DESIGN OF A CARBON COMPOSITE RADIO TELESCOPE FOR THE NEXT GENERATION VERY LARGE ARRAY

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ABSTRACT

The National Research Council of Canada's (NRC) Herzberg Astronomy and Astrophysics (HAA) Research Centre is developing an 18 metre diameter radio telescope for the next generation Very Large Array (ngVLA). The ngVLA is an American project to build a radio astronomy telescope array of 244 18m reflectors and 19 6m reflectors which will operate up to 116 GHz in frequency. The design specifications are challenging because of the large aperture and the high operating frequency. HAA has designed a single piece rim supported carbon-epoxy reflector with a carbon-epoxy backup structure. The development of the design, and the use of optimization routines such as topology optimization and size optimization will be discussed.

KEYWORDS: *carbon composites, radio telescopes, vacuum infusion*

1 INTRODUCTION

Single piece composite radio telescope development has been ongoing at HAA since 2007. At that time a proof of concept 10m symmetric radio telescope reflector was fabricated, the Mk1 (Chalmers et al 2009). The Mk1 featured a cored surface with an integrated backup structure of cored structural ribs all fabricated in a single infusion. The RMS surface error of 1.0 mm was higher than desired on the Mk1 so a second reflector was built on the same mould in 2008, the Mk2. An RMS best fit error of 0.5mm RMS was achieved which easily met the design goal. The increased surface accuracy was achieved by fabricating the backup structure separately and then bonding it on post infusion, thereby removing the 'print-through' from the integrally moulded structure (Chalmers et al 2009) of the Mk1. The Mk1 and Mk2 served to show the possibility of single piece radio dish fabrication using the vacuum infusion process. After 2008 the pursuit of higher performance and larger dishes led to a period of several years of design effort. By 2014 a 15m Offset Gregorian telescope, the Dish Verification Antenna-1 (DVA-1) was fabricated (Hovey et al 2014). Previously the Mk1 and Mk2 had a surface consisting of a Kevlar-skinned foam core sandwich directly supported by carbon beams. The DVA-1had a thin carbon surface which was edge and centre supported. The outer edge of the primary was stiffened with an integrally moulded vertical carbon rim as well as a bonded-on carbon 'rim stiffening structure'. The purpose of these reinforcements was to stiffen the carbon dish structure at the rim which was otherwise supported only at 13 discrete points. A thin diaphragm central support connected the dish surface to the steel backup structure. It was designed to take the sheer loads between the steel backup structure and the dish surface, but allow flexure normal to the dish surface. In this way wind and gravity loads did not create a hard point or bump in the dish surface at its centre, while still allowing stress transfer tangent to the dish surface, allowing the steel backup structure to be substantially lighter than would otherwise be the case (Lacy 2015).

The advantages of the rim supported single piece carbon surface are many. First, with no variation in laminate thickness or ply orientation across the entire dish surface, and with no stiffeners attached to the primary dish surface except right at the outer rim, the entire surface moves in a very uniform manner in response to wind, gravity, and thermal loads. In fact, surface deformation in response to wind loading is almost negligible (at wind speeds typical for normal astronomical telescope design specifications). Gravity and thermal loads also produce very smooth low-spatial-frequency responses.

2 THE NGVLA-18 PROJECT

The concept design of the ngVLA-18 is presented in figure 1. It is an 18m offset Gregorian design, similar in many ways to the DVA-1. Optically the main difference is that this is a feed-down design which means simply that at the lowest elevation angle the feed and secondary support structure are on the low side of the primary reflector instead of the high side (the main advantage being that access to the feeds is easier). Feed down designs do present some structural challenges, mostly to do with the required offset needed on the turn-head or yoke (top part of the tower), this is not within the scope of this document. In common with the DVA-1, the new design is rim supported, has a single skin carbon primary surface and is an offset Gregorian optical configuration. Apart from those common elements the ngVLA-18 differs substantially. First, it is larger, 18m instead of 15m in aperture which will push the envelope for fabrication. Second, it will operate at up to 116GHz versus 15GHz for the DVA-1, and this means a much more accurate optical surface. Third, the primary surface is only edge supported, it has no central partially-constrained connection with the backup structure. Fourth, what we call the OBUS (Outer Backup Structure) is a carbon shell on the ngVLA-18, as opposed to the steel tube structure on the DVA-1. Additionally the primary surface edge connection is a different concept on the ngVLA-18.

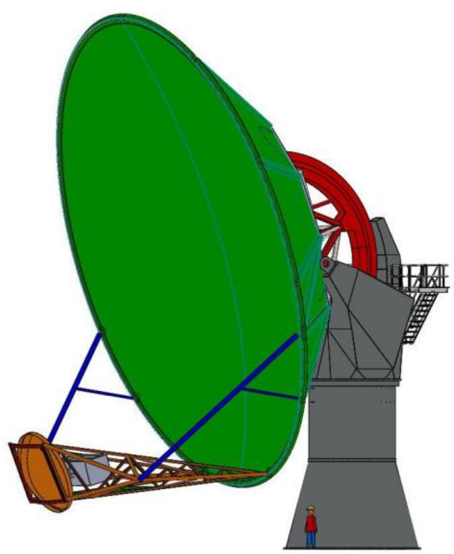

Figure 1: The ngVLA-18 concept design

2.1 Primary Surface

The primary surface on the ngVLA-18 is structurally very similar to the DVA-1. It consists of what is essentially a 'black aluminum' layup, a constant thickness highly orthotropic carbon layup designed to minimize process-induced-distortion as well as thermal distortions. Lessons learned from the DVA-1 (and another higher accuracy prototype, the DVA-2, see Islam, Lacy (2018)) are very relevant here so we carry these elements into the new design. One big difference is the lack of a central connection. While the central connection worked well on the DVA-1, it does introduce additional stresses into the primary surface, stresses which are not compatible with the increased frequency requirements of the ngVLA-18. During the development of another prototype, the ngVLA-15 (Lacy, Islam 2018), we found that these stresses were not acceptable at the now much higher frequency (and thus tighter surface accuracy) regimes. The down-side is that the backup structure must now carry all of the shear loads that get induced into the structure at low elevation angles (primary rim near vertical), something that required a redesign of the backup structure.

2.2 Outer Backup Structure (OBUS)

Figure 2 shows the DVA-1 (a), and the ngVLA-18 (b) for comparison. On the ngVLA-18, the OBUS, a carbon fiber shell structure is shown in green. Without the central diaphragm connection used on the DVA-1 the OBUS must now carry all the shear loads induced in the structure at low elevation angles (such as the orientation in figure 2(b)). The shell-type structure is more efficient than a tube-truss structure at carrying these shear loads. The shell type OBUS also provides continuous support of the primary surface, which was found to be necessary (see Section 3). The carbon OBUS also provides a better CTE match to the dish surface.

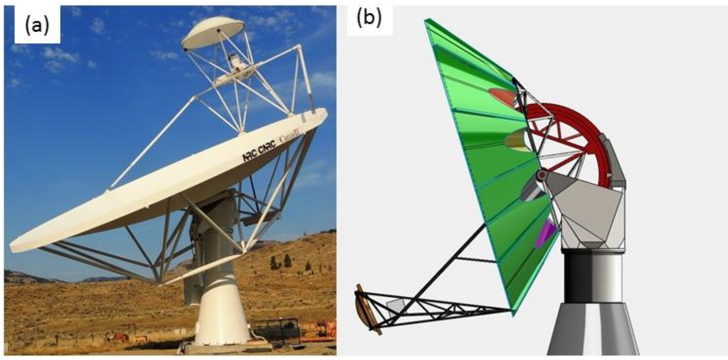

Figure 2: DVA-1 (a), and the ngVLA-18 (b)

2.3 Primary Surface Edge Connectors

With the DVA-1 there was some adjustability of the primary surface through changes in the length of the 13 tubes comprising the outer backup structure of the dish (figure 2(a)). This was found to be adequate for this design. The ngVLA-18 has a carbon shell OBUS which will require a different type of adjustment system. Several systems were tried and rejected. The current solution is shown in figure 3. Here the load passes directly through the center of the surface so that no out of plane moments are induced. One of these adjusters will be placed every ~300mm around the rim of the primary.

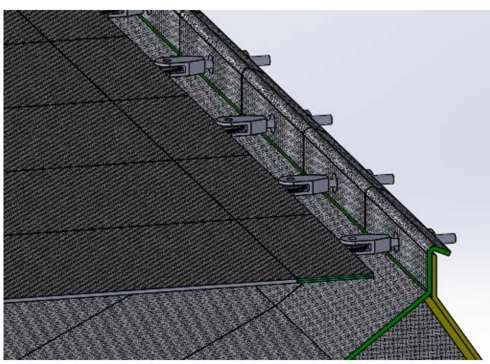
Figure 3: Edge connectors around primary surface of ngVLA-18

2.4 Inner Backup Structure (IBUS)

The IBUS can be seen in figure 2(b). It is the silver and red truss-type structure connecting the OBUS to the mount. The loads in this area are high as are the stiffness requirements, but in an area where high weight was actually desired (to act as a balancing counterweight), so steel was chosen as the best solution. Topology optimization was used to arrive at the current design. The interface between this steel structure and the OBUS is important to the overall design, and a challenge because of manufacturing tolerances of the large structures. A smaller number of discrete hard points connecting these two parts is the current favoured solution, but no detailed design work has been completed to date on this part of the design.

2.5 Optimization

Topology and free size optimization have been attempted as exploratory tools in the early stages of the design loop with some success and some failure. Neither works that well under a gravity-only load scenario. Both work best with defined loads and defined connection points. Some success was achieved using topology for the IBUS and for the feed and secondary support structure. For the OBUS, manual iteration and engineering intuition seem to work better. Later in the design cycle we will also use size optimization along with more directed approaches such as super-ply laminate optimization (to determine best laminate layer thickness and ply orientation).

3 DESIGN ITERATION AND ANALYSIS RESULTS

The first iteration of the new ngVLA-18 design attempted to use a steel tube OBUS similar to the DVA-1 approach, which we called the Tubular Back Structure (TBS). The TBS was tried first because of the success we had had developing another prototype, a wheel and track 15m rim-supported design (Lacy 2015). Figure 4 shows the primary surface residual errors at three elevation angles, 15^o, 52^o, and 90^o, representative of the range of elevation angles the telescope will move through. The residual errors are surface errors after solid body translations and rotations have been removed (in fact we typically remove two translations and one rotation, translations in the plane of symmetry and rotations about this plane (Islam, Lacy 2018)). As can be seen the errors are mostly around the outer edge, but are much higher than those allowable in the error budget for gravity (~40 microns).

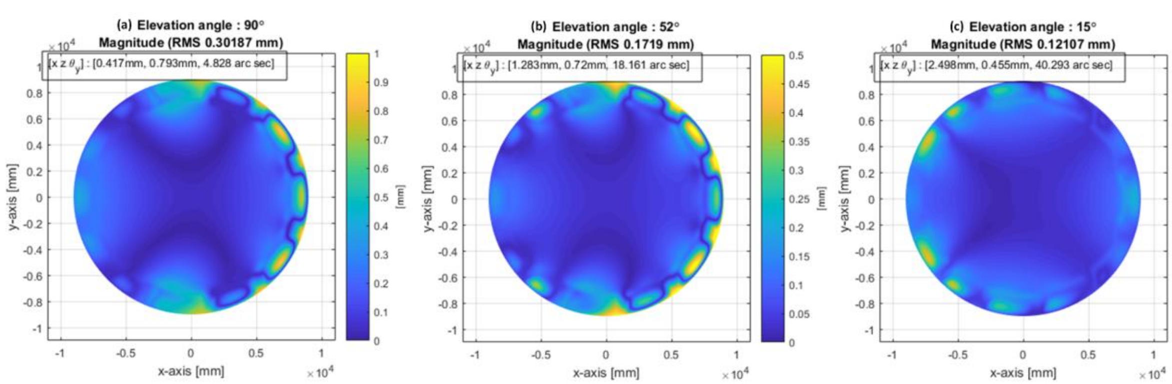

Figure 4: Residual errors in the primary surface, for the TBS design

To reduce the surface distortions inherent in the TBS design, development of a carbon shell OBUS structure was begun and further analysis of the TBS was suspended. The carbon shell OBUS development was initially done without the IBUS structure and with simplified mass and stick model for the secondary structure (figure 5). We will call this Iteration 0, the new baseline.

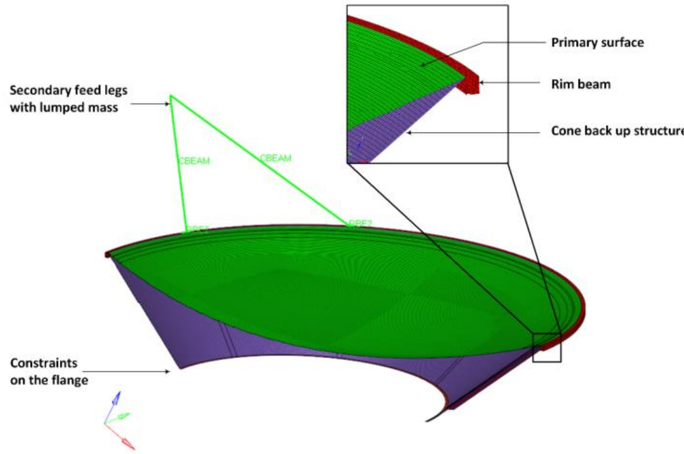

Figure 5. Simple carbon-cone OBUS and simplified secondary structure, Iteration 0.

The first results are shown in figure 6. As can be seen the RMS values are much reduced from the earlier TBS design (26%, 41%, and 42% of the earlier errors respectively). The errors are also highly concentrated at the outer edge of the structure, which is good from an electromagnetics point of view (the important thing in radio telescope development!). Clearly the distortions caused by the hard connection points around the rim and the reinforcing structure that had to be added there on the earlier TBS design are absent. We still do have some distortion from the connection points from the secondary structure, something that it is difficult to avoid, but overall it is clear that this new approach represents a large improvement over the TBS design.

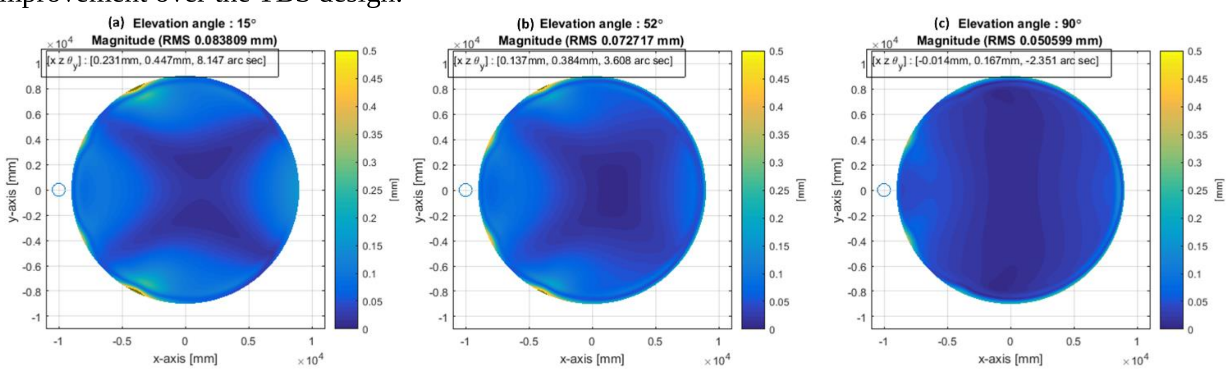

Figure 6. Iteration 0 residual deformation plots.

The next design cycle, Iteration 1, involved making the structure more realistic and buildable. Figure 7 shows the OBUS and surface configuration. The OBUS now has a much more buildable structure of panels, and radial and circumferential beams. An elastomer adhesive was tried as the connection detail between the primary surface and the OBUS at this stage.

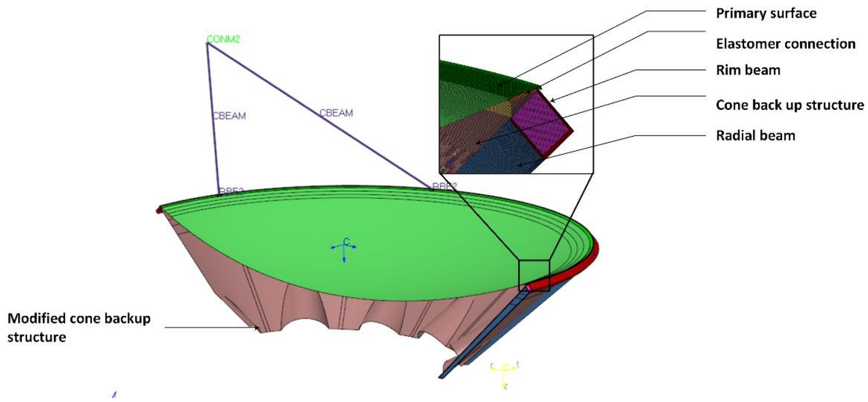

Figure 7. Iteration 1, OBUS structure

Figure 8 shows the residual errors for Iteration 1. As can be seen, the RMS errors have all increased slightly, but the changes are quite small. It may seem a step backwards, but the Iteration 1 structure is much more realistic than Iteration 0, so we are not disappointed.

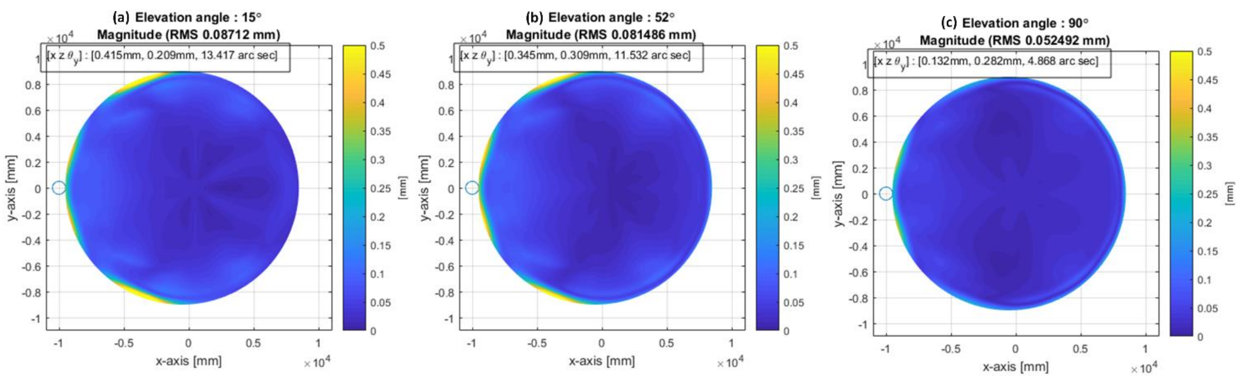

Figure 8, Primary reflector residual surface errors, Iteration 1

Iteration 2 was one of manual optimization. By looking at the strain values from FEA analysis in plots such as Figure 9 of the OBUS, 'hot spots' could be identified and additional material added.

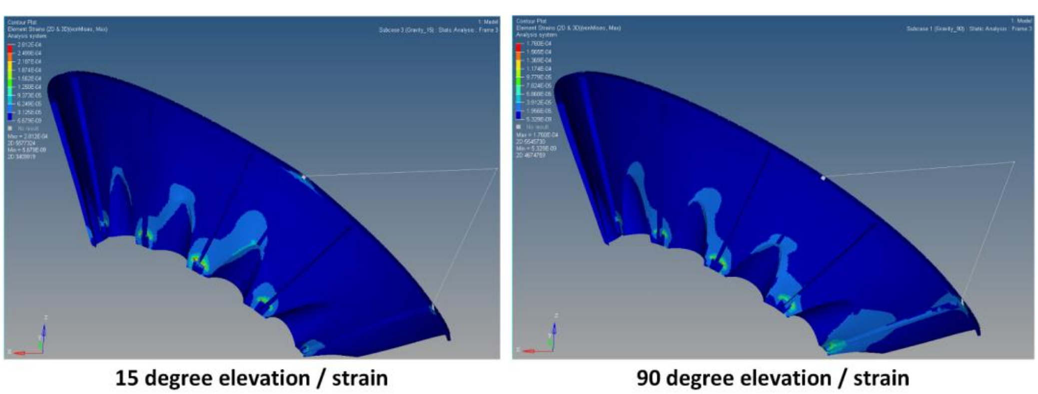

Figure 9, Strain contours in the OBUS for Iteration 1 design.

Based on this strain analysis, additional layers of carbon were added in localized areas in the OBUS, in the radial and circumferential beams, and in the primary surface. Additionally the foam core thickness in the OBUS panels was reduced. The results of this manual optimization process are shown in the primary surface residual distortion plot shown in Figure 10.

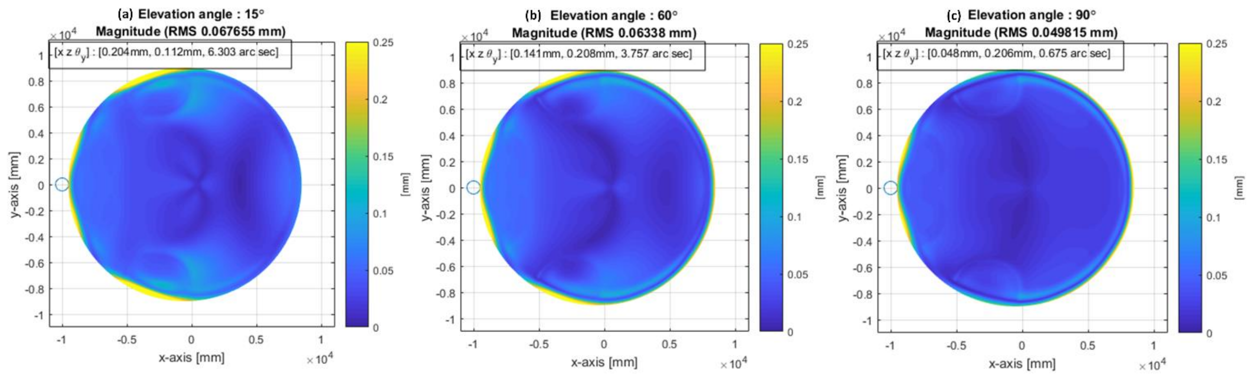

Figure 10. Primary surface residual errors, Iteration 2.

Clearly some reductions in RMS errors have been achieved especially at the lower elevation angles. We are not yet down to the desired ~40microns allowed for gravity, but we are close, and it is felt that this is achievable.

3.1 Wind and Thermal Distortion

As might be anticipated, a featureless orthotropic surface suspended only at its edge performs very well both thermally and under wind loads. Figure 11 shows the dish surface behaviour under what was considered a worst case wind load, 80^o elevation and 80^o azimuth angle at 7m/s (operating condition).

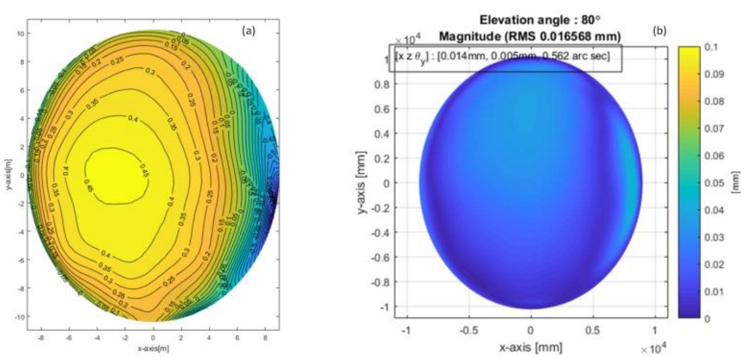

Figure 11. Wind load pressure coefficients (a), and (b) RMS residual plot

Clearly the wind induced primary dish surface distortion is very low (~17µm RMS). Similarly, RMS distortion induced by a 30 degree thermal bath was ~40µm, higher than the wind induced distortion, but still quite low.

4 CONCLUSION

The proposed ngVLA-18 design, being a single piece edge supported carbon composite structure, has some unique advantages over conventional metal panel design. While more iterations on the structural design will very likely lead to further reductions in the surface distortion under gravity, the current design is very close to meeting the targeted distortions. Furthermore, distortions under wind loads are much smaller than those normally seen in a traditional panelised metal design. Thermal distortions are also small. It should also be noted that the additional promise of the moulded composite surface is a high degree of uniformity between dishes, a distinct advantage in the modern world of telescope arrays (in this case an array of over 200 dishes), and something that is much more difficult to achieve with the traditional multi-panel surface approach.

5 ACKNOWLEDGEMENTS

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