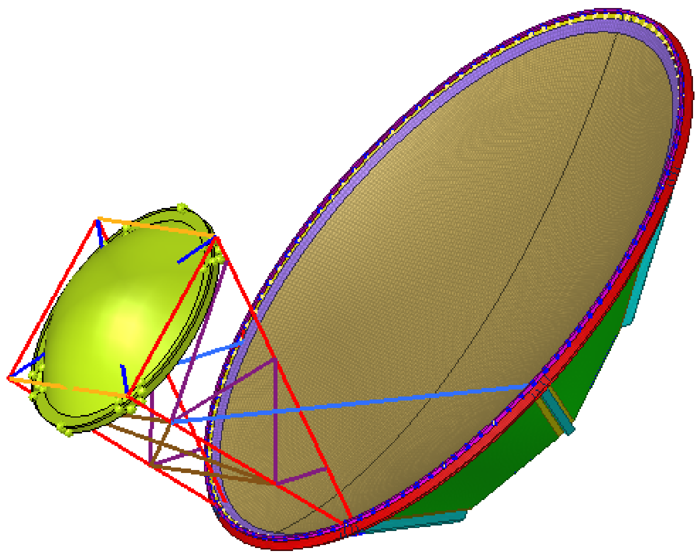

Figure 13 6m Reflector Assembly

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

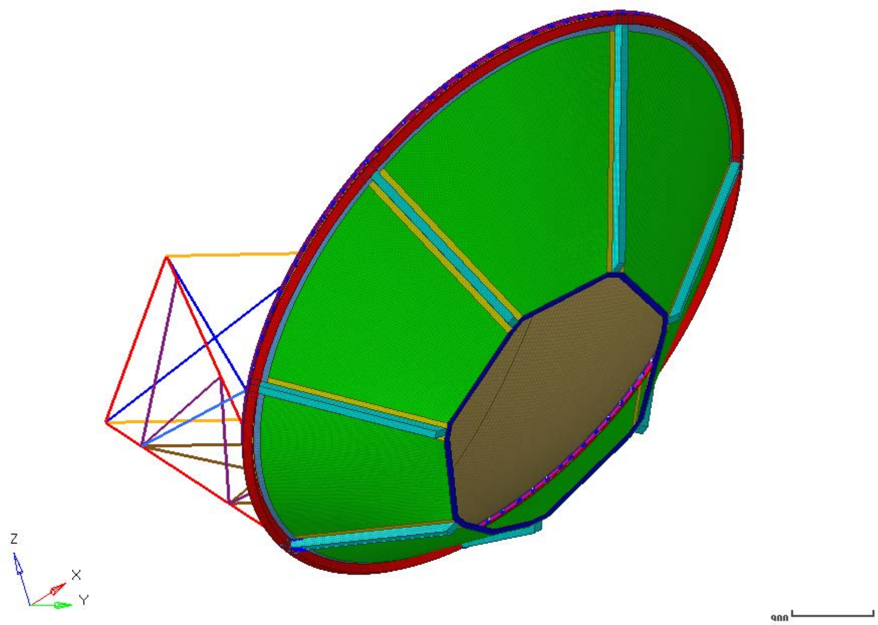

Figure 14 6m oBUS

7.2.1.1 Laminate schedule

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

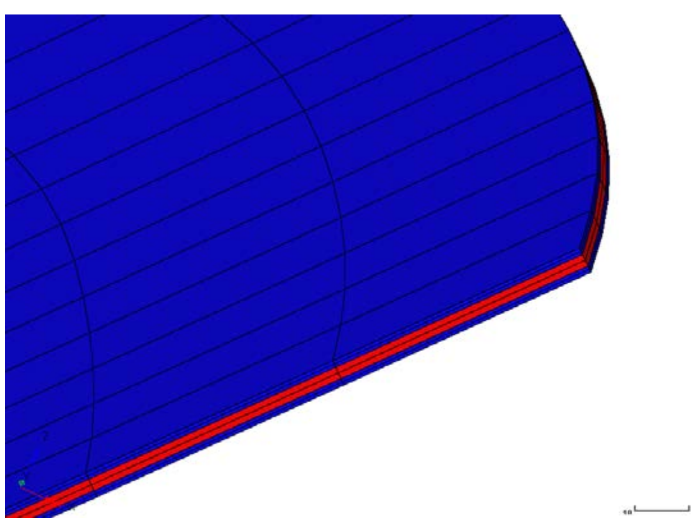

Figure 15 Primary surface Laminate schedule (blue layer: carbon qiso, red layer: triaxial carbon).

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

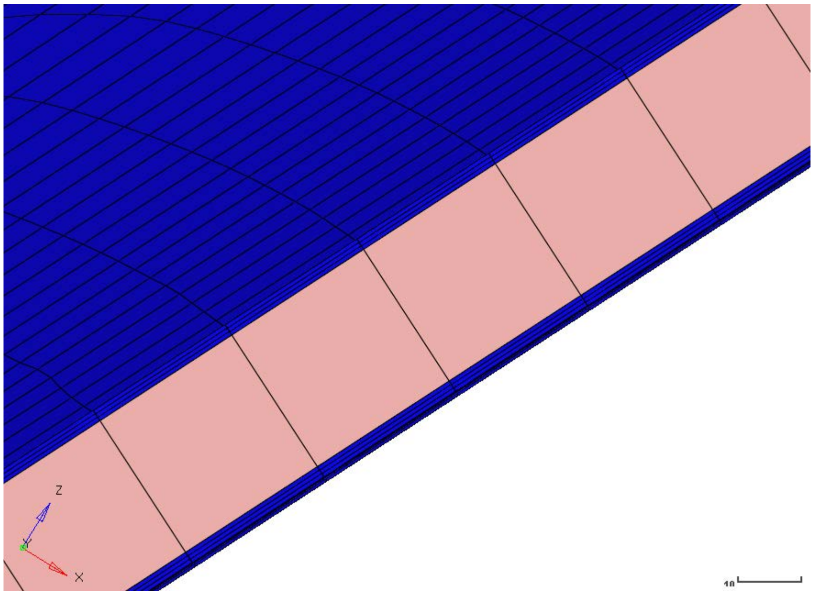

Figure 16 oBUS Laminate schedule (blue layer: carbon qiso, pink layer: foam core)

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

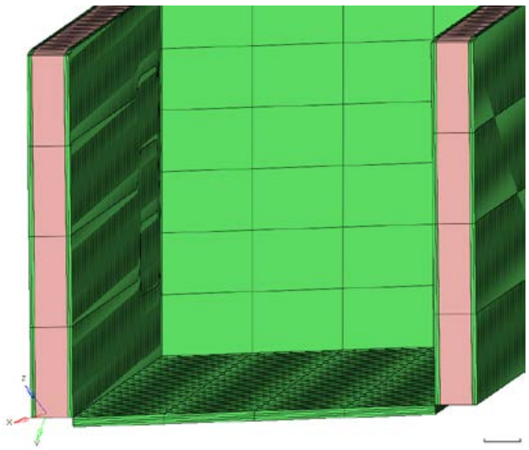

Figure 17 oBUS rib Laminate schedule (green layer: carbon qiso, pink layer: foam core)

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.

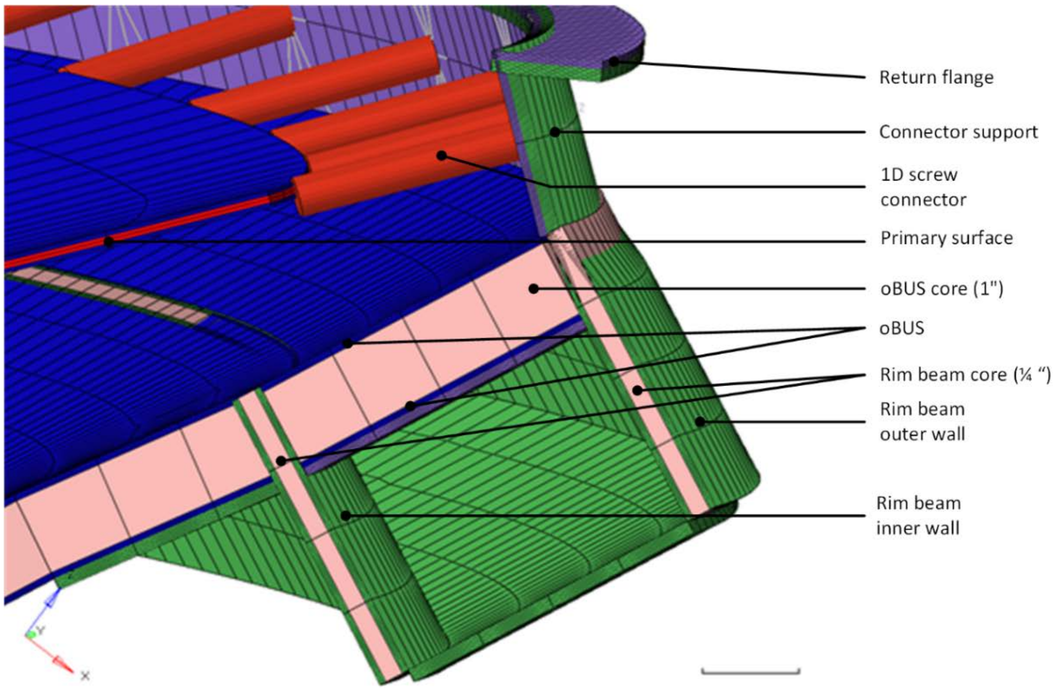

Figure 18 Cone back-primary laminate schedule and foam core (blue layer: carbon QISO, magenta layer: carbon uni, grey layer: foam core).

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.

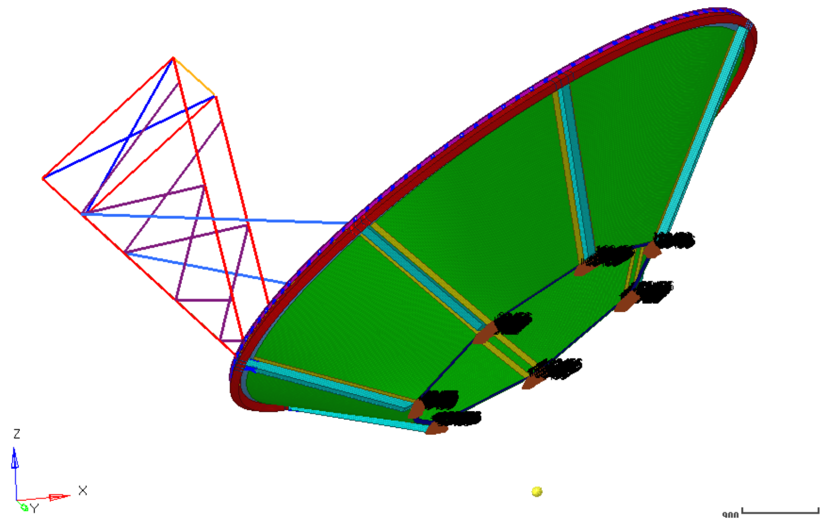

Figure 19 ngVLA 6m FE model constraints

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.

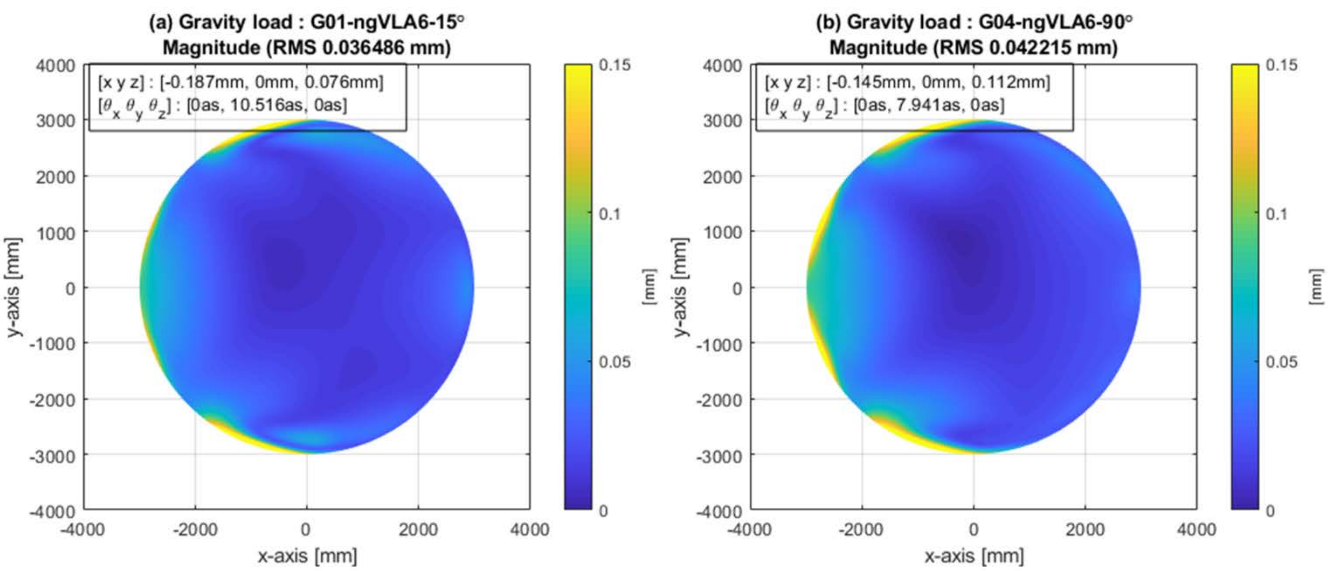

Figure 20 ngVLA 6m surface RMS error under Gravity load cases (a) 15° and (b) 90° elevation angle.

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.

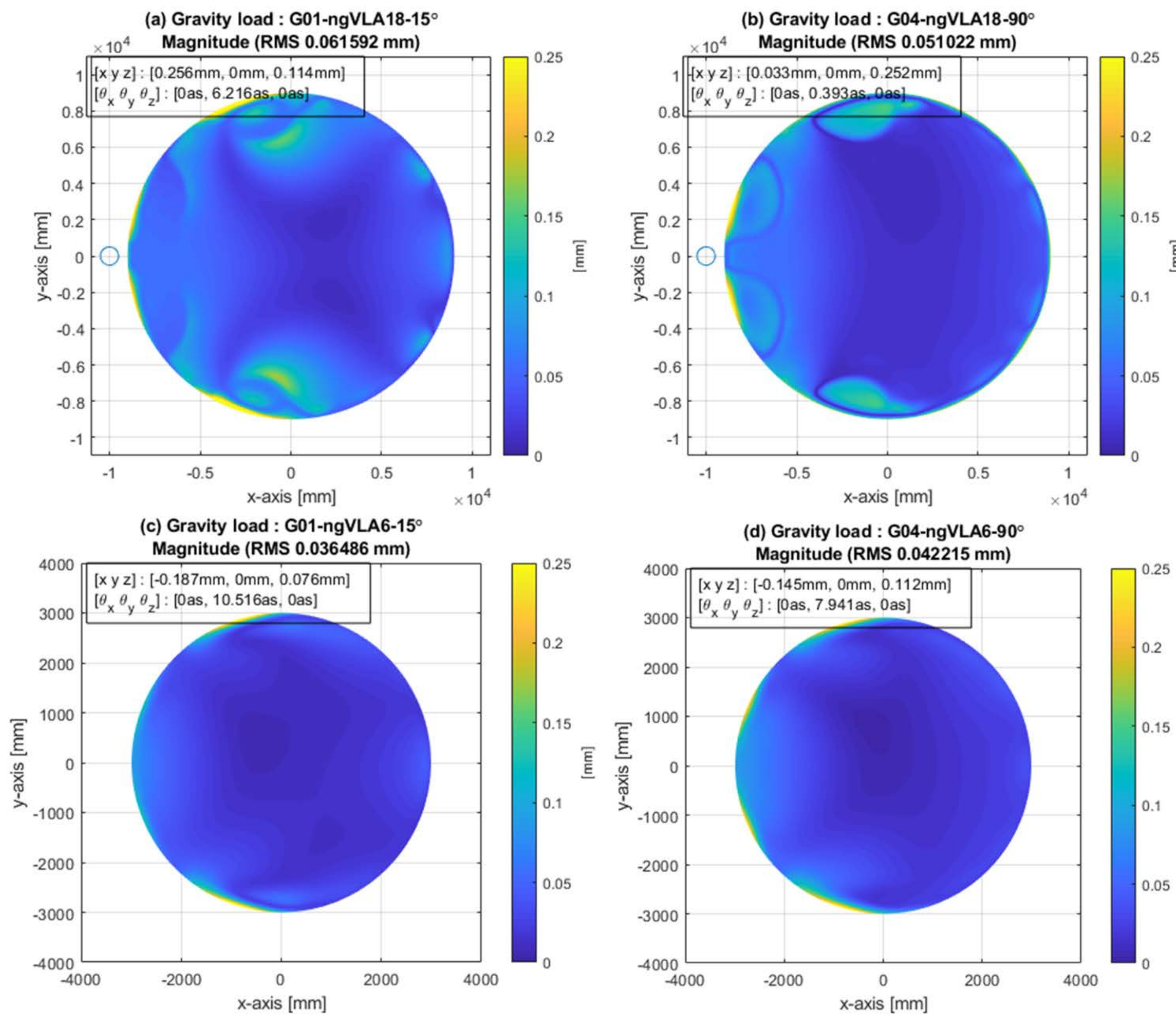

Figure 21 Surface RMS error under Gravity load cases for ngVLA 18m (a) 15° and (b) 90° elevation angles and ngVLA 6m (c) 15° and (d) 90° elevation angles.

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.

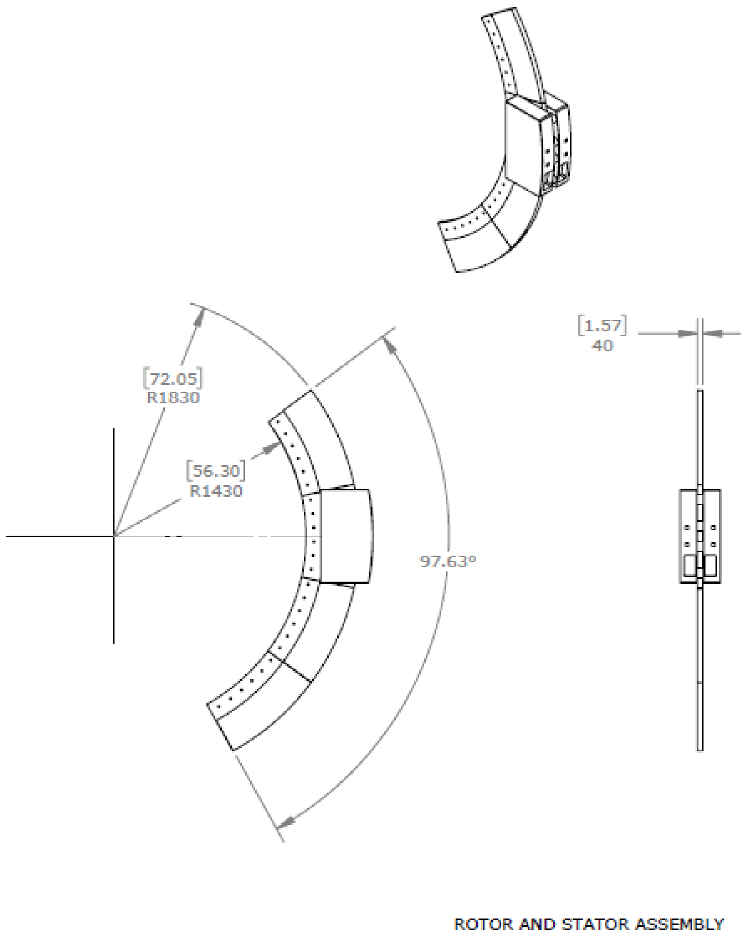

Figure 22 Elevation Drive Configuration

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).

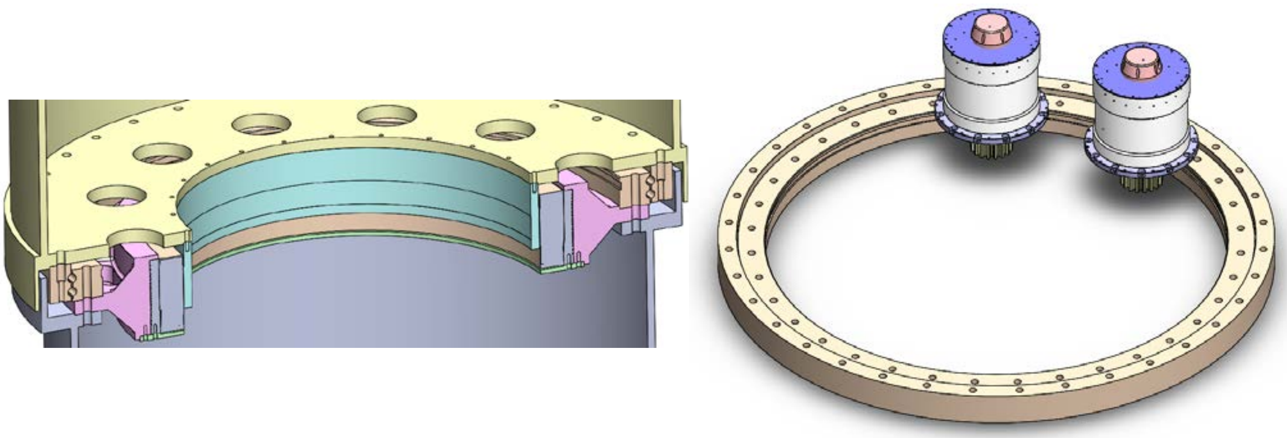

Figure 23 Azimuth Drive Options

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

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Final Audit Report 2019-07-30

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