ngVLA Memo # 26

# ngVLA Technical Study

# Offset Gregorian Antenna

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**Abstract**

A 15m offset Gregorian feed-low antenna design concept has been developed by the NRC Herzberg Astronomy Technology Program team and its collaborators to meet ngVLA requirements.

## 1 Introduction

NRC has been developing composite reflector antenna technology for radio astronomy applications since 2006. The project is targeted at developing antenna technology that is cost effective and suitable for quantity production while leveraging the high performance properties of modern composite materials. Key technological developments came in three areas; composite reflector materials, single piece reflector construction and the rim supported reflector concept. Initially targeted at antennas operating up to 10 GHz for the SKA project it has resulted in the construction of the very successful DVA-1 antenna at DRAO. The DVA-1 project was a collaboration between NRC (elevation assembly design, system engineering and site provision), Minex Engineering (mount and drive systems design) and Lynn Baker (optical design and EM analysis).

In support of the ngVLA project NRC has undertaken further development of the Single-piece Rim-supported Composite (SRC) reflector technology drawing on the experience and utilizing the expertise of DVA-1 team. The higher operating frequencies of the ngVLA require development in three areas; increased surface accuracy, improved surface reflectivity and increased structural rigidity. The first two aspects are being addressed with a combination of prototyping and testing and the third through design.

This memo outlines the work undertaken to date on the Elevation Rotating Assembly (ERA) and presents a 15m antenna design concept with a cost estimate. The development Azimuth Rotating Assembly (ARA) design included in the concept design is presented in ngVLA Memo #X [1].

# 2 Acronyms

## Acronyms used in this document

| | |
|---|---|
| ARA | Azimuth Rotating Assembly |
| ERA | Elevation Rotating Assembly |
| NRC | National Research Council of Canada |
| SKA | Square Kilometer Array |
| DVA-1 | Dish Verification Antenna 1 (SKA precursor) |
| DVA-2 | Dish Verification Antenna 2 (50GHz test antenna) |
| SRC | Single-piece Rim-supported Composite |
| CFRP | Carbon Fiber Reinforced Plastic |
| ESO | European Southern Observatory |
| ALMA | Atacama Large Millimeter/submillimeter Array |
| BUS | Backup-Structure |
| SSS | Secondary Support Structure |
| RMS | Root Mean Square |

# 3 Development Status

## 3.1 Surface Accuracy

The surface accuracy achievable with the SRC reflector technology is dependent on; materials selection, process control and the accuracy of the mold. Over the course of the SRC development NRC has gained a comprehensive understanding of each of these aspects and the ability to predict and achieve higher surface accuracy.  For a given mold accuracy the first two factors, materials selection and process control, will govern the accuracy of the part produced from it. A graph of the part accuracy to mold accuracy achieved for the 6 large reflectors produced by NRC, Figure 1, shows the progress that has been made.

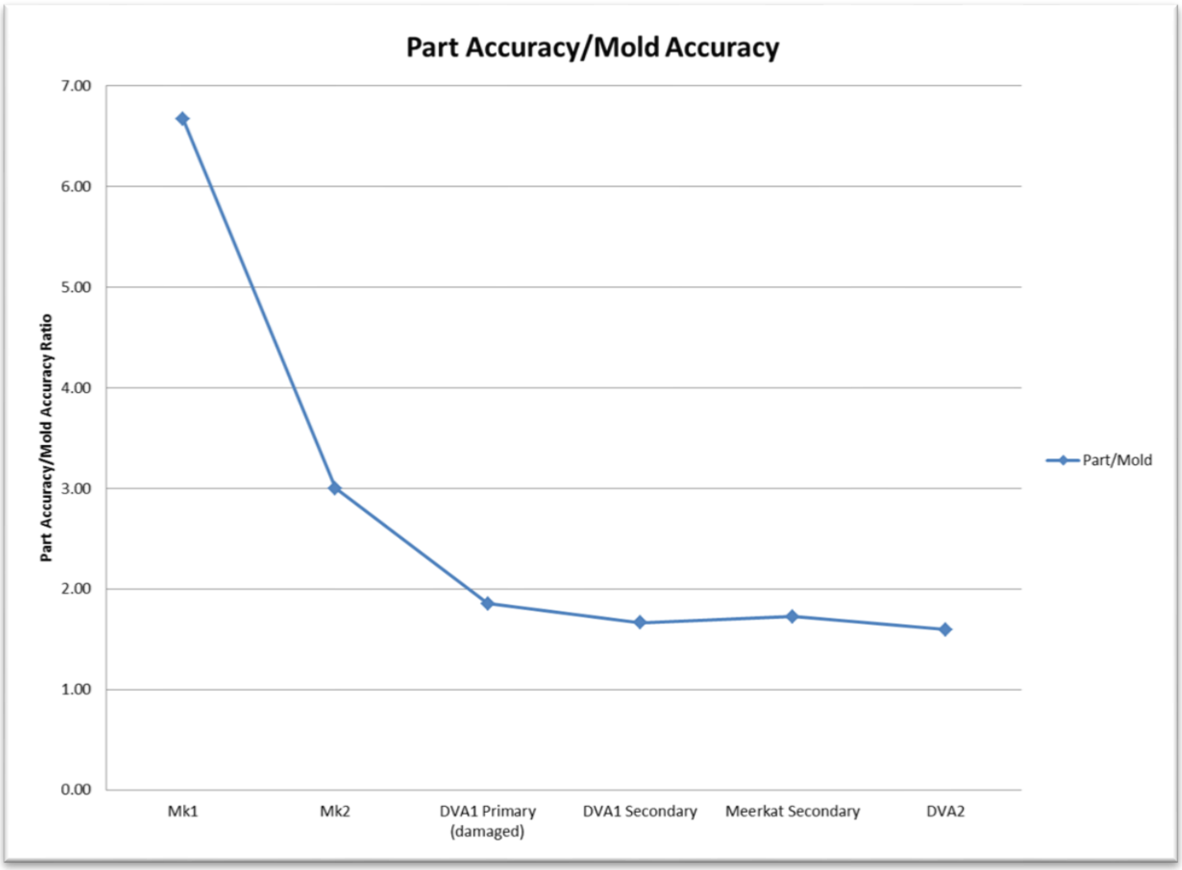


*Figure 1NRC SRC Reflector Part vs. Mold Accuracy*

The part to mold ratio steadily decreased over the first few parts until leveling off around 1.6 for the latter parts.  It is important to note that although the mold errors are amplified in the part they are replicated in detail down to a very fine level as can be seen in Figure 2.

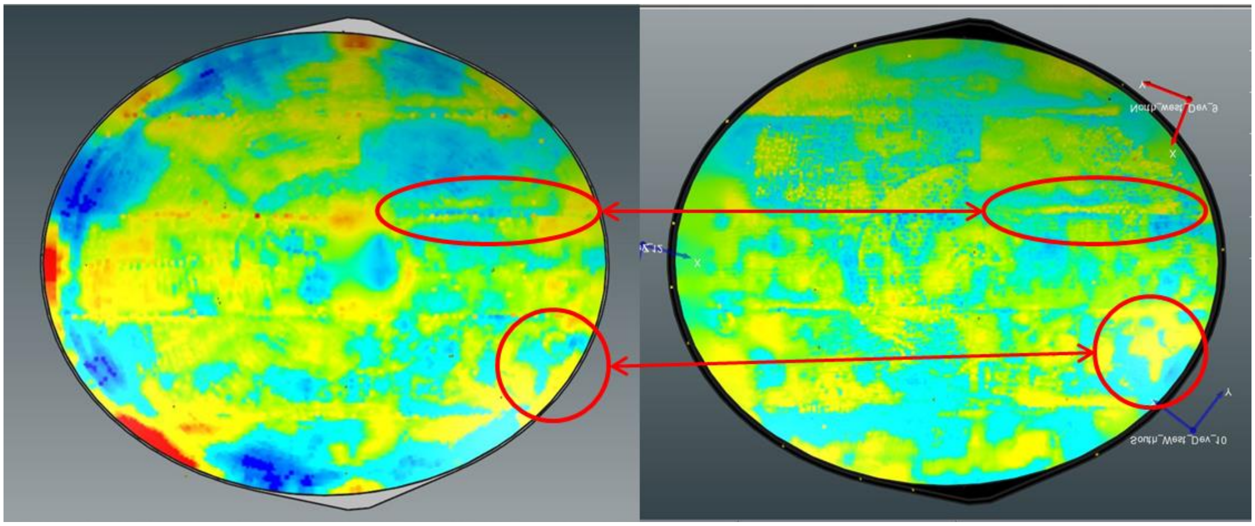

*Figure 2 DVA-2 Mold and Part Measurement Plots*

Although there may be some opportunity for more gains and investigations will continue it is anticipated further improvements will be small.

With material selection and process control well understood the remaining factor is the mold accuracy. Achievable mold accuracy is dependent on the capability of the mold manufacturer, the measurement capability and the stability of the mold.

The required surface accuracy at the main aperture plane for the ngVLA combined optics is 160 microns RMS. In order to determine the mold accuracy requirements the individual primary and secondary reflector accuracies must be derived. It is reasonable to expect that a high quality sub-4m secondary reflector mold can be produced to 50 microns accuracy (the DVA-2 secondary mold is 58 microns RMS at the aperture plane, the part is under construction at this time) and that the resulting part could be 83 microns RMS. Based on these assumptions the required primary reflector surface accuracy is calculated to be 137 microns RMS and therefore the required mold accuracy is 90 microns at the aperture plane or 131 microns at the surface (assuming a similar relationship between accuracy at the aperture and surface as was seen on DVA-2).

The current state of the art mold manufacturers are capable of machining mold surfaces to 50 micron accuracy on parts up to 30m x 6m x 2.4m. The measurement of the surface to this same accuracy is possible using a laser tracker and careful environmental and measurement process control. Finally the stability of the mold is dependent on materials selection, construction and environmental control. The construction and cost of molds used for the fabrication of composites structures varies a great deal from wooden structures with a machined putty surface to full carbon fiber structure with a machined carbon fiber surface depending on the accuracy, stability and durability requirements.

The DVA-2 mold, which is the DVA-1 mold reworked to achieve higher accuracy, is a steel frame, fiberglass surface and machined tooling gelcoat surface. The steel frame was underbuilt and despite this and the CTE mismatch between the steel frame and fiberglass surface a surface accuracy of 210 microns was achieved.

In order to repeatedly achieve the ngVLA required surface accuracy a mold constructed of a steel support structure with a machined hybrid carbon/glass fiber surface would provide the required stability and durability at the least cost. By using hybrid carbon/glass the CTE of the surface can be matched to that of the underlying steel structure to minimize thermal distortions. This type of mold in a wellinsulated facility with a quality industrial HVAC system would provide the necessary thermal stability for accurate measurement of the mold and consistent surface shape from part to part.

With a better quality mold, careful setup and some final polishing it is realistic to believe that 131 microns is achievable.

## 3.2 Reflectivity

The radio reflector surface in the NRC SRC technology consists of a discontinuous metallic layer embedded within the composite layup. In the lead up to DVA-1 extensive development and testing of materials was conducted in order to minimize the noise temperature contribution of the reflector surface. Testing from 8 to 18 GHz was conducted using waveguide resonators apparatus resulting in a noise temperature contribution from the reflector of 0.4K, very near the 0.2K of the aluminum reference reflector.

For testing of materials at higher frequencies, a measurement setup using a Fabry-Perot resonator has been developed, Figure 3 . Fabry-Perot resonators are well known to give high-Q resonances and are suitable to measure low-loss materials. Open resonators have the inherent advantage that the quality of resonance is not affected by any sidewalls or corner air gaps, as in waveguide resonators, and various samples of mirrors can be easily swapped within the system. Details of the test apparatus and methods can be found in [2].

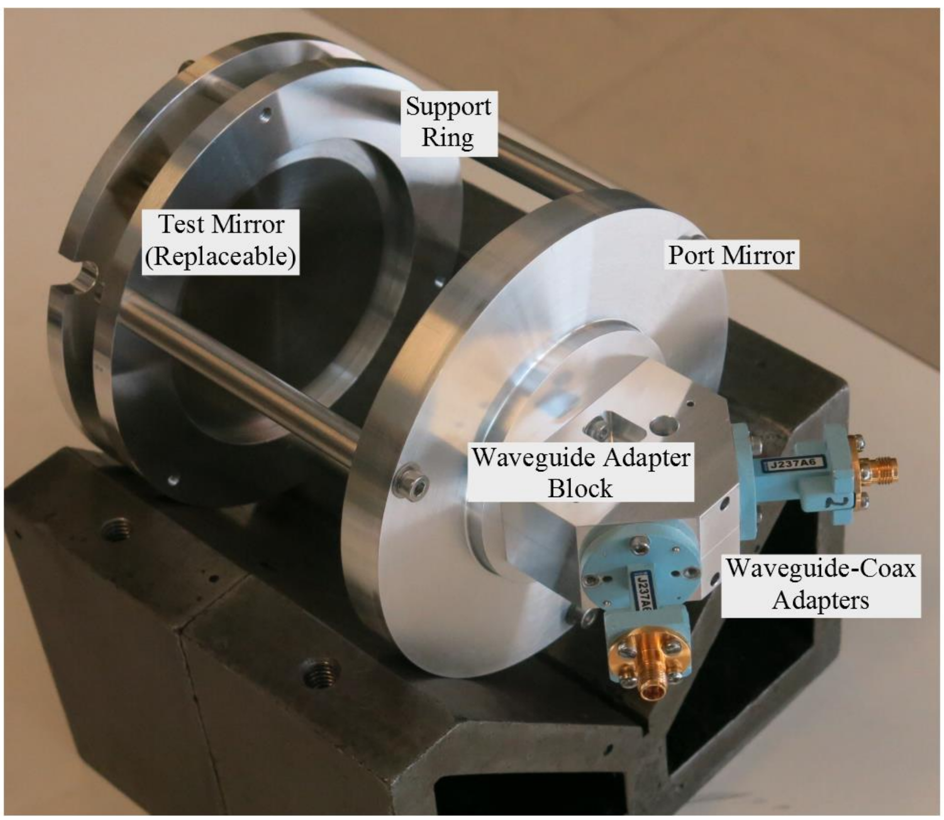


*Figure 3 Fabry-Perot Resonator*

Initial testing 33 to 50 GHz was carried out in support of the DVA-2 project target of high performance at 50GHz. Initial testing of the DVA-1 material showed a noise temperature contribution of ~1.5K at 50 GHz compared to the 0.3K for aluminum and 1.25K for stainless steel reference reflectors, Figure 4.

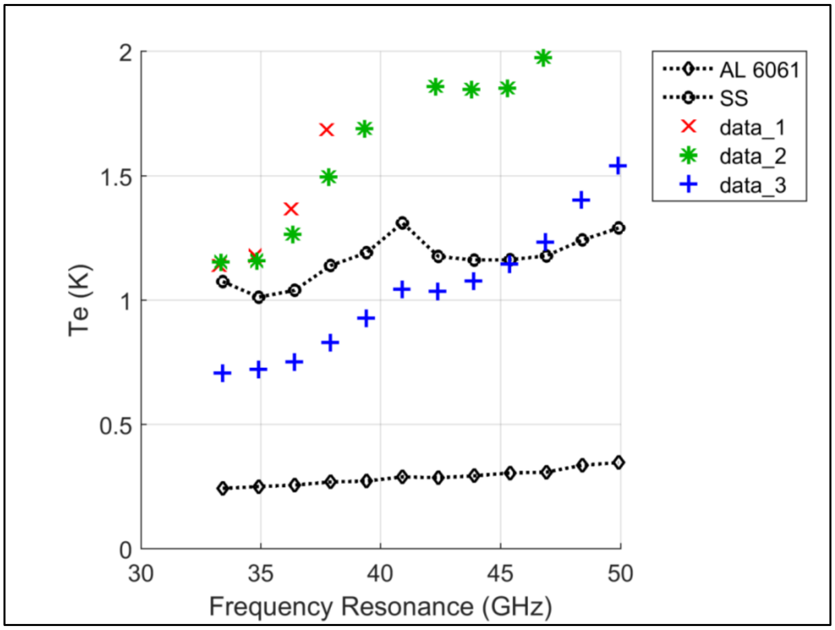


*Figure 4 DVA-1 Reflector Material 33 to 50 GHz Test Results*

Further material development was undertaken and resulted in a noise temperature 0.5K for the material that was then used for DVA-2, Figure 5 .

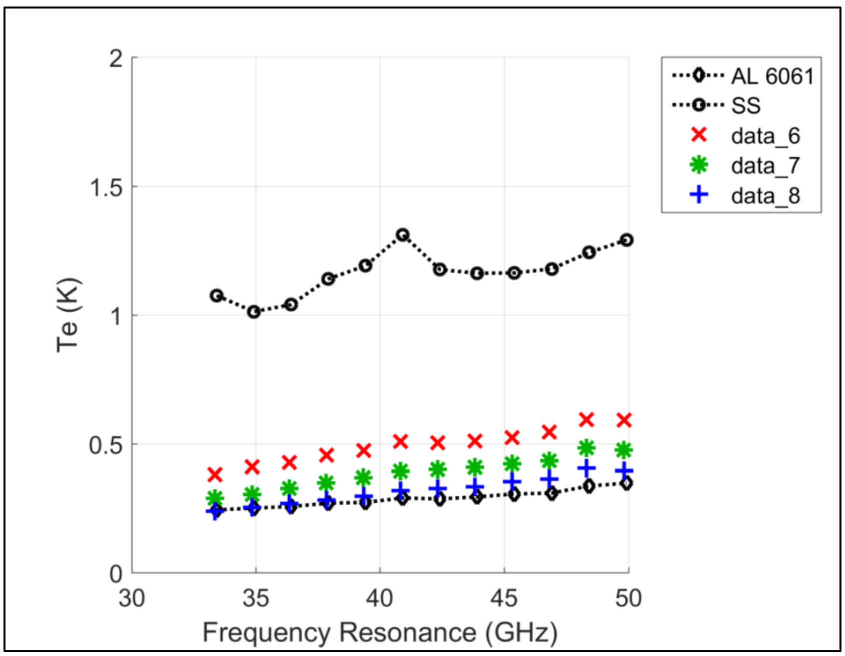


*Figure 5 DVA-2 Reflector Material 33 to 50 GHz Test Results*

As part of our ngVLA project supporting efforts a new W-band (80-116GHz) Fabry-Perot test fixture has been fabricated. Initial tests of the DVA-2 material have been conducted but results were not yet available at the time of this memo.

# 4 Design Description

## 4.1 Overview

The design study was undertaken to produce a concept design for a fixed position (non-reconfigurable array) 15m offset Gregorian alt-az feed down antenna, capable of meeting the draft ngVLA antenna requirements. The design has been taken to a sufficient level of detail to allow a cost to be estimated by a combination of parametric and analogous means.

The design, designated the ngDVA-15, features SRC reflector elevation assembly with a CFRP and steel backup structure in a steel wheel and track azimuth rotating structure, Figure 6.

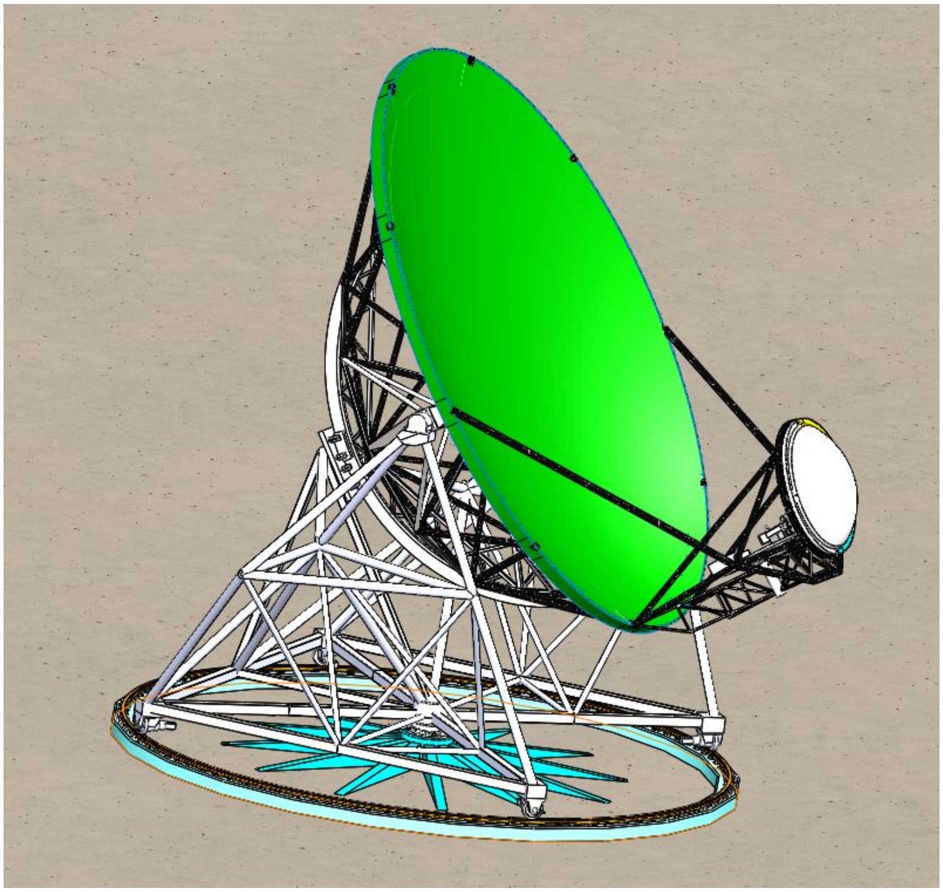

*Figure 6 ngDVA-15 Antenna*

Both pedestal and wheel and track mounts have been considered. Reaching the required low elevation angle (<15°) with the feed down offset reflector on a pedestal mount requires using a tall thin pedestal with either a large offset of the elevation axis, Figure 7 a), and/or a gap in the backup structure in the critical area adjacent to the feed arm, Figure 7 b), this would make it very difficult to achieve the ngVLA pointing requirements.

a) b)

*Figure 7 a) Offset elevation axis, b) gap in backup structure*

The wheel and track azimuth rotating structure is particularly well suited to the SRC reflector as it enables the elevation axis to be located at the rim of the primary reflector for a short, direct load path from primary reflector surface to the azimuth rotating structure. With the elevation axis located at the rim of the reflector the middle of the azimuth structure can be open allowing the elevation assembly to rotate to low elevation angles, Figure 8.

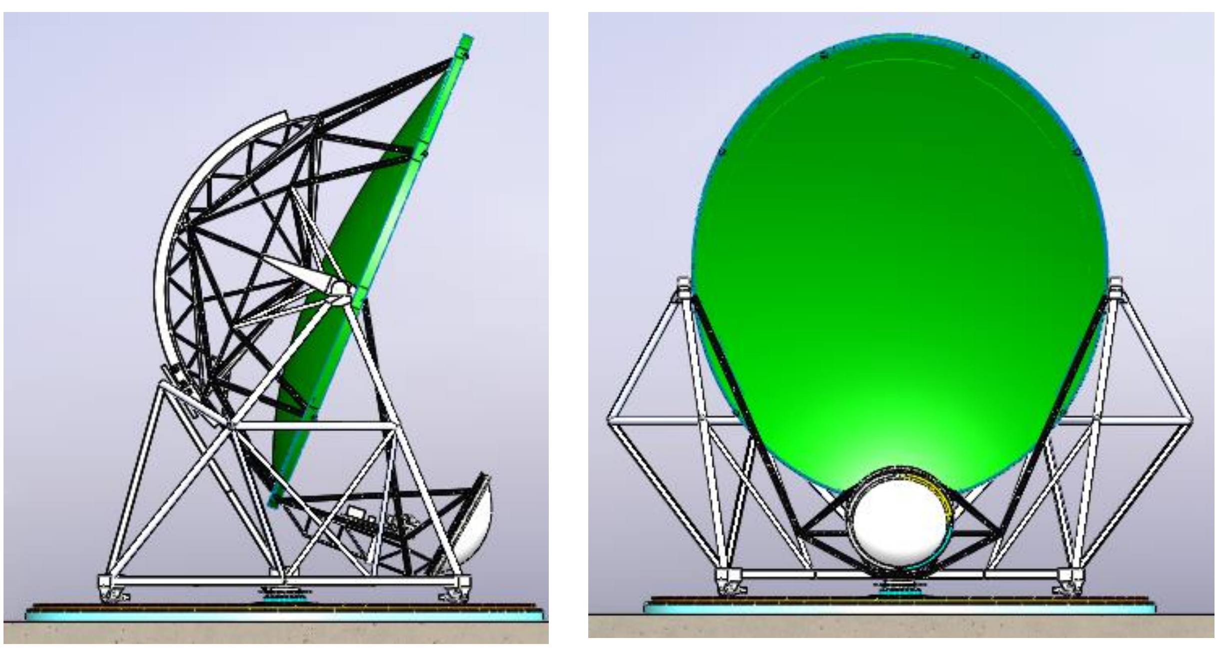

*Figure 8 ngDVA Antenna at 12° Elevation Angle*

The elevation drive uses direct drive technology (similar to ESO ALMA antennas) with a curvilinear rotor incorporated into the BUS and the stator mounted to the ARA. The azimuth axis is driven by friction of the four drive wheels, driven by servo motors through gearboxes, on the azimuth track. A large pintle bearing at the center of the ARA provides lateral stiffness. Further details of the mount concept selection can be found in [1].

## 4.2 Elevation Rotating Assembly

The ngDVA-15 Elevation Rotating Assembly, Figure 9, is designed around the DVA-1 optical prescription. The ngVLA optical prescription has not yet been designed but it is anticipated that it will be similar enough to the DVA-1 prescription that the differences would not have a large effect on the structural design.

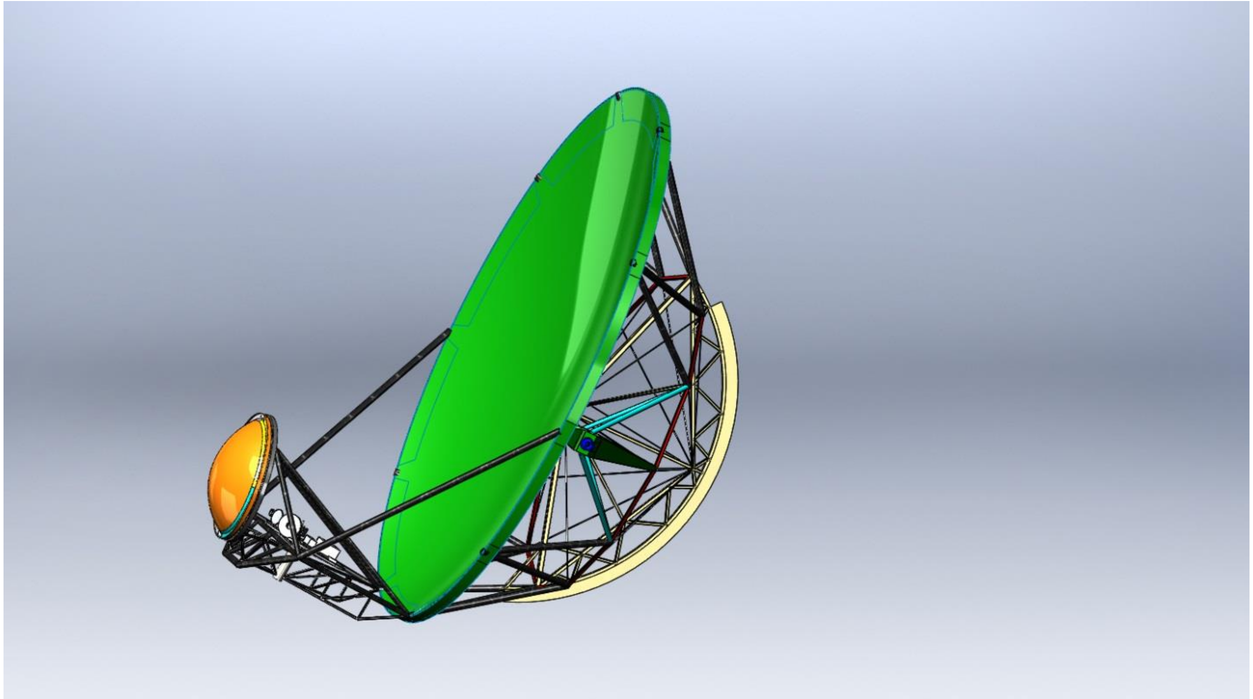

*Figure 9 ngDVA-15 Elevation Rotating Assembly*

The primary and secondary reflectors are rim supported single piece carbon composite structures, the same proven design as used on the DVA-1. The primary Backup-Structure and Secondary Support Structure retain some of the elements of the DVA-1 design but have optimized for the wheel-and-track ARA, feed-down configuration and increased stiffness requirements.

### 4.2.1 The Single Piece Carbon Composite Primary Reflector

The primary reflector is fabricated from vacuum infused carbon composite structures, Figure 10, primary reflector (green), with the composite backing pieces (red), and the dish rim connectors (cyan). The primary reflector with the vertical outer rim is molded in a single piece, the composite backing pieces and dish rim connectors are bonded on separately.

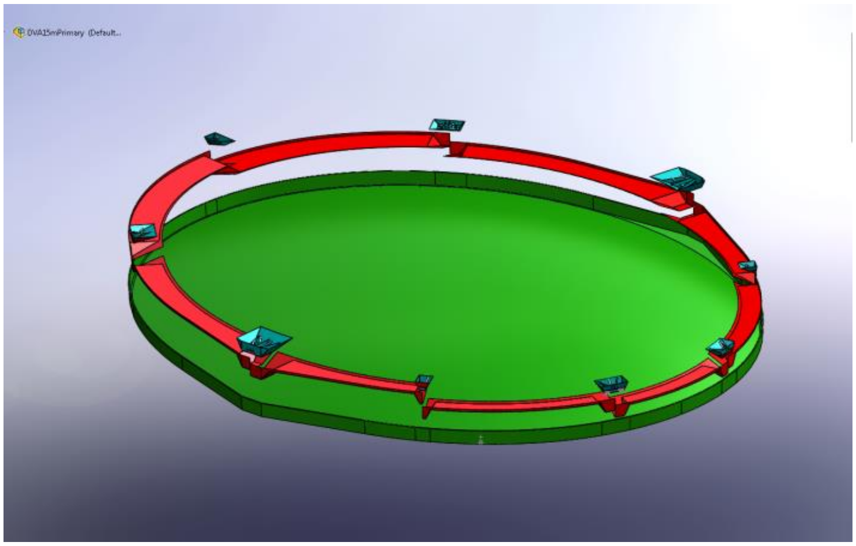

*Figure 10 Exploded view of the DVA-2 Primary Reflector*

### 4.2.2 The Backup Structure

The main components of the BUS, Figure 11, are; the central drive quadrant and truss (orange), inner diamond structure (red), elevation support structures (green), elevation support-box tubes (cyan), and outer back structure (black). The design presented here is the result of extensive optimization studies targeted at the lightest, stiffest and most cost efficient structure.

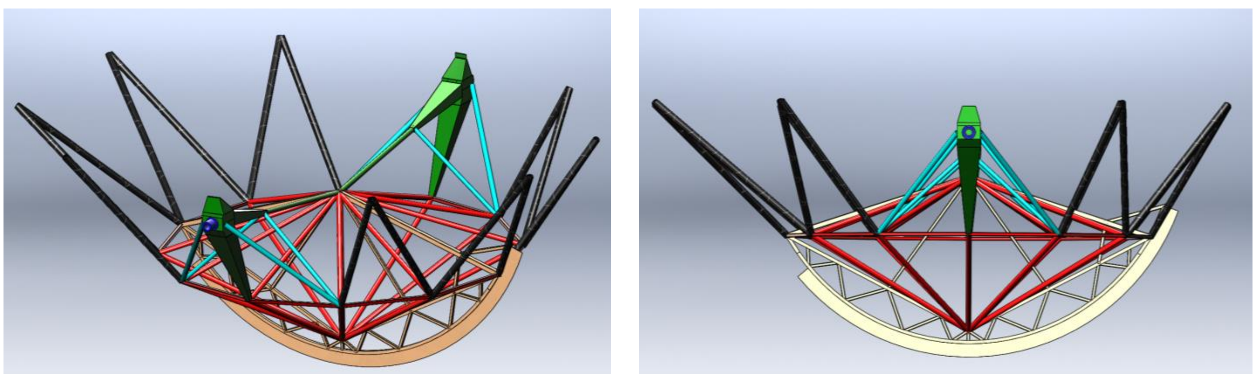

*Figure 11 ngDVA-15 Primary Reflector Backup Structure*

#### *4.2.2.1 The Inner Backup Structure*

The inner back structure, Figure 12, is made up of the drive quadrant (orange) and diamond (red).

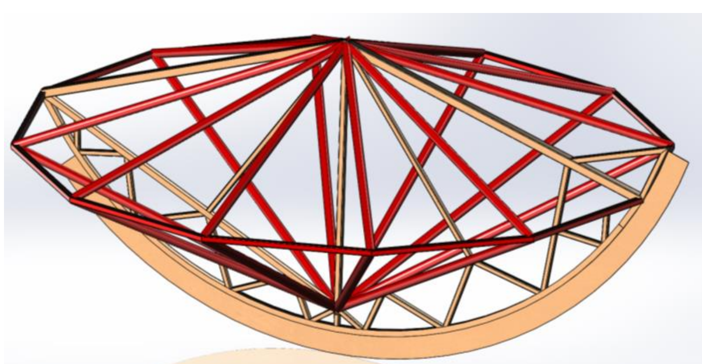

*Figure 12 Inner Backup Structure*

The quadrant is the least defined element of this design and the model shown in Figure 13 is notional, awaiting feedback from the linear drive company. The structure will be refined, will certainly change in detail, but for initial design purposes this is sufficient. It will be a welded steel truss structure with some bolted or field welded connections to allow transport from the factory. It would be essentially a planer structure, but would likely have more thickness than shown to support lateral loads from the linear drive system.

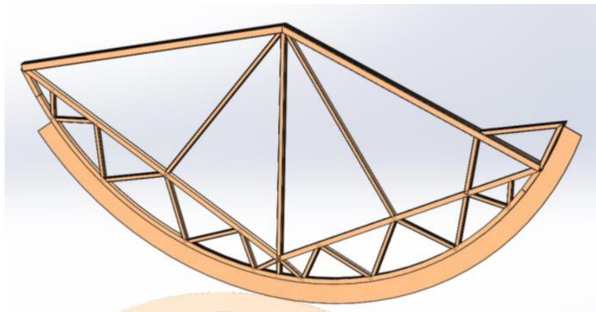

*Figure 13 Drive Quadrant*

The inner back structure (diamond structure) is an efficient way to provide a stiff structure that integrates support of the central drive quadrant as well as providing a landing point for the outer back structures tubes. In addition, the elevation bearing assemblies must be supported and a great deal of moment stiffness provided between the two elevation bearings located out at the rim of the primary reflector. The diamond structure in Figure 12 is modeled as a welded and bolted steel structure. Alternatively the radial members of the diamond could be tension members, either carbon fibre or solid stainless rods, Figure 14. Such a structure could represent a significant cost and weight saving, as well as simplicity of assembly.

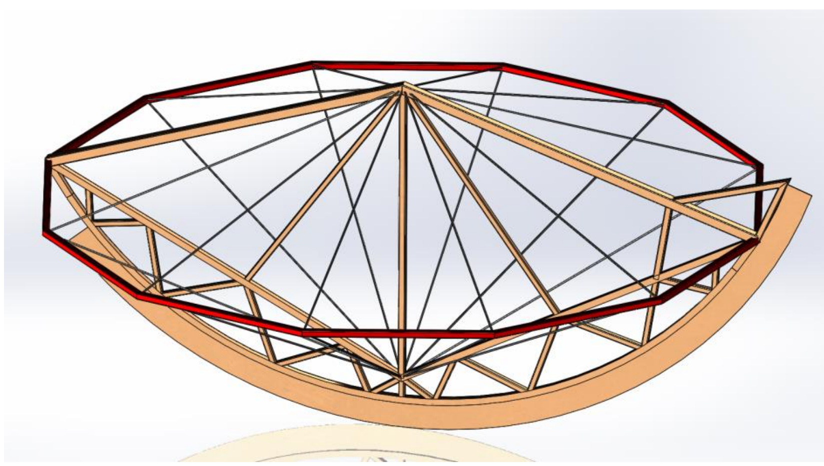

*Figure 14 Inner back structure with carbon rod rigging for the radial members of diamond.*

Figure 5: The inner back structure "diamond" represented as a welded steel rim with carbon rod rigging for the radial members.

#### *4.2.2.2 Elevation Support Structures*

The elevation support structures are shown in Figure 15. The left hand image shows the elevation support structures on the inner back structure. The right hand image is a detail of one of the elevation support structures. The purpose of this structure is to support the elevation bearing (dark blue), and to tie the loads from this bearing into the back structure. Since the separate elevation bearings on the wheel and track base structure are not stiff in the axial direction, the elevation support structure must provide stiffness in this direction.

This load path (from elevation bearing to elevation bearing), is the primary reason why the back structure for this ngDVA-15 is so different than the DVA-1. Additionally the elevation support structure must handle local moments generated by off axis loads through the elevation bearing. The elevation support structure (green in Figure 15) is designed to provide this moment support. It is a welded plate structure consisting of a hollow steel box with internal stiffeners in areas such as behind the elevation bearing and where the cyan legs attach. Because of the high stiffness and strength requirements together with a lower emphasis on weight saving at points near the elevation bearing, steel is the logical choice for this part of the structure.

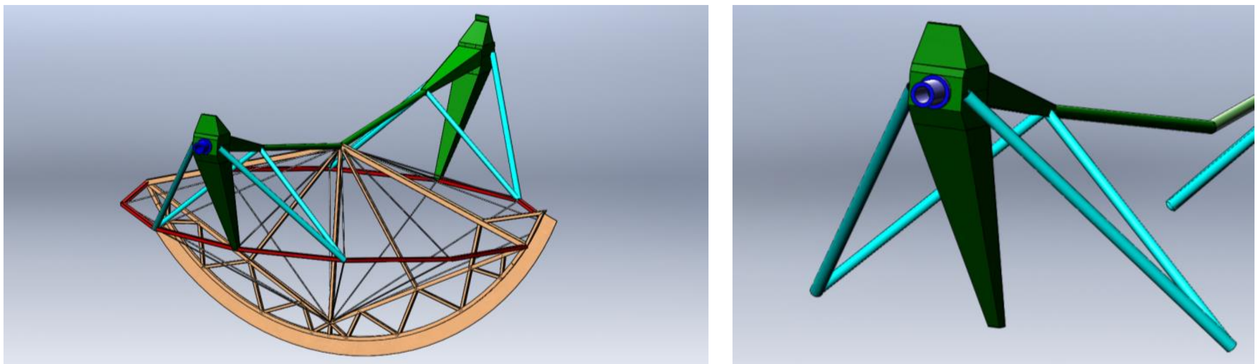

*Figure 15 Elevation Support Structures*

#### *4.2.2.3 Outer Back Structure*

The outer back structure is a system of tubes connecting between the outer edge of the inner back structure and the rim of the primary reflector. Carbon is the better choice for these tubes because of the high specific stiffness. Additional weight in this area increases gravitational deflections in the reflector surface so performance gains can be made with carbon tubes. The low weight of carbon tubes is also advantageous for reducing second-moment effects which are important for telescope rapid slewing and drive considerations and light weight carbon tubes are much easier for assembly.

This structure provides, together with a special shear connection to the Elevation Support Structure, the necessary support to the primary reflector surface. These tubes are shown in black in Figure 3 and Figure 7. Figure 7 shows just the outer back structure together with the elevation support structure. At the top end intersection point of each pair of black tubes there is a connection to the primary surface through the dish-rim-connector. At these points the composite dish is free to expand and contract independently from any thermal movement of the inner back structure. In addition to the eight connection points provided by the black tubes, there are two additional connection points provided on the top of the Elevation Support Structure.

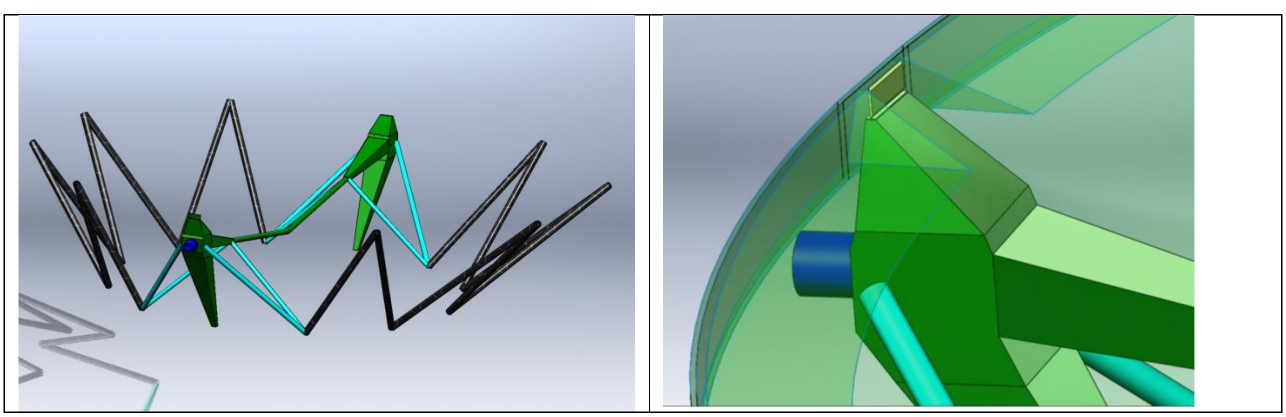

Figure 7: LHS, The Outer Back Structure, RHS, the Shear Connection at the Elevation Support Structure.

In the right-hand-side image in Figure 7 the connection between the composite reflector surface (shown as a translucent part) and the Elevation Support Structure is modelled as a yellow plate with knife edges top and bottom. This represents a doubly hinged plate structure which is stiff in directions perpendicular to the elevation axis yet flexible along the elevation axis direction. This connection is required instead of a fixed connection for two reasons. The first reason is structural flexing of the back structure. This joint isolates the dish surface from the small (but real) gravitational sag of the back structure between elevation bearings. This slight sag causes a small decrease in length between the support points from one elevation bearing to the other (which in turn distorts the surface). The second reason for these joints is differences in the coefficient of thermal expansion (CTE) between the composite front surface and the steel and composite back structure. Also this connection is necessary to provide a similar load path to that provided by the central diaphragm connection on the DVA-1, except now that the loads are all being transferred at the rim instead of between the central diaphragm and the rim (as on the DVA-1), the stress induced wrinkles seen near the center of the DVA-1 (and DVA-2), no longer exist, further improving the RMS error of the dish.

### 4.2.3 Secondary Support Structure

The secondary and feed support structure for the ngDVA-15 is shown in Figure 7. Considerable topological optimization work was carried out to develop this design. A major difference between the feed up DVA-1 design and this feed down design is the orientation of the feed indexer. In this example the indexer is notional and was adopted directly from an SKA prototype design; the final version will likely differ in detail, but will at least be of the same general configuration.

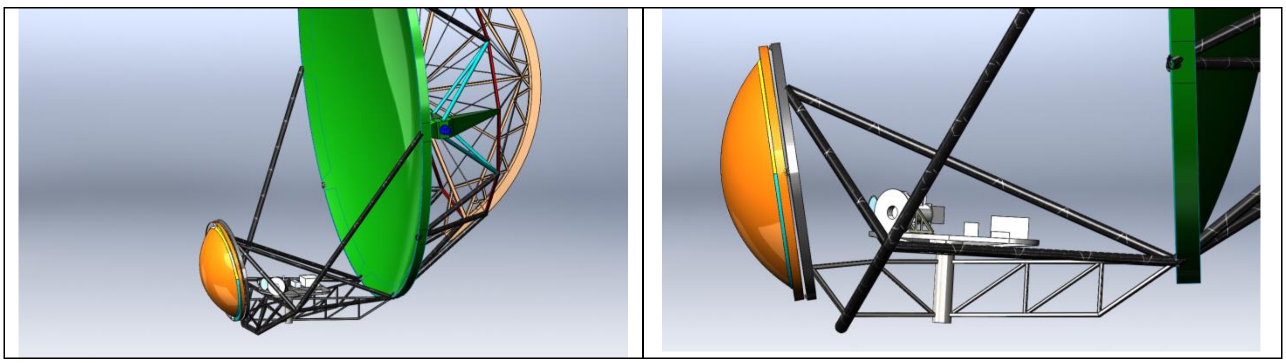

Figure 7: The secondary and feed support structure for the ngDVA-15

Figure 8 shows the primary carbon tube frame in the left hand side image and the X truss frame which supports the indexer and the lower part of the secondary support ring. This X frame was modeled as a steel component as a cost saving, but to bias to the higher performance side, this component should also be made from carbon fibre.

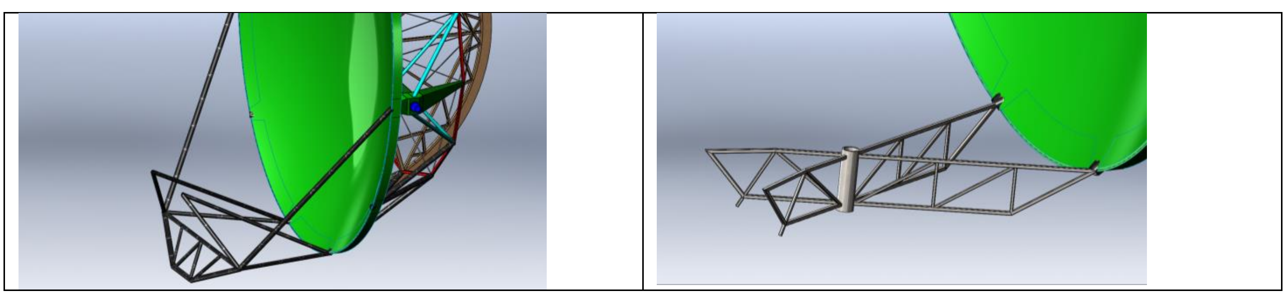

Figure 8: LHS Carbon support frame, RHS the X truss frame.

Not as much effort was expended on this structure as that spend on the primary back structure. More refinement is likely as the design moves from the concept stage to a detailed design.

### 4.2.4 Computational Results

To develop the primary and secondary support structure for the ngDVA-15, analysis of the surface shape of the primary and secondary reflectors is paramount. The initial design requirement is for the reflector surfaces to retain their shape under gravity for all elevation angles. Once this requirement has been met, then performance under wind conditions would be examined. For this design exercise only performance under gravity was examined. Previous design work on the DVA-1 under wind conditions showed that the rim supported composite design is very stable under wind and this result was taken as sufficient for this stage of the design process.

The outer back structure of the ngDVA-15 primary reflector allows eight points of adjustment. Subtle changes in "pretention" have been investigated both in the FEA model used for the ngDVA-15 and in the real world on the DVA-2. These tension changes on the outer support legs can be used to adjust global (low spatial frequency) errors in the primary dish shape. Furthermore, it is possible to optimize the dish shape at different elevation angles. In the FEA model this exercise was carried out and showed that the surface RMS error could be minimized for one elevation angle, with the consequence that it was slightly worse for elevation angles outside of this "rigging angle". Clearly, one could build "active" adjusters on some or all of the 8 support legs to further increase the performance of the primary reflector.

Figure 9 shows the primary surface residual error at 15 degrees elevation for one condition of pretention. The left hand plot is the 3-dimentional error, while the right hand plot shows the error in the "Z" direction which is perpendicular to a plane through the rim of the dish. The primary reflector is actually elliptical, but is represented as circular in these plots. As can be seen the 3-D error is 81 microns and the Z component error 60 microns. In this example the RMS minimum was set at 55 degrees elevation (see figure 10). Also further tweaking of the pretensions would also have led to slightly better (ie lower) RMS values. Figure 11 shows the results at 15 degrees elevation. Again this is by design; the minimum was chosen at 55 degrees. If the desired minimum RMS value was set at 15 degrees then this angle would show the lowest RMS.

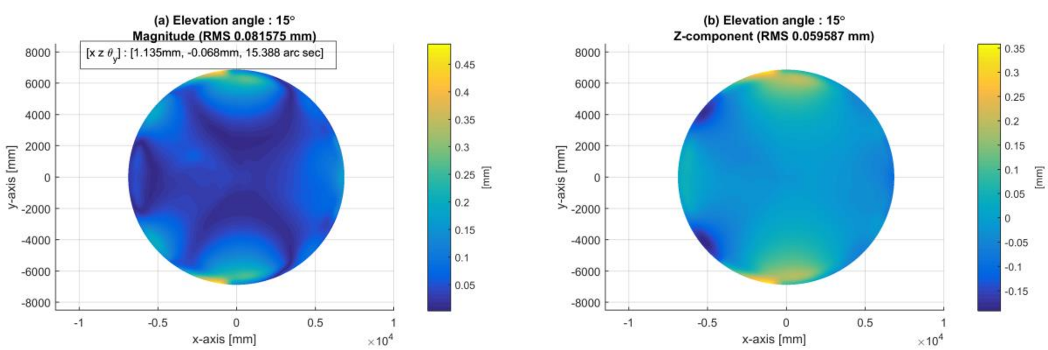


Figure 9: One case of RMS error plots for the ngDVA-15 telescope prototype design.

If the target gravitational RMS error is about 50-60 microns, then the root-sum-square error when combining this with the as-molded primary surface error (target around 160 microns) would yield a total combined error (molded error plus gravity) of 170 microns which puts us in the ball park for the ngVLA design requirements.

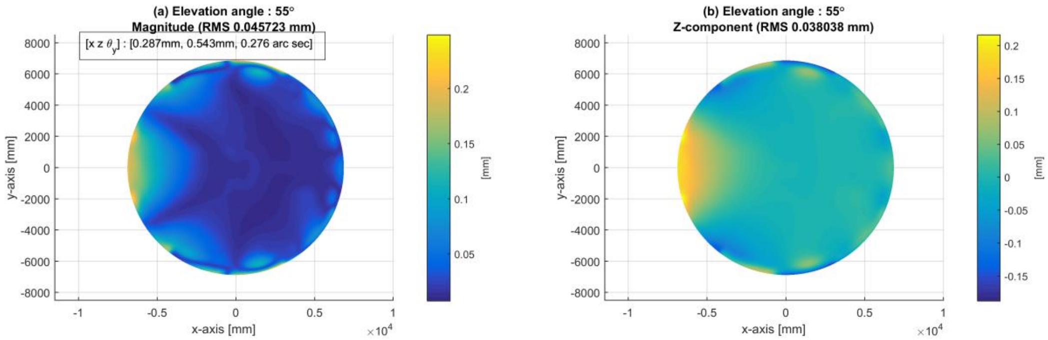


Figure 10: RMS residual error plots for the ngDVA-15 primary reflector at 55 degrees.

Further refinement is possible of course. These results are preliminary and would be further optimized as the backup structure is further refined. The surface must also be adjusted at a "best" elevation angle (rigging angle), and either allowed to fall slightly away from the optimum when at angle far away from this angle or some small number of outer back structure support legs (probably two or four) should be equipped with active adjusters and an open loop control set to a simple function of elevation angle.

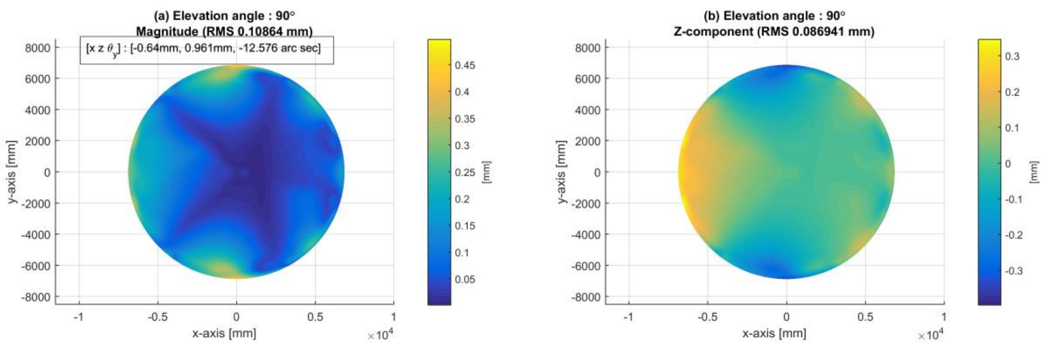


Figure 11: RMS residual error plots for the ngDVA-15 primary reflector at 90 degrees elevation.

# 5 Cost Estimation

Bottom-up cost estimates were performed for the ngDVA-15 ERA and ARA and a combined cost determined. Within these estimates analogous and parametric techniques were applied as appropriate depending on the level of detail and information available for a particular component.

## 5.1 Elevation Rotating Assembly Cost Estimate

The cost estimate summary for the ERA is shown in Table 1.

*Table 1 ngDVA-15 ERA Cost Estimate*

| | | | | | |
|---|---|---|---|---|---|
| INSTRUMENT | ngVLA | | | | |
| Quatity | 308 | | | | |
| OPTION: | **15m Feed-Low Offset Gregorian Elevation Rotating Assembly** | | | | |
| | **ITEM NAME** | **ngDVA-15** | **COST ($)** | **Contingency %** | **Total + Contingency k$** |
| | **GRAND TOTAL** | | **840566.7** | **17%** | **987659.9** |
| **1** | **Dish Structure Management** | | **90602.7** | | **99663.0** |
| 1.1 | Management | 5% | 36241.1 | 10% | 39865.2 |
| 1.2 | System Engineering | 5% | 36241.1 | 10% | 39865.2 |
| 1.3 | Product Assurance | 3% | 18120.5 | 10% | 19932.6 |
| **2** | **Dish Structure Manufacturing** | | **724822.0** | | **862854.8** |
| 2.2 | Elevation Rotating Structure | | 724822.0 | | 862854.8 |
| 2.2.1 | Primary Reflector | | | | |
| 2.2.1.1 | Primary Reflector Surface | | 155725.9 | 20% | 186871.1 |
| 2.2.1.2 | Primary Composite Backing Pieces | | 31989.8 | 18% | 37747.9 |
| 2.2.1.3 | Dish Rim Connectors | | 8947.0 | 40% | 12525.8 |
| 2.2.2 | Secondary Reflector | | | | |
| 2.2.2.1 | Secondary Reflector Surface | | 22594.9 | 20% | 27113.8 |
| 2.2.2.2 | Secondary Composite Backing Pieces | | 5420.3 | 18% | 6396.0 |
| 2.2.2.3 | Sub reflector Mount/Adjusters | | 5860.0 | 12% | 6563.2 |
| 2.2.3 | Primary Reflector Backup Structure | | | | |
| 2.2.3.1 | Diamond and Quadrant Structure | | 81538.6 | 18% | 96215.6 |
| 2.2.3.2 | Elevation Shaft Support Structure | | 64958.1 | 10% | 71453.9 |
| 2.2.3.3 | Outer Back Structure Tubes | | 150134.8 | 20% | 180161.8 |
| 2.2.3.4 | Elevation Shaft Support Tubes | | 17519.8 | 10% | 19271.8 |
| 2.2.4 | Feed and Seconary Reflector Support Structure | | | | |
| 2.2.4.1 | Feed indexer Support Structure | | 22097.0 | 18% | 26074.5 |
| 2.2.4.2 | Secondary Support Tubes | | 98863.8 | 20% | 118636.6 |
| 2.2.4.3 | Secondary Support Ring | | 9172.0 | 18% | 10823.0 |
| 2.2.5 | Feed Indexer | | 50000.0 | 26% | 63000.0 |
| **3** | **Dish Structure Integration & Verification** | | **25142.0** | | **25142.0** |
| 3.1 | Assembly On Site | | 14142.0 | 18% | 16687.6 |
| 3.2 | Test & Verification | | 5000.0 | 12% | 5600.0 |
| 3.3 | Miscellaneous | | 5000.0 | 5% | 5250.0 |
| 3.4 | Documentation | | 1000.0 | 18% | 1180.0 |

Contingencies are calculated using the Risk Factors shown in Table 2 and the Risk Percentages shown in Table 3 with the following formula;

$$\%Contingency = RF_t * RP_t + RF_c * RP_c + RF_s * RP_s$$

*Table 2 Contingency Risk Factors*

| | Risk Factors | | |
|---|---|---|---|
| | **Technical** | **Cost** | **Schedule** |
| 1 | Existing design and off-the-shelf hardware | Off the shelf or catalog item | not used |
| 2 | Minor modifications to an existing design | Vendor quote from established drawings | No schedule impact on any other item |
| 3 | Extensive modifications to an existing design | Vendor quote with some design sketches | not used |
| 4 | New design within established product line | In-house estimate for item within current product line | Delays completion of non-critical path subsystem item |
| 6 | New design different from established product line. Existing technology | In-house estimate for item with minimal company experience but related to existing capabilities | not used |
| 8 | New design. Requires some R&D development but does not advance the state-of-the-art | In-house estimate for item with minimal company experience and minimal inhouse capability | Delays completion of critical path subsystem item |
| 10 | New design. Development of new technology which advances the state-of-the-art | Top down estimate from analogous programs | not used |
| 15 | New design way beyond the current state-of-the-art | Engineering judgment | not used |

*Table 3 Contingency Risk Percentages*

| Risk Percentages | | |
|---|---|---|
| | Condition | Risk Percentage |
| Technical | Design OR Manufacturing concerns only | 2% |
| | Design AND Manufacturing concerns | 4% |
| Cost | Material cost OR Labour rate concerns only | 1% |
| | Material cost AND Labour rate concerns | 2% |
| Schedule | | 1% |

## 5.2 Azimuth Rotating Assembly Cost Estimate

The ARA cost estimate is taken directly from [1].

*Table 4 ARA Cost Estimate*

| | ARA Cost Summary | K$ |
|---|---|---|
| 1.0 | Struct Steel Fabrication, Painting & Shipping to Site | $252.1 |
| 2.0 | Mechanical Components (Incl Packing & Shipping) | $412.1 |
| 3.0 | Site Assembly of ARA | $117.9 |
| 5.0 | Foundation Construction W& T | $140.2 |
| | Total | $922.3 |

## 5.3 ngDVA-15 Cost Estimate

The cost estimate for the ngDVA-15 Antenna is 1.9M US$.

This estimate includes the cost of the foundation.

Composite tooling (molds) cost is not included but has been estimated to only add ~20k US$ per antenna.

# 6 Conclusions and Recommendations

An antenna design concept has been presented to inform the ngVLA project. The initial analysis shows the potential to fulfill the ngVLA requirements at a reasonable cost. Further analysis would need to be performed in order to determine full compliance of this design to ngVLA requirements but as the ngVLA reference design was produced part way through this study and includes the requirement for 18m diameter antenna this analysis was not completed.

Single-piece Rim-Supported Composite reflector technology has been developed for an 15m diameter antenna operating at up to 50 GHz. Further development is required in the areas of surface reflectivity and surface accuracy in order to meet the ngVLA requirements but no show stoppers have as yet been identified.

For an offset-low antenna configuration with high pointing accuracy requirements the mount design presents a challenge [1]. The SRC ERA combined with a wheel and track ARA shows very good potential for meeting the requirements at a reasonable cost.

# 7 References


1. Matt Fleming, "Exploration of Suitable Mounts for a 15m Offset Antenna Next Generation Very Large Array NRC 15m Mount", ngVLA Memo #25, Oct, 2017
2. Doug Henke, Gordon Lacy, Ivan Wevers, Pat Niranjanan, and Felipe Miranda, "Fabry-Perot Resonator Design for the Measurement of Surface Reflectivity" GSMM2016 Presentation, June 2016.

# Appendix A ERA Cost Estimate Details

*Table 5 ERA Component Cost Details*

| | Primary Reflector Surface | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.1.1** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.1.1.1 | A&P QISO 537gsm T700 fibre | FEM | 850 | kg | N10 | $51 | - | | | | | $ 43,350.00 | |
| 2.2.1.1.2 | 1/4" H130 core grooved one side both ways and perfed | EE,FEM | 1 | kit | N10 | $2,700 | | | | | | $ 2,700.00 | |
| 2.2.1.1.3 | Resin, Proset INF 114-4 Infusion Epoxy | EE,FEM | 840 | l | N10 | $16 | - | | | | | $ 13,532.40 | |
| 2.2.1.1.4 | Surface Reflective Material | EE,FEM | 330 | m^2 | N10 | $57 | | | | | | $ 18,810.00 | |
| 2.2.1.1.5 | Saertex 2712gm/m^2 50-50 eglass-carbon hybrid | EE,FEM | 765 | kg | N10 | $27 | | | | | | $ 20,272.50 | |
| 2.2.1.1.6 | Eglass Veil | EE,FEM | 1250 | m^2 | N10 | $2 | | | | | | $ 2,625.00 | |
| 2.2.1.1.7 | Triangle Paint | EE,FEM | 700 | m^2 | N10 | $5 | | | | | | $ 3,500.00 | |
| 2.2.1.1.8 | Epoxy primer | EE,FEM | 700 | m^2 | N10 | $5 | | | | | | $ 3,150.00 | |
| 2.2.1.1.9 | Adhesive, Hysol | FEM | 48 | tube | N10 | $85 | - | | | | | $ 4,080.00 | |
| 2.2.1.1.10 | Materials Preparation Labour | EE | | | | | | | | | | $ 9,500.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.11 | Mold Prep Labour | EE | | | | | | | | | | $ 1,206.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.12 | Layup Labour | EE | | | | | | | | | | $ 20,259.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.13 | Infusion Labour | EE | | | | | | | | | | $ 3,564.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.14 | Post Cure Labour | EE | | | | | | | | | | $ 2,793.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.15 | Bonding labour | EE | | | | | | | | | | $ 4,632.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.16 | Demolding Labour | EE | | | | | | | | | | $ 543.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.1.17 | Finishing Labour | EE | | | | | | | | | | $ 1,209.00 | See ngVLA 15m ERS Assembly.mpp |
| | | | | | | | | | | | | $155,725.9 | |

| | Primary Composite Backing Pieces | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.1.2** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.1.2.1 | A&P QISO 537gsm T700 fibre | FEM | 192 | kg | N10 | $51 | - | | | | | $ 9,792.00 | |
| 2.2.1.2.2 | 1/4" H130 core grooved one side both ways and perfed | EE,FEM | 1 | kit | N10 | $2,700 | | | | | | $ 2,700.00 | |
| 2.2.1.2.3 | Resin, Proset INF 114-4 Infusion Epoxy | FEM | 112 | l | N10 | $16 | - | | | | | $ 1,792.00 | |
| 2.2.1.2.4 | Adhesive, Hysol | FEM | 59 | tube | N10 | $85 | - | | | | | $ 5,015.00 | |
| 2.2.1.2.5 | Materials Preparation Labour | EE | | | | | | | | | | $ 2,145.88 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.6 | Mold Prep Labour | EE | | | | | | | | | | $ 272.41 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.7 | Layup Labour | EE | | | | | | | | | | $ 4,576.15 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.8 | Infusion Labour | EE | | | | | | | | | | $ 805.04 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.9 | Post Cure Labour | EE | | | | | | | | | | $ 630.89 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.10 | Bonding labour | EE | | | | | | | | | | $ 1,046.29 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.11 | Demolding Labour | EE | | | | | | | | | | $ 122.65 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.12 | Finishing Labour | EE | | | | | | | | | | $ 273.09 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.2.13 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.25 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.35 | 2337.2 | |
| 2.2.1.2.14 | Trucking Shipmet to Site (1500 mi) - 0.25 trucks x 2 days | EE | 0.25 | Day | N9 | $276 | Driver B-34( | 0.25 | 24 | 6 | $68.70 | 481.2 | 0.25 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $31,989.8 | |

| | Dish Rim Connectors | Mat | | | | Mat / Equi | Labor | | | | Labor & | Total Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quan | Mat | Unit | Ref | Unit Cost | Crew | | | Labor | Equip N2 | Incl O&P | Remarks |
| | | Ref | Quan | Meas | Mat $ | $/Unit | Ref (N2) | | | Hrs | Cost $/Hr | K$ | |
| **2.2.1.3** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.1.3.1 | A&P QISO 537gsm T700 fibre | FEM | 42 | kg | N10 | $51 | - | | | | | 2142.0 | |
| 2.2.1.3.2 | Resin, Proset INF 114-4 Infusion Epoxy | FEM | 41 | l | N10 | $16 | - | | | | | 656.0 | |
| 2.2.1.3.3 | Adhesive, Hysol | FEM | 37 | tube | N10 | $85 | - | | | | | 3145.0 | |
| 2.2.1.3.4 | Mold Prep Labour | EE | | | | | | | | | | $ 106.03 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.5 | Layup Labour | EE | | | | | | | | | | $ 13.46 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.6 | Infusion Labour | EE | | | | | | | | | | $ 226.12 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.7 | Post Cure Labour | EE | | | | | | | | | | $ 39.78 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.8 | Bonding labour | EE | | | | | | | | | | $ 31.17 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.9 | Demolding Labour | EE | | | | | | | | | | $ 51.70 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.10 | Finishing Labour | EE | | | | | | | | | | $ 6.06 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.1.3.11 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.25 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.35 | 2337.2 | |
| 2.2.1.3.12 | Trucking Shipmet to Site (1500 mi) - 0.25 trucks x 4 days | EE | 0.1 | Day | N9 | $276 | Driver B-34( | 0.1 | 24 | 2.4 | $68.70 | 192.5 | 0.1 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $8,947.0 | |

| | Secondary Reflector Surface | Mat | | | | Mat / Equi | Labor | | | | Labor & | Total Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quan | Mat | Unit | Ref | Unit Cost | Crew | | | Labor | Equip N2 | Incl O&P | Remarks |
| | | Ref | Quan | Meas | Mat $ | $/Unit | Ref (N2) | | | Hrs | Cost $/Hr | K$ | |
| **2.2.2.1** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.2.1.1 | A&P QISO 537gsm T700 fibre | FEM | 58 | kg | N10 | $51 | - | | | | | $ 2,958.00 | |
| 2.2.2.1.2 | 1/4" H130 core grooved one side both ways and perfed | EE,FEM | 1 | kit | N10 | $410 | | | | | | $ 410.00 | |
| 2.2.2.1.3 | Resin, Proset INF 114-4 Infusion Epoxy | EE,FEM | 70 | l | N10 | $16 | - | | | | | $ 1,120.00 | |
| 2.2.2.1.4 | Surface Reflective Material | EE,FEM | 26 | m^2 | N10 | $57 | | | | | | $ 1,482.00 | |
| 2.2.2.1.5 | Saertex 2712gm/m^2 50-50 eglass-carbon hybrid | EE,FEM | 50 | kg | N10 | $27 | | | | | | $ 1,325.00 | |
| 2.2.2.1.6 | Eglass Veil | EE,FEM | 105 | m^2 | N10 | $2 | | | | | | $ 220.50 | |
| 2.2.2.1.7 | Triangle Paint | EE,FEM | 52 | m^2 | N10 | $5 | | | | | | $ 260.00 | |
| 2.2.2.1.8 | Epoxy primer | EE,FEM | 52 | m^2 | N10 | $5 | | | | | | $ 234.00 | |
| 2.2.2.1.9 | Adhesive, Hysol | FEM | 10 | tube | N10 | $85 | - | | | | | $ 850.00 | |
| 2.2.2.1.10 | Materials Preparation Labour | EE | | | | | | | | | | $ 1,192.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.11 | Mold Prep Labour | EE | | | | | | | | | | $ 729.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.12 | Layup Labour | EE | | | | | | | | | | $ 4,399.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.13 | Infusion Labour | EE | | | | | | | | | | $ 1,183.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.14 | Post Cure Labour | EE | | | | | | | | | | $ 1,713.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.15 | Bonding labour | EE | | | | | | | | | | $ 489.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.16 | Demolding Labour | EE | | | | | | | | | | $ 243.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.17 | Finishing Labour | EE | | | | | | | | | | $ 969.00 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.1.18 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.25 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.35 | 2337.2 | |
| 2.2.2.1.19 | Trucking Shipmet to Site (1500 mi) - 0.25 trucks x 2 days | EE | 0.25 | Day | N9 | $276 | Driver B-34( | 0.25 | 24 | 6 | $68.70 | 481.2 | 0.25 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $22,594.9 | |

| | Secondary Composite Backing Pieces | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.2.2** | **Fabrication** | | | | | | | | | | | | |
| 2.2.2.2.1 | A&P QISO 537gsm T700 fibre | FEM | 20 | kg | N10 | $51 | - | | | | | $ 1,020.00 | |
| 2.2.2.2.2 | 1/4" H130 core grooved one side both ways and perfed | EE,FEM | 1 | kit | N10 | $300 | | | | | | $ 300.00 | |
| 2.2.2.2.3 | Resin, Proset INF 114-4 Infusion Epoxy | FEM | 10 | l | N10 | $16 | - | | | | | $ 160.00 | |
| 2.2.2.2.4 | Adhesive, Hysol | FEM | 6 | tube | N10 | $85 | - | | | | | $ 510.00 | |
| 2.2.2.2.5 | Mold Prep Labour | EE | | | | | | | | | | $ 411.03 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.6 | Layup Labour | EE | | | | | | | | | | $ 251.38 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.7 | Infusion Labour | EE | | | | | | | | | | $ 1,516.90 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.8 | Post Cure Labour | EE | | | | | | | | | | $ 407.93 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.9 | Bonding labour | EE | | | | | | | | | | $ 590.69 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.10 | Demolding Labour | EE | | | | | | | | | | $ 168.62 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.2.2.11 | Finishing Labour | EE | | | | | | | | | | $ 83.79 | See ngVLA 15m ERS Assembly.mpp |
| | | | | | | | | | | | | $5,420.3 | |

| | Sub reflector Mount/Adjusters | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.2.3** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.2.3.1 | Aluminum Bar 8" for end fittings | EE,FEM | 8 | ft | N10 | $275 | | | | | | $ 2,200.00 | |
| 2.2.2.3.2 | Machine Mounts/adjusters | EE,FEM | | | | | Crew B1 | 8 | 2 | 16 | $183.00 | $ 2,928.00 | 8 fittings - 2hrs machine time each |
| 2.2.2.3.3 | Bond End fittings | EE,FEM | | | | | Crew B1 | 8 | 0.5 | 4 | $183.00 | $ 732.00 | 8 fittings - 1/2hrs bond time each |
| | | | | | | | | | | | | $5,860.0 | |

| | Diamond and Quadrant Structure | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | Qty | Hrs/per | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.3.1** | **Struct Steel Frabricaiton, Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.3.1.1 | Steel Rd & Sq Section Members (Raw Mat + Del) | FEM | 6 | tons | N5 | $3,400 | - | | | | | $ 20,400.00 | |
| 2.2.3.1.2 | Cut fit and join for length, Add Plate End Fab | EE,FEM | 0.5 | tons | N6 | $3,000 | Crew B1 | 55 | 2 | 110 | $183.00 | $ 21,630.00 | Number Members = 55 from FEM, 2 hr/mer |
| 2.2.3.1.3 | Joint Struct. Simple Weldmt (2-5 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 32 | 2 | 64 | $183.00 | $ 11,712.00 | 32 Jts @4 hr/Jt |
| 2.2.3.1.4 | Joint Struct Medium Weldmt (6- 9 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 7 | 4 | 28 | $183.00 | $ 5,124.00 | 7 Jts @8 hr/Jt |
| 2.2.3.1.5 | Joint Struct Complex Weldmt (10 + Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 2 | 8 | 16 | $183.00 | $ 2,928.00 | 2 Jts @16 hr/Jt |
| 2.2.3.1.6 | Prep. (Sand Bast) | EE | 1000 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.38 | $ 6,147.50 | |
| 2.2.3.1.7 | Prime & Paint | EE | 1000 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.38 | $ 5,747.50 | |
| 2.2.3.1.8 | Skid & Crate Const - Load Mat on skids and crates | EE | 3 | Ea | N3 | $500 | Crew E17 | | | 24 | $184.38 | $ 5,925.00 | |
| 2.2.3.1.9 | Trucking Shipmet to Site (1500 mi) - 1 trucks x 2 days | EE | 1 | Day | N9 | $276 | Driver B-34( | 1 | 24 | 24 | $68.70 | $ 1,924.63 | 1 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $81,538.6 | |

| | Elevation Shaft Support Structure | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.3.2** | **Struct Steel Frabricaiton, Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.3.2.1 | Steel Rd & Sq Section Members (Raw Mat + Del) | FEM | 1.5 | tons | N5 | $4,758 | - | | | | | $ 7,136.25 | Risa Mat Take-off Steel |
| 2.2.3.2.2 | Cut fit and join for length, Add Plate End Fab | EE,FEM | 0.1 | tons | N6 | $3,000 | Crew B1 | 17 | 2 | 34 | $279.35 | $ 9,797.82 | Number Members = 17 from FEM, 2 hr/me |
| 2.2.3.2.3 | Joint Struct. Simple Weldmt (2-5 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 64 | 2 | 128 | $279.35 | $ 35,756.48 | 64 Jts @4 hr/Jt |
| 2.2.3.2.4 | Joint Struct Medium Weldmt (6- 9 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 0 | 4 | 0 | $279.35 | $ - | 0 Jts @8 hr/Jt |
| 2.2.3.2.5 | Joint Struct Complex Weldmt (10 + Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 0 | 8 | 0 | $279.35 | $ - | 0 Jts @16 hr/Jt |
| 2.2.3.2.6 | Prep. (Sand Bast) | EE | 325 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.35 | $ 4,486.50 | |
| 2.2.3.2.7 | Prime & Paint | EE | 325 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.35 | $ 4,356.50 | |
| 2.2.3.2.8 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.5 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.35 | $ 2,462.20 | |
| 2.2.3.2.9 | Trucking Shipmet to Site (1500 mi) - 0.5 trucks x 2 days | EE | 0.5 | Day | N9 | $276 | Driver B-34( | 0.5 | 24 | 12 | $68.70 | $ 962.31 | 0.5 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $64,958.1 | |

| | Outer Back Structure Tubes | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.3.3** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.3.3.1 | Carbon Fiber 8" Tube Members (Raw Mat + Del) | FEM | 80 | m | N10 | $1,400 | - | | | | | $112,000.00 | CST Composite quote |
| 2.2.3.3.2 | Aluminum Bar 8" for end fittings | EE,FEM | 2880 | lb | N6 | $5 | | | | | | $ 12,960.00 | 16 tubes x 2 ends x 1.5'/end |
| 2.2.3.3.3 | Machine End Fittings | EE,FEM | 32 | ea | N6 | | | 32 | 2 | 64 | $100.00 | $ 6,400.00 | 32 fittings - 2hrs machine time each |
| 2.2.3.3.4 | Bond End fittings | EE,FEM | 32 | ea | N6 | | Crew B1 | 32 | 1 | 32 | $183.00 | $ 5,856.00 | 32 fittings - 1hrs bond time each |
| 2.2.3.3.5 | Prep. (Clean) | EE | 560 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.38 | $ 5,065.10 | |
| 2.2.3.3.6 | Prime & Paint | EE | 560 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.38 | $ 4,841.10 | |
| 2.2.3.3.7 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.5 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.38 | $ 2,462.50 | |
| 2.2.3.3.8 | Trucking Shipmet to Site (1500 mi) - 1 trucks x 2 days | EE | 0.5 | Day | N9 | $276 | Driver B-34( | 0.5 | 12 | 6 | $68.70 | $ 550.11 | 0.5 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $150,134.8 | |

| | Elevation Shaft Support Tubes | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.3.4** | **Struct Steel Frabrication, Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.3.4.1 | Steel Rd & Sq Section Members (Raw Mat + Del) | FEM | 0.5 | tons | N5 | $3,000 | - | | | | | $ 1,500.00 | Risa Mat Take-off Steel |
| 2.2.3.4.2 | Cut fit and join for length, Add Plate End Fab | EE,FEM | 0.05 | tons | N6 | $3,000 | Crew B1 | 8 | 2 | 16 | $183.00 | $ 3,078.00 | Number Members = 8 from FEM, 2 hr/mem |
| 2.2.3.4.3 | Joint Struct. Simple Weldmt (2-5 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 4 | 2 | 8 | $183.00 | $ 1,464.00 | 4 Jts @4 hr/Jt |
| 2.2.3.4.4 | Prep. (Sand Bast) | EE | 150 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.38 | $ 4,056.50 | |
| 2.2.3.4.5 | Prime & Paint | EE | 150 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.38 | $ 3,996.50 | |
| 2.2.3.4.6 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.5 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.38 | $ 2,462.50 | |
| 2.2.3.4.7 | Trucking Shipmet to Site (1500 mi) - 0.5 trucks x 2 days | EE | 0.5 | Day | N9 | $276 | Driver B-34( | 0.5 | 24 | 12 | $68.70 | $ 962.31 | 0.5 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $17,519.8 | |

| | Feed indexer Support Structure | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.4.1** | **Struct Steel Frabricaiton, Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.4.1.1 | Steel Rd & Sq Section Members (Raw Mat + Del) | FEM | 0.5 | tons | N5 | $3,000 | - | | | | | $ 1,500.00 | Risa Mat Take-off Steel |
| 2.2.4.1.2 | Cut fit and join for length, Add Plate End Fab | EE,FEM | 0.05 | tons | N6 | $3,000 | Crew B1 | 26 | 1 | 26 | $183.00 | $ 4,908.00 | Number Members = 8 from FEM, 1 hr/mem |
| 2.2.4.1.3 | Joint Struct. Simple Weldmt (2-5 Members) | EE,FEM | 0 | tons | N6 | $3,000 | Crew B1 | 12 | 2 | 24 | $183.00 | $ 4,392.00 | 12 Jts @2 hr/Jt |
| 2.2.4.1.4 | Prep. (Sand Bast) | EE | 110 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.38 | $ 3,958.10 | |
| 2.2.4.1.5 | Prime & Paint | EE | 110 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.38 | $ 3,914.10 | |
| 2.2.4.1.6 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.5 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.38 | $ 2,462.50 | |
| 2.2.4.1.7 | Trucking Shipmet to Site (1500 mi) - 0.5 trucks x 2 days | EE | 0.5 | Day | N9 | $276 | Driver B-34( | 0.5 | 24 | 12 | $68.70 | $ 962.31 | 0.5 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $22,097.0 | |

| | Secondary Support Tubes | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.4.2** | **Fabrication, Assembly Painting & Shipping to Site** | | | | | | | | | | | | |
| 2.2.4.2.1 | Carbon Fiber 8" Tube Members (Raw Mat + Del) | FEM | 27 | m | N5 | $1,200 | - | | | | | $ 32,400.00 | CST Composite quote |
| 2.2.4.2.2 | Carbon Fiber 6" Tube Members (Raw Mat + Del) | FEM | 38 | m | N5 | $850 | - | | | | | $ 32,300.00 | CST Composite quote |
| 2.2.4.2.3 | Carbon Fiber 5" Tube Members (Raw Mat + Del) | FEM | 7 | m | N5 | $700 | - | | | | | $ 4,900.00 | CST Composite quote |
| 2.2.4.2.4 | Aluminum Bar 8" for end fittings | EE,FEM | 5 | ft | N6 | $275 | | | | | | $ 1,375.00 | 5 tubes x 2 ends x 0.5'/end |
| 2.2.4.2.5 | Aluminum Bar 6" for end fittings | EE,FEM | 7 | ft | N6 | $275 | | | | | | $ 1,925.00 | 7 tubes x 2 ends x 0.5'/end |
| 2.2.4.2.6 | Aluminum Bar 5" for end fittings | EE,FEM | 4 | ft | N6 | $275 | | | | | | $ 1,100.00 | 4 tubes x 2 ends x 0.5'/end |
| 2.2.4.2.7 | Machine End Fittings | EE,FEM | 32 | ea | N6 | | | 32 | 2 | 64 | $100.00 | $ 6,400.00 | 32 fittings - 2hrs machine time each |
| 2.2.4.2.8 | Bond End fittings | EE,FEM | 32 | ea | N6 | | Crew B1 | 32 | 1 | 32 | $183.00 | $ 5,856.00 | 32 fittings - 1hrs bond time each |
| 2.2.4.2.9 | Prep. (Clean) | EE | 400 | SF | N7 | $2.46 | Crew E17 | | | 20 | $184.38 | $ 4,671.50 | |
| 2.2.4.2.10 | Prime & Paint | EE | 400 | SF | N8 | $2.06 | Crew E17 | | | 20 | $184.38 | $ 4,511.50 | |
| 2.2.4.2.11 | Skid & Crate Const - Load Mat on skids and crates | EE | 0.5 | Ea | N3 | $500 | Crew E17 | | | 12 | $184.38 | $ 2,462.50 | |
| 2.2.4.2.12 | Trucking Shipmet to Site (1500 mi) - 1 trucks x 2 days | EE | 0.5 | Day | N9 | $276 | Driver B-34( | 1 | 12 | 12 | $68.70 | $ 962.31 | 0.5 Trucks, 1500 mi, 2 day, 24 hr |
| | | | | | | | | | | | | $98,863.8 | |

| | Secondary Support Ring | Mat Quan Ref | Mat Quan | Unit Meas | Ref Mat $ | Mat / Equi Unit Cost $/Unit | Labor Crew Ref (N2) | | | Labor Hrs | Labor & Equip N2 Cost $/Hr | Total Cost Incl O&P K$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2.2.4.3** | **Fabrication** | | | | | | | | | | | | |
| 2.2.4.3.1 | A&P QISO 537gsm T700 fibre | FEM | 34.8 | kg | N10 | $51 | - | | | | | $ 1,774.80 | |
| 2.2.4.3.2 | 1/4" H130 core grooved one side both ways and perfed | EE,FEM | 1 | kit | N10 | $300 | | | | | | $ 300.00 | |
| 2.2.4.3.3 | Resin, Proset INF 114-4 Infusion Epoxy | FEM | 17.4 | l | N10 | $16 | - | | | | | $ 278.40 | |
| 2.2.4.3.4 | Adhesive, Hysol | FEM | 10 | tube | N10 | $85 | - | | | | | $ 850.00 | |
| 2.2.4.3.5 | Mold Prep Labour | EE | | | | | | | | | | $ 715.20 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.6 | Layup Labour | EE | | | | | | | | | | $ 437.40 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.7 | Infusion Labour | EE | | | | | | | | | | $ 2,639.40 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.8 | Post Cure Labour | EE | | | | | | | | | | $ 709.80 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.9 | Bonding labour | EE | | | | | | | | | | $ 1,027.80 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.10 | Demolding Labour | EE | | | | | | | | | | $ 293.40 | See ngVLA 15m ERS Assembly.mpp |
| 2.2.4.3.11 | Finishing Labour | EE | | | | | | | | | | $ 145.80 | See ngVLA 15m ERS Assembly.mpp |
| | | | | | | | | | | | | $9,172.0 | |

| | **Site Assembly of ERS** | Mat | | | | Mat / Equi | Labor | | | | Labor & | Total Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quan | Mat | Unit | Ref | Unit Cost | Crew | | | Labor | Equip N2 | Incl O&P | Remarks |
| | | Ref | Quan | Meas | Mat $ | $/Unit | Ref (N2) | | | Hrs | Cost $/Hr | K$ | |
| **3.1.2** | **On Site Fabrication, Assembly & Painting** | | | | | | | | | | | | |
| 3.1.2.1 | Remove Primary from Building | EE | | | | | - | | | | | $606.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.2 | Paint primary frontside | EE | | | | | - | | | | | $1,086.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.3 | Assemble Secondary/Feed Support Structure | EE | | | | | - | | | | | $1,086.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.4 | Assemble BUS on Primary | EE | | | | | | | | | | $4,344.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.5 | Flip Primary/BUS | EE | | | | | | | | | | $606.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.6 | Attach SSS to P-BUS | EE | | | | | | | | | | $606.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.7 | Align and measure | EE | | | | | | | | | | $1,944.0 | See ngVLA 15m ERS Assembly.mpp |
| 3.1.2.8 | Installation on Pedstal | EE | | | | | | | | | | $3,864.0 | See ngVLA 15m ERS Assembly.mpp |
| | | | | | | | | | | | | $14,142.0 | See ngVLA 15m ERS Assembly.mpp |
| | | | | | | | | | | | | | |

# ERA Assembly Costing Notes

The fabricated steel components ERA structures cost have been estimated referencing the RS Means methods consistent with the ARA, crew definitions are shown in Table 6. The composite structures and assembly has been costs have been estimated out based on the schedule shown in Table 7. Labor rates are consistent across all costing.

*Table 6 ERA Crew Costs*

| Crew $/hr | Crew Definition |
|---|---|
| $ 183.00 | Crew B-1: 1 Labor Foreman, 2 Laborers |
| $ 184.38 | Crew E-17: 1 Struc. Steel Foreman (outside), 1 Structural Steel Worker |

*Table 7 ERA Production Estimate*

| ID | Task Name | Duration | Predecessors | Resource Names | Cost |
|---|---|---|---|---|---|
| 1 | **Elevation Rotating Assembly Production** | **15.25 days** | | **Supervisor** | **$25,400.00** |
| 2 | **Reflector Fabrication Phase** | **12.63 days** | | | **$17,290.00** |
| 3 | **Primary Reflector Fabrication** | **11 days** | | | **$10,640.00** |
| 4 | **Primary Mold prep** | **0.25 days** | | | **$374.00** |
| 5 | clean surface | 1 hr | | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $187.00 |
| 6 | Wax surface | 1 hr | 5 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $187.00 |
| 7 | **Layup** | **5.63 days** | | | **$6,279.00** |
| 8 | Eglass | 2 hrs | 6 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $374.00 |
| 9 | Reflective | 4 hrs | 8 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $748.00 |
| 10 | Eglass | 2 hrs | 9 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $374.00 |
| 11 | QISO 1 | 2 hrs | 10 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $374.00 |
| 12 | QISO 2 | 2 hrs | 11 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $374.00 |
| 13 | Hybrid | 2 hrs | 12 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Lab | $374.00 |
| 14 | QISO 3 | 4 hrs | 13 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Technician 1[50%] | $410.00 |
| 15 | QISO 4 | 4 hrs | 14 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Technician 1[50%] | $410.00 |
| 16 | Eglass | 4 hrs | 15 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Technician 1[50%] | $410.00 |
| 17 | Rim/flange build | 4 hrs | 13 | Labour 7,Labour 8,Technician 1[50%],Labour 6 | $266.00 |
| 18 | Peel ply | 3 hrs | 17,16 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $453.00 |
| 19 | Manifolds | 4 hrs | 18 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $554.00 |
| 20 | Vacuum bag | 4 hrs | 19 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $302.00 |
| 21 | Vacuum system | 4 hrs | 20 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $302.00 |
| 22 | Leakdown | 4 hrs | 21 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $554.00 |
| 23 | **Infusion** | **3.13 days** | | | **$1,118.00** |
| 24 | Setup/prep | 2 hrs | 19 | Labour 8,Technician 1[50%] | $61.00 |
| 25 | Decanting | 2 hrs | 24 | Labour 8,Technician 1[50%] | $61.00 |
| 26 | Chemistry | 2 hrs | 25 | Labour 8,Technician 1[50%] | $61.00 |
| 27 | Infusion | 4 hrs | 22,26 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Tec | $748.00 |
| 28 | Debag | 1 hr | 27FS+1 day | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Tec | $187.00 |
| 29 | **Post Cure** | **1.38 days** | | | **$905.00** |
| 30 | Post Cure Prep | 2 hrs | 28 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Tec | $374.00 |
| 31 | Post Cure | 8 hrs | 30 | Labour 1,Technician 1 | $344.00 |
| 32 | Post Cure Remove | 1 hr | 31 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Tec | $187.00 |
| 33 | **Bonding** | **1.63 days** | | | **$1,414.00** |
| 34 | Dry Fit Composite Backing Pieces | 2 hrs | 32,74 | Labour 1,Technician 1[50%],Labour 2 | $61.00 |
| 35 | Bonding Composite Backing Pieces | 5 hrs | 34 | Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Labour 9 | $630.00 |
| 36 | Dry Fit DRC Pieces | 2 hrs | 34 | Labour 1,Technician 1[50%],Labour 2 | $61.00 |
| 37 | Bonding DRC Pieces | 4 hrs | 36,35 | Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Labour 9 | $504.00 |
| 38 | Dry Fit Central Reinforcement | 2 hrs | 36 | Labour 1,Technician 1[50%],Labour 2 | $61.00 |
| 39 | Bond Central Reinforcement | 2 hrs | 37 | Labour 2,Technician 1[50%],Labour 1 | $97.00 |

| ID | Task Name | Duration | Predecessors | Resource Names | Cost |
|---|---|---|---|---|---|
| 40 | **Demold** | **0.13 days** | | | **$169.00** |
| 41 | Release | 1 hr | 39 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Labour 8,Tec | $169.00 |
| 42 | **Finish** | **0.38 days** | | | **$381.00** |
| 43 | Trim Flange | 1 hr | 41 | Labour 1,Labour 2,Labour 3,Technician 1 | $79.00 |
| 44 | Paint Backside | 2 hrs | 43 | Labour 1,Labour 2,Labour 3,Labour 4,Labour 5,Labour 6,Labour 7,Technician 1 | $302.00 |
| 45 | **Secondary Reflector Fabrication** | **7 days** | | | **$3,174.00** |
| 46 | **Secondary Mold prep** | **0.38 days** | | | **$237.00** |
| 47 | clean surface | 1 hr | | Labour 11,Labour 10,Labour 12,Technician 2 | $79.00 |
| 48 | Wax surface | 2 hrs | 47 | Labour 10,Labour 11,Technician 2,Labour 12 | $158.00 |
| 49 | **Layup** | **2.88 days** | | | **$1,420.50** |
| 50 | Eglass | 1 hr | 48 | Labour 11,Labour 10,Technician 2,Labour 12 | $79.00 |
| 51 | Reflective | 2 hrs | 50 | Labour 10,Labour 11,Technician 2,Labour 12 | $158.00 |
| 52 | Eglass | 1 hr | 51 | Labour 10,Labour 11,Technician 2,Labour 12 | $79.00 |
| 53 | QISO 1 | 1 hr | 52 | Labour 10,Labour 11,Technician 2,Labour 12 | $79.00 |
| 54 | QISO 2 | 1 hr | 53 | Labour 10,Labour 11,Technician 2,Labour 12 | $79.00 |
| 55 | Hybrid | 1 hr | 54 | Labour 10,Labour 11,Technician 2,Labour 12 | $79.00 |
| 56 | QISO 3 | 2 hrs | 55 | Labour 10,Labour 11,Technician 2[50%] | $97.00 |
| 57 | QISO 4 | 2 hrs | 56 | Labour 10,Labour 11,Technician 2[50%] | $97.00 |
| 58 | Eglass | 2 hrs | 57 | Technician 2[50%],Labour 11,Labour 10 | $97.00 |
| 59 | Rim/flange build | 2 hrs | 55 | Technician 2[50%],Labour 12 | $61.00 |
| 60 | Peel ply | 1 hr | 58,59 | Labour 11,Labour 10,Technician 2,Labour 12 | $79.00 |
| 61 | Manifolds | 4 hrs | 60 | Labour 10,Labour 12,Technician 2[50%] | $194.00 |
| 62 | Vacuum bag | 2 hrs | 61 | Labour 12,Labour 10,Technician 2[50%] | $97.00 |
| 63 | Vacuum system | 2 hrs | 62 | Labour 12,Labour 10,Technician 2[50%] | $97.00 |
| 64 | Leakdown | 1 hr | 63 | Labour 12,Labour 10,Technician 2[50%] | $48.50 |
| 65 | **Infusion** | **2 days** | | | **$382.50** |
| 66 | Setup/prep | 1 hr | 61 | Labour 11,Technician 2[50%] | $30.50 |
| 67 | Decanting | 1 hr | 66 | Labour 11,Technician 2[50%] | $30.50 |
| 68 | Chemistry | 1 hr | 67 | Technician 2[50%],Labour 11 | $30.50 |
| 69 | Infusion | 2 hrs | 64,68 | Labour 12,Technician 2,Labour 10,Labour 11 | $158.00 |
| 70 | Debag | 1 hr | 69FS+1 day | Labour 1,Labour 2,Labour 3,Labour 4,Labour 7,Labour 8,Technician 2 | $133.00 |
| 71 | **Post Cure** | **1.38 days** | | | **$581.00** |
| 72 | Post Cure Prep | 2 hrs | 70 | Labour 12,Technician 2,Labour 11,Labour 10 | $158.00 |
| 73 | Post Cure | 8 hrs | 72 | Labour 12,Technician 2 | $344.00 |
| 74 | Post Cure Remove | 1 hr | 73 | Labour 10,Labour 11,Technician 2,Labour 12 | $79.00 |
| 75 | **Bonding** | **0.38 days** | | | **$165.00** |
| 76 | Dry Fit Composite Backing Pieces | 1 hr | 69 | Labour 12,Technician 2 | $43.00 |
| 77 | Bonding Composite Backing Pieces | 2 hrs | 76 | Technician 2,Labour 11,Labour 10 | $122.00 |
| 78 | **Demold** | **0.13 days** | | | **$79.00** |
| 79 | Release | 1 hr | 77,69FS+3 day | Labour 12,Labour 11,Labour 10,Technician 2 | $79.00 |
| 80 | **Finish** | **0.38 days** | | | **$309.00** |
| 81 | Trim Flange | 1 hr | 79 | Labour 11,Labour 10,Labour 12,Technician 2 | $79.00 |
| 82 | Paint Backside | 2 hrs | 81 | Labour 12,Labour 10,Labour 11,Technician 2 | $158.00 |
| 83 | Paint Frontside | 2 hrs | 81 | Labour 10,Labour 11 | $72.00 |

| ID | Task Name | Duration | Predecessors | Resource Names | Cost |
| --- | --- | --- | --- | --- | --- |
| 84 | **Materials Preparation** | **5.63 days** | | | **$3,476.00** |
| 85 | Eglass X 125 | 16 hrs | 83,82 | Labour 12,Labour 11,Labour 10,Technician 2 | $1,264.00 |
| 86 | Reflective X 125 | 25 hrs | 85 | Labour 10,Labour 11,Labour 12,Technician 2 | $1,896.00 |
| 87 | Rim core kit fitting | 4 hrs | 86 | Labour 10,Labour 11,Labour 12,Technician 2 | $316.00 |
| 88 | **Final Assembly** | **4.25 days** | | | **$4,450.00** |
| 89 | Remove primary reflector from building | 2 hrs | 44 | Labour 1,Labour 2,Labour 3,Labour 4,Technician 1 | $194.00 |
| 90 | Paint primary frontside | 4 hrs | 89 | Labour 1,Labour 2,Labour 3,Labour 4,Technician 1[50%] | $338.00 |
| 91 | Assemble Secondary/Feed Support Structure | 4 hrs | 44 | Labour 8,Labour 7,Labour 6,Labour 5,Technician 1[50%] | $338.00 |
| 92 | Assemble BUS on Primary | 8 hrs | 90,91 | Labour 5,Labour 6,Labour 7,Labour 8,Technician 1,Labour 1,Labour 2,Labour 3 | $1,352.00 |
| 93 | Flip Primary/BUS | 2 hrs | 92 | Labour 5,Labour 6,Labour 7,Labour 8,Technician 1 | $194.00 |
| 94 | Attach SSS to P-BUS | 2 hrs | 93,83 | Labour 5,Labour 6,Labour 7,Labour 8,Technician 1 | $194.00 |
| 95 | Align and measure | 8 hrs | 94 | Labour 5,Labour 6,Labour 7,Technician 1 | $632.00 |
| 96 | Installation on Pedstal | 8 hrs | 95 | Labour 5,Labour 6,Labour 7,Technician 1,Labour 1,Labour 2,Labour 3,Labour 4 | $1,208.00 |