



Memo 106

Composite Applications for Radio Telescopes (CART):

The Mk2 Reflector Results.

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01/09

SKA Memo 106

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January 19, 2009

ABSTRACT

This document describes the design, fabrication and measurement results of the CART Mk2 10 m radio reflector prototype constructed at the Dominion Radio Astrophysical Observatory.

Introduction

The Composite Applications for Radio Telescopes (CART) project at the Herzberg Institute of Astrophysics' (HIA) Dominion Radio Astrophysical Observatory (DRAO) in Penticton Canada is an ongoing effort to investigate the application of composite materials to radio telescope structures to provide cost effective collecting area for the Square Kilometer Array (SKA). The first phase of the project is focused on reflectors as they are seen to have the highest potential for cost/performance gains from the application of composite materials. The first 10-m prototype reflector was completed in the summer of 2007. The result was a light (~1000 kg), stiff reflector with a surface accuracy of 1.2 mm RMS. While the RMS value of the surface was low the deviations were not uniformly distributed and some large scale deviations existed. In addition many lessons were learned during the construction process and there were seen to be opportunities for improvement. The design of a second reflector, dubbed the Mk2, was initiated immediately after completion of the first with the focus on improvements in surface accuracy, structural design and manufacturability.

The Mk1 prototype proved the feasibility of the concept. On the Mk2, design and process were further optimized, which will enable designers to develop SKA specific reflectors with a high degree of confidence. The CART Mk 2 reflector is an improvement on the Mk1 in all aspects. The change of design approach to separately fabricated beams and hub bonded to a monolithic surface and rim improved manufacturability and yielded a more accurate surface.



Design

Table 1 CART Prototype Reflector Design Goals

Reflector Diameter	10 m.
Optics	Center-fed parabolic reflector.
f/D ratio	0.45
Max operating frequency	10 GHz (using a 1/20 feed-weighted RMS deflection criterion).
Operating wind speed	35 km/hr (22 mph or 10 m/s)
Slew to stow at	50 km/hr (31 mph or 14 m/s)
Survival wind speed	160 km/hr (100 mph or 44 m/s)

The Mk2 reflector was designed to the same design goals as the Mk1, (Table 1). However, the design of the Mk2 is different from that of the Mk1 in several important aspects, (Figure 1). The Mk1 consisted of six solid foam core beams that were molded in place. These were of three different heights. The tallest two of which were bent out to pick up the feedleg loads. At the time of the Mk 1 design the reflector mount had not been identified. To accommodate different potential mounts the design incorporated a universal 2-m square box structure at the centre of the reflector into which a mounting interface frame could be fitted. The Mk2 features eight radial beams arranged around a central hub. The beams and the central hub are molded as separate parts, and then bonded on to the one-piece surface/rim. The hub was designed to interface directly with the MV-1 mount.

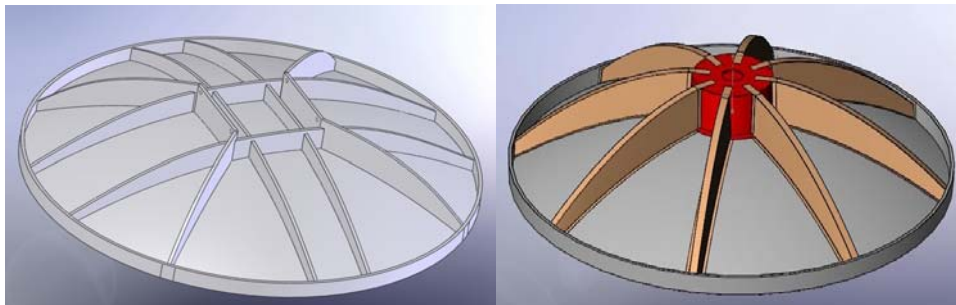


Figure 1 Mk1 (left) and Mk2 (right) reflector designs.

Construction of the Mk1 was labour intensive. The four smaller beams were infused with the surface/rim and the two larger beams were added in a secondary infusion. The molded-on beams required a lot of setup time and a more complicated infusion scheme. In addition, the large scale deviations that were measured in the Mk1 surface are partly attributed to the curing of the secondary infusion.

For the Mk2 the reflector surface and rim were infused as one piece to reduce labour, the elapsed time, and the time-in-mold. The hub and beams were fabricated in parallel and then bonded on to the surface/rim while it was still on the mold, capturing the surface shape.



The separately molded beams are made with thin core in their webs and caps to stabilize their surfaces from local buckling. As a result they are stronger, stiffer and lighter than the molded-on foam-core Mk1 beams.

Few material changes were made between the Mk1 and Mk2 except where the design changes required it.

Deflection analysis, stress analysis, first ply failure, normal modes etc. were calculated using Finite Element Analysis (FEA) to ensure that the reflector would meet all of the performance criteria under all operating conditions.

Fabrication & Costing

Fabrication of the Mk2 reflector took place during the period of May to August of 2008 with a crew of three working one shift/day five days/week. As with most prototypes much of the time was spent in technique development and actual construction time was less than six weeks.

Table 2 Mk2 Reflector Fabrication Cost Breakdown.

	Cost US\$	US\$/m ²
Materials	\$48,689	\$619
Labour	\$35,339	\$450
Total	\$84,028	\$1,069

Table 2 shows the cost breakdown for the Mk2 prototype; preliminary investigation indicates that the cost can be reduced by as much as 40%. As part of its PrepSKA work HIA has engaged an industry partner to carry out a detailed study of manufacturing composite reflectors for the SKA. The results of this study are expected in mid-2009.

Surface Measurement Results

Measurements of the Mk2 reflecting surface were conducted using a laser tracker. Previous experience with the Mk1 showed that this method revealed the same results as holography but is easier to perform. The laser tracker was mounted in the centre of the reflector and tracks a retro-reflector as it is drawn over the surface. Point coordinates were recorded every 50 mm of motion (Figure 2).

A parabola is best fit to the point cloud data taking into account the retro-reflector offset and the deviations of each point from the parabolic surface is calculated. From this the Root Mean Square (RMS) of the deviations, and the RMS half-pathlength error σ , (half-pathlength error is the normal component of the deformation vector times the direction cosine with respect to the focal axis) were calculated. The Ruze efficiency [1], a quantification of reflector efficiency in terms of wavelength λ and half-pathlength error, was then calculated at $\lambda = 3$ cm (10 GHz), Equation 1.



$$\eta = \exp\left(-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right) \quad \text{Eq. 1}$$

The same technique was used to analyze the deviations of the nodes on the reflector surface from the finite element analysis results.



Figure 2 Measuring reflector surface with laser tracker.

An initial surface scan of the reflector was performed with the reflector pointing straight up resting on the hub mounting face. A plot of the deviation from a best-fit parabola is shown in Figure 3. The RMS of the deviations is calculated to be 0.54 mm. The half-path length error is 0.50 mm, giving a Ruze efficiency of 0.96 at $\lambda = 3$ cm.

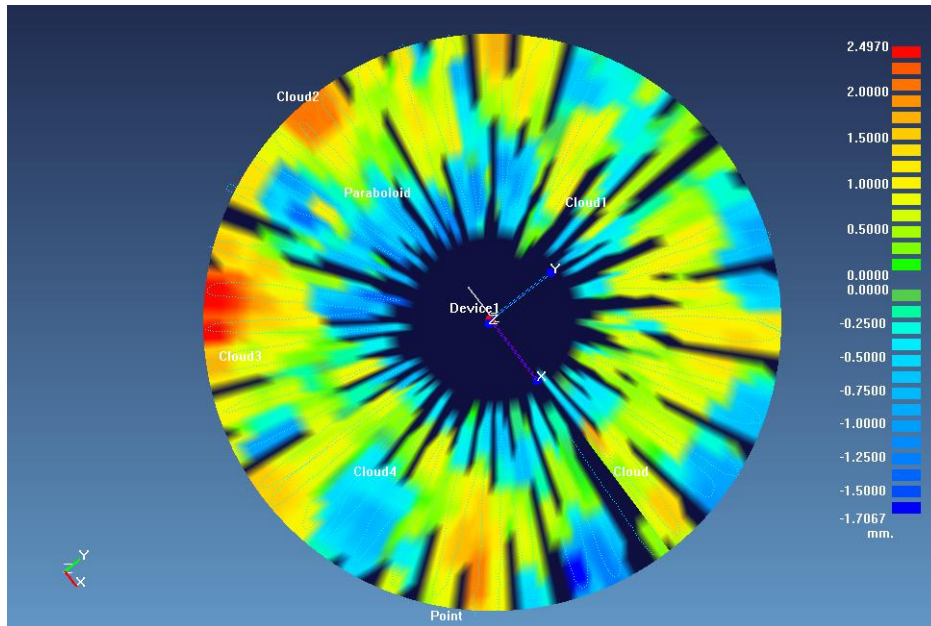


Figure 3 Measurement with no feed structure.

The reflector was then lifted on to the mount and the Phased Array Demonstrator (PHAD) installed (Figure 4). The surface was then rescanned. Figure 5 shows a plot of the results.



Figure 4 Mk2 Reflector on Positioner with PHAD in place.



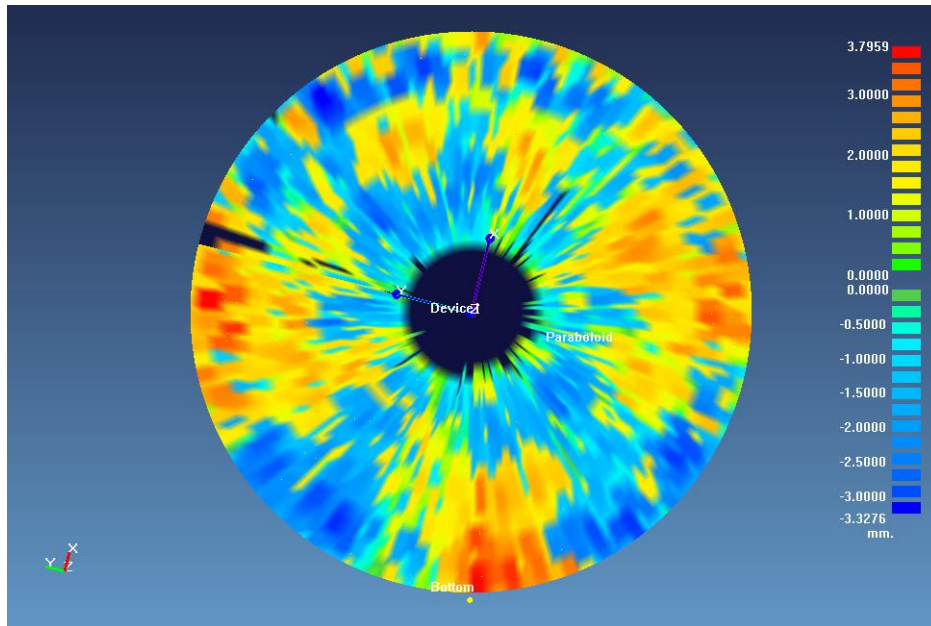


Figure 5 Surface deviation plot with PHAD feed mounted.

The RMS of the deviations from a best fit parabola is 0.86 mm and the half-path length error 0.80 mm giving a Ruze efficiency at 10 GHz of 0.89. It should be noted that the Mk2 reflector was designed for a feed and support structure mass of 250 kg but the mass of the PHAD feed and structure, a non-optimized test system, is 390 kg.

In order to be able to compare the measured results with the FEA model results it was necessary to rerun the finite-element simulations with the actual feed and feed structure mass loading and to account for the as-built surface accuracy deviations. A parabola was fit to the updated FEA results and the RMS surface accuracy deviation calculated. To this the as-built surface accuracy was added using Equation 2.

$$RMS_{model} = \sqrt{rms_{FEA}^2 + rms_{ab}^2} \quad \text{Eq. 2}$$

where:

- RMS_{model} = total calculated model RMS surface accuracy
- rms_{FEA} = calculated RMS surface accuracy from FEA analysis
- rms_{ab} = measured as-built RMS surface accuracy.

It can be seen from the results is shown in Table 3. There is a very good agreement between the measured and model surface accuracy.

Table 3 Comparison of Measured and Modeled Surface Accuracy

	RMS (mm)	η ($\lambda = 3$ cm)
Model	0.75	0.93
Measured	0.86	0.89

A second set of measurements was made with the laser tracker of the reflector deflection under gravitational loading with changing elevation angle. Twelve targets were arranged on one half of the reflector, as shown in Figure 6, assuming the structure is symmetric about the vertical.

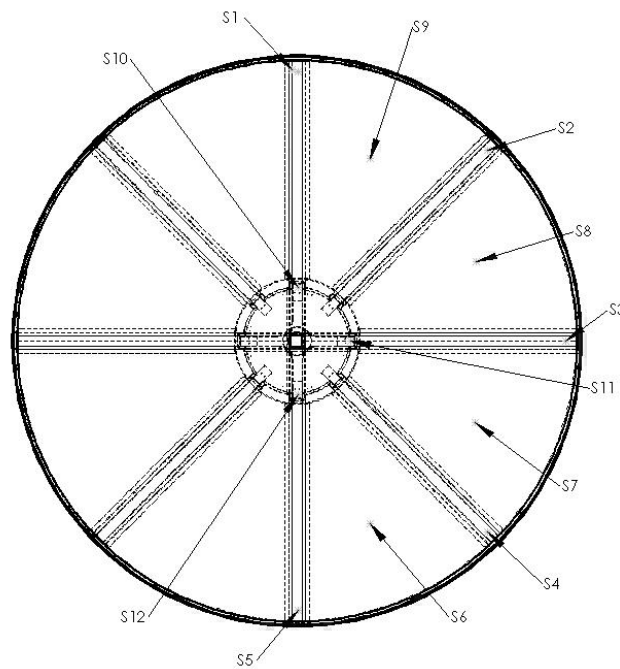


Figure 6 Laser tracker target locations.

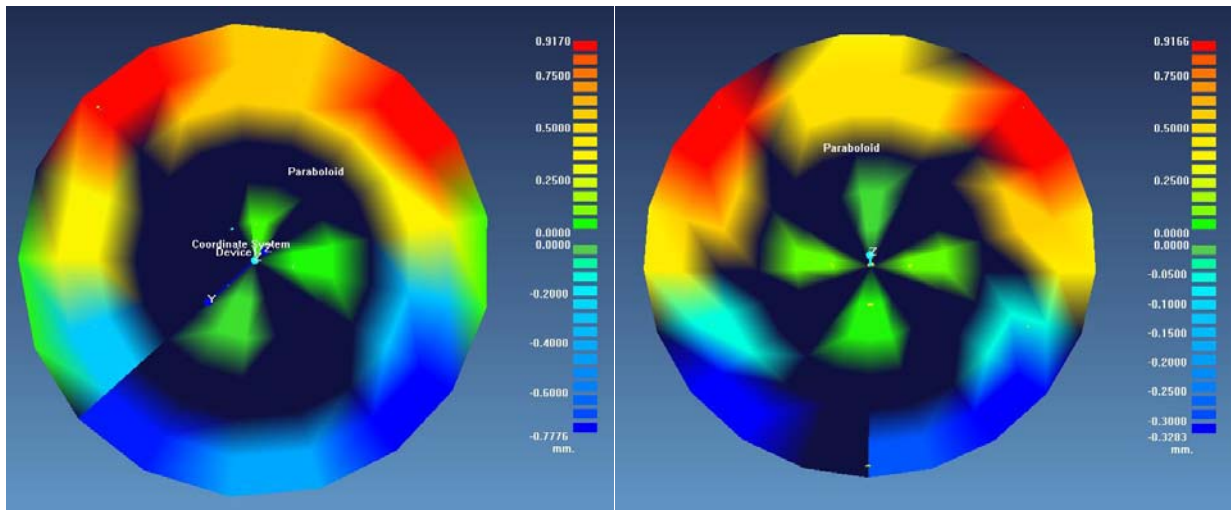
With the laser tracker mounted in the centre of the reflector, measurements were made of each target's location with the reflector at elevation angles of 90° , 75° , 60° , 45° , 30° and 15° . It was assumed that deflections at Targets 10, 11 and 12 (close to the reflector centre) were negligible so these points were used to null out the deflection of the tracker mount relative to the reflector surface. Note that target 6 was not used due to a problem with the target at that location.

The Mk2 reflector has some deviations from the designed parabola due to manufacturing whereas the FEA model that references the design parabola does not. In order to be able to compare the measurements from the Mk2 and the FEA model it is necessary to plot only the deviations due to the changed gravity vector with changing elevation angle. The following procedure was used to analyze the data and enable comparison to FEA results:

1. The output node data from the FEA results at the 90° elevation angle were imported into metrology software, in the same file as the measurement data. For each of the measured target points the closest FEA node point was selected.



2. The selected FEA points and measured points were mapped to the surface of the nominal parabola.
3. The selected node points were extracted from the FEA output for all elevation angles considered.
4. The deviation of each point from its position at 90° elevation angle was calculated for every elevation angle data set for both the FEA and measured data.
5. These deviations were then added to the coordinates of the corresponding points on the parabola surface.
6. This data was then mirrored about the vertical plane of symmetry to allow a plot over the whole surface. Deviations from the nominal parabola surface were then plotted using large color patches for better visualization. Figure 7 shows examples of these plots.



a) FEA

b) Measured

Figure 7 Deviations due to gravity at 75 deg elevation angle. a) FEA, b) Measured

Table 4 Summary of Elevation Angle Deviation Results from FEA and Measurement.

Elevation Angle	75°	60°	45°	30°	15°
Maximum Difference (mm)	0.449	0.970	1.060	0.478	1.481
Minimum Difference (mm)	-0.181	-0.350	-0.024	-0.734	-0.025
Average Difference (mm)	0.146	0.324	0.465	0.049	0.695

Table 4 shows a summary of the maximum, minimum and average differences in FEA predicted deflections and measured deflections for each elevation angle. It can be seen there is a good agreement between the measured and FEA



predicted deflections. The FEA predicted deflections are on average within 0.34 mm of the measured values.

The calculated RMS surface accuracy from the FEA predicted deflections is on average within 0.6 % of that calculated from the measured deflections. Although calculating the RMS surface accuracy from only 17 points is not a great indicator of the surface quality the agreement of the measured and predicted RMS further validates the FEA model.

Design Performance

Having validated the FEA model under the loading of the PHAD array it is now of interest to look at the performance of the Mk2 reflector under the original design feed mass of 250 kg. By combining the analysis results with the as-built surface accuracy using Eq. 2 the surface accuracy that could be expected for the reflector operating under design conditions can be predicted, (Table 5).

Table 5 Predicted Surface Accuracy with Design Loading.

Elevation Angle	Wind* (km/hr)	RMS Surface Accuracy (mm)	η ($\lambda = 3$ cm)
15°	0	0.993	0.86
60°	0	0.633	0.93
90°	0	0.635	0.94
15°	35	0.996	0.86
60°	35	0.931	0.88
90°	35	0.657	0.93

* Wind azimuth direction is 0° (straight into the reflector), pressure contours applied as per [2].

The reflector was designed to operate at a maximum frequency of 10 GHz. Therefore, using a 1/20 wavelength criteria, the RMS surface accuracy must not exceed 1.5 mm. The CART Mk 2 reflector easily achieves this under all analyzed conditions. It is possible that other wind angles may cause higher deflections and RMS values but given the large margins it is safe to assume that it would still be within specification.

Future Activities

The thermal performance of the Mk2 reflector remains to be fully characterized. It is known that the composite materials used in the reflector have a lower Coefficient of Thermal Expansion (CTE) than aluminum but determining the stability of the structure as a whole is under investigation. Measurement of the CTE of the different laminates used in the construction of the Mk2 has been carried out. These values will be input to an FEA model and thermal loading



applied to predict the thermal performance of the reflector. In parallel, measurement of the reflector surface under different thermal load conditions will be carried out as conditions permit.

A contract has been let to an industrial partner to study manufacturing processes for composite reflector for the SKA. Quantities and production rates required for both Phase 1 and 2 will be considered with an emphasis on manufacturing cost reduction. Results of this study are expected in mid-2009.

Design of offset reflectors to meet the SKA preliminary specifications is underway as well as a multi-piece reflector design. These activities will be reported over the coming two years as part of the PrepSKA Work Package 2.

Conclusions

The CART Mk 2 reflector is an improvement on the Mk1 in all aspects. The change of design approach to separately fabricated beams and hub bonded to a monolithic surface and rim improved manufacturability and yielded a more accurate surface.

Measurement of the deflection due to gravitational loading at various elevation angles and comparison to the FEA model served to validate the model's accuracy and build confidence in the modeling methods.

Under design loading conditions (150 kg feed) the CART Mk2 reflector meets or exceeds all of the design criteria. Under all analyzed loading conditions the RMS surface accuracy is below 1 mm. Even with the nearly 400 kg PHAD feed the reflector is capable of 10 GHz operation with a RMS surface accuracy deviation under operating conditions of 1.2 mm.

Cost for the prototype is 1 kUSD/m². The cost for reflectors in a production scenario is estimated to be 20 to 40% less than this due mainly to savings in labour. A manufacturing study has been contracted to an industry partner to investigate the production of composite reflectors at production rates and quantities required for the SKA to determine the production costs.

References

- [1] Ruze, J.: Antenna Tolerance Theory, Proc. IEEE vol.54, no.4, pp.633–640, 1966
- [2] Levy, Roy, "Structural Engineering of Microwave Antennas", IEEE Press, 1996.

