An Update on the Mechanical and EM Performance of the Composite Dish Verification Antenna (DVA-1) for the SKA

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Abstract − **This paper will give an overview of the unique mechanical and optical design of the DVA-1 telescope. The rim supported carbon fibre reflector surfaces are designed to be both low cost and have high performance under wind, gravity, and thermal loads. The shaped offset Gregorian optics offer low and stable side lobes along with a large area at the secondary focus for multiple feeds with no aperture blockage. Telescope performance under ideal conditions as well as performance under gravity, wind, and thermal loads will be compared directly using calculated radiation patterns for each of these operating conditions.**

1 INTRODUCTION

The Dish Verification Antenna (DVA-1) is a joint project between the Composite Applications in Radio Telescope (CART) program at the National Research Council (NRC) in Penticton Canada and the Technology Development Program (TDP) in the USA (funded by the National Science Foundation). The aim of the project is to design and build an operational prototype for the Square Kilometer Array (SKA) project. Figure 1 is a computer rendering of the DVA-1 design. The DVA-1 project has successfully completed a series of design reviews and construction of a working prototype is scheduled to be completed in early 2013. The DVA-1 design is currently the only radio telescope concept that meets all of the SKA requirements [1]. The antenna will be located at the NRC Dominion Radio Astrophysical Observatory (DRAO) facility in Penticton where it will be characterized for aspects of use as an SKA antenna.

Figure 1: The 15m offset Gregorian DVA-1 telescope.

2 OPTICS

The optics for DVA-1 is an offset, dual reflector design providing a 15m clear aperture and utilizing shaped reflectors to achieve optimum Aeff / Tsys. Figure 2 shows a cross section drawing of the optics with ray tracing shown. The primary reflector has a rim dimension of 15m x 18.23m, and an area of 226.6m^2, or 1.282 times the aperture area. The secondary reflector is 3.99m in diameter, with an area of 15.0m^2. The opening half angle at the focus is 55° with the tilt angle of the bore sight being 30 degrees. The tilt angle is chosen to minimize the cross polarization introduced by the optics.

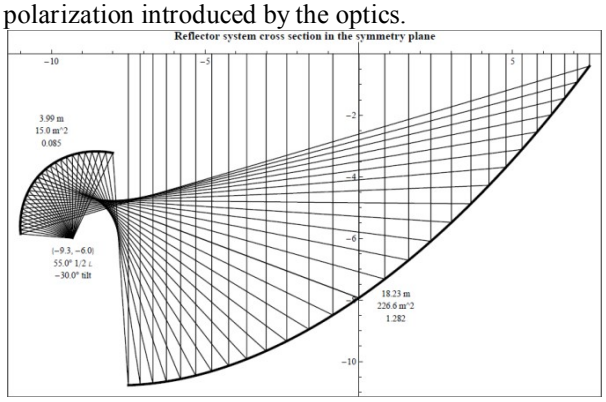

Figure 2: DVA-1 shaped optics

The shaped, offset design has numerous advantages. The most obvious is the clear aperture with no blockage of any radiation. This is one of the prime contributors to the very low wide angle pattern of this design and helps raise the aperture efficiency. Also obvious in the figure is the large size of the secondary. The large secondary provides good low frequency performance, down to 350 MHz. Such a large secondary would not be practical in axi-symmetric optics; the blockage would be prohibitively large. Another advantage of the offset design is the large volume below the focus available to accommodate receiver systems.

The opening angle presented from the focus to the secondary has been chosen to accommodate a variety

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of feeds. Very wide band feeds, 4:1 to over 10:1 bandwidths are one possibility and corrugated horns are a higher performance alternative. Different opening angles can be accommodated by changing the subreflector shape while keeping the same primary reflector shape.

The effect of shaping the reflectors can be seen in the distribution of the rays in the aperture and extended caustic between the reflectors. The optics are designed to take a -16 dB edge taper from the feed and produce a more uniform aperture distribution. The rays show a spreading of the feed pattern in the center of aperture and a squeezing together at the edges, giving an aperture distribution with a -11 dB edge taper. The calculated performance with a perfect Gaussian feed is an aperture efficiency of .78 and a -22 dB first sidelobe (compared to aperture efficiency below 0.6 for a parabolic reflector with the same feed). The cross polarization is zero along the symmetry plane and peaks at -36 dB in the orthogonal plane. Performance with a realistic corrugated horn is only slightly worse.

The very low edge tapers on both reflectors and the clear aperture produce a wide angle pattern below -50 dB in all directions beyond the main beam and the first few sidelobes. In the forward direction this gives very low response to strong sources and RFI. In the ground direction, noise pickup is minimized. The antenna noise temperature (sky + galactic + ground) is between 5 and 10 Kelvin, depending on elevation angle. Combined with the high aperture efficiency and assuming a receiver with 15 Kelvin noise temperature, DVA-1 has an Aeff / Tsys over 6 m^2/Kelvin at zenith.

3 MECHANICAL DESIGN

The mechanical design will be broken into three components: the primary reflector and backing structure, the secondary reflector with the feed support structure, and the tower and turning head.

3.1 Primary Reflector and Backing Structure

The DVA-1 design consists of a composite reflector surface, molded in a single piece with a composite rim beam. The backing structure consists of round tubes spanning between the composite primary dish rim and two structural frames, one pentagonal and one triangular in shape (Figure 3). The composite reflector is a relatively thin membrane-like structure with a fixed rim support and a semi-compliant central support. Since the rim support is at discrete points, the load must be spread into the composite surface by the rim structure. Also because the reflector surface is to be made from low CTE (Coefficient of Thermal Expansion) Carbon Fibre Reinforced Plastic (CFRP), the rim must also be made from the same material to avoid differential expansion issues. The backing structure was designed to be manufactured from steel. The advantage of steel is its high stiffness-to-cost ratio and its relatively low CTE. The disadvantage is its weight, but the majority of the backing structure mass is positioned behind the elevation axis which helps with overall balance.

The central semi-compliant connector between the primary back-structure and the primary reflector shell is an important design feature [2]. Figure 3 shows the connector (grey disk near centre). The connector is a thin panel bolted around its rim to the backing structure and bonded near its centre to the backside of the primary reflector. Because of its geometry, the connector will restrict movement in a plane parallel to its surface and allow nearly unrestricted movement (over a short range) perpendicular to this plane.

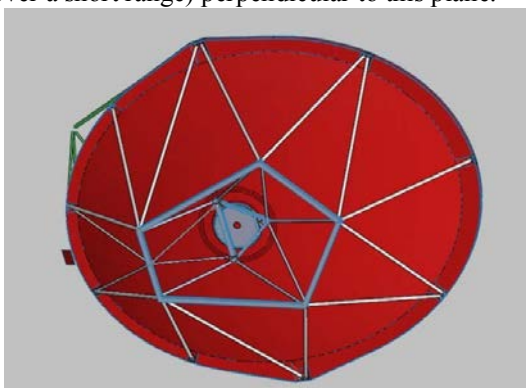

Figure 3 Underside of the primary reflector showing arrangement of backing structure

3.2 Secondary Reflector and Feed Support Structure

The development of the feed and secondary support has been extensive. Several finite element (FE) models were created and analysed for total deflection, and a series of optimization studies commissioned. At issue was the inherent lack of stiffness in the feed and secondary support structure of the typical offset design. The stiff feed and secondary support structure shown in Figure 1 is a direct result of these optimization and FE studies.

3.3 Tower and Turning Head.

The backing structure arrangement in the DVA-1 reflector-set design offers an open area in the centre behind the primary. This allows a compact turning head containing the azimuth and elevation bearings and drives to be nested very close to the reflector back surface. This location is ideal because it is close to the centre of mass for gravitational loads and the area centre of wind loads. Since bearing and drive size are primarily based on resisting moment

loads, the shorter distances from a load centre to each axis produce smaller moments.

The mount is composed of 3 welded steel sections. The turning head housing contains the majority of precision aligned surfaces. The azimuth bearing and support tube are about 1/10 the aperture diameter. The bearing is a preloaded double row angular contact ball type with an internal gear. The support tube is a 12.7mm thick circular tube with a length about 1.36 times the diameter, creating a very stiff support. The azimuth drive employs two identical removable drive modules engaging the bearing internal gear and allowing zero backlash operation.

Figure 4: The DVA-1 mount design.

The elevation drive is a rod and cylinder type linear actuator using a fully protected 100mm diameter ball screw with a 2200mm stroke. A chrome plated finish on the rod allows a simple and effective seal. Backlash is controlled with tensioning from the offset gravitational load from the reflector set.

Both azimuth and elevation drive systems employ a full oil bath for bearings and gearing providing an expected 5 year lubrication maintenance interval.

4 PERFORMANCE

To fully evaluate the radio frequency performance of this telescope, aperture power and phase distributions, as well as beam patterns were calculated.

4.1 Aperture Power and Phase Distributions

Figures 5, 6, and 7 shown the calculated aperture power and phase density distributions (using electromagnetic ray tracing) under gravity deformation for 90°, 55°, and 15° elevation, respectively, and at a frequency of 1.4 GHz.

The resultant phase distribution errors are quite small in terms of wavelengths (at 1.4 GHz); the largest phase errors are at 15° elevation where the white area at the bottom has a phase error of +0.0062λ. By frequency scaling to 10 GHz this corresponds still to only 1/22 wavelength, which is quite good for an entirely passive structure. Clearly this telescope will perform well at frequencies of at least 10 to 12 GHz as shown in the next section, and therefore will meet the SKA frequency range specification.

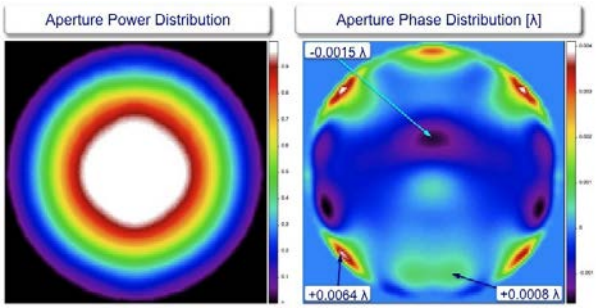

Figure 5: Aperture power and phase distribution at 90° Elevation.

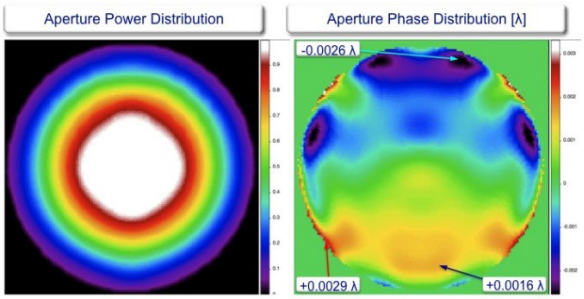

Figure 6: Aperture power and phase distribution at 55° Elevation (bird-bath).

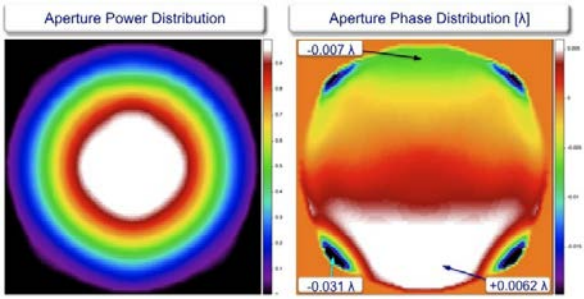

Figure 7: Aperture power and phase distribution at 15° Elevation.

Table 1 gives the beam pointing variations under gravity for the full optics system. The right hand column shows the beam pointing deviation (in half power beam widths) as a function of elevation angle at 1.4GHz (referenced at 55°). The deviations are very small between 90° and 55° elevation, and increases to 1/56th HPBW at 15° respectively.

Elevation Angle	$\Delta\theta_{BEAM}$ [arcsec]	$\Delta\theta_{BEAM/55^o}$ [arcsec]	$\Delta\theta_{BEAM/55^o}$ [HPBW]
15°	110.638	62.2	1/56
55°	47.434	----------	----------
90°	43.314	-4.12	-1/850

Table 1: Beam Pointing Variations under Gravity.

4.2 Beam Patterns

Beam patterns were generated for several operating conditions using physical optics (PO). Figures 8, and 9 show the beam patterns for gravity at 90, and 15 degrees elevation respectively. All beam patterns are at 10GHz. The plots also show the undistorted beam pattern for comparison (red line).

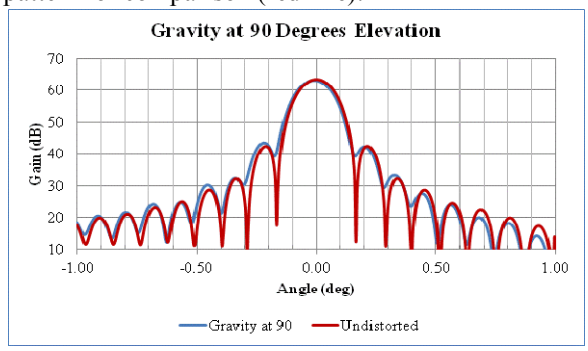

Figure 8: Antenna pattern at 90° elevation (blue) compared with undistorted (red)

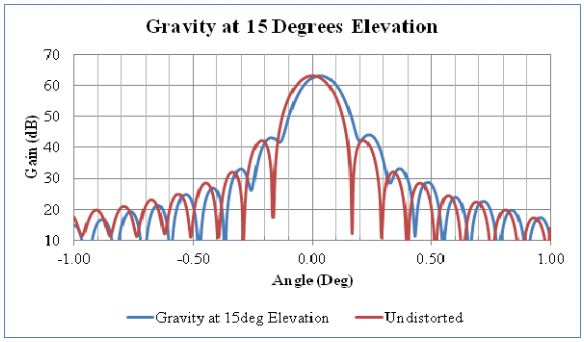

Figure 9: Antenna pattern at 15° elevation (blue) compared with undistorted (red)

Figure 10 shows the beam pattern with the entire telescope under a +25°C thermal bath; showing that temperature has very little effect on the beam pattern.

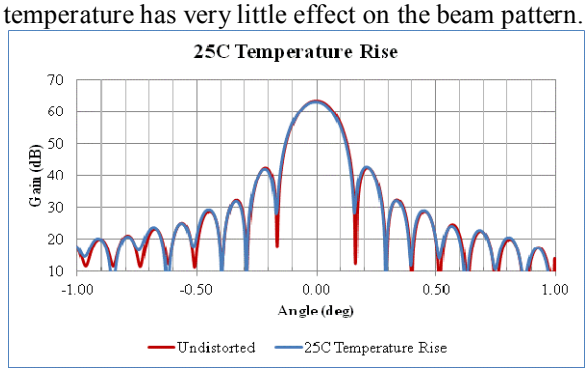

Figure 10: Antenna pattern at +25°C temperature rise from fabricated temperature (blue) compared with undistorted (red)

Table 2 summarizes all of the beam pattern results for 10 GHz. Peak gain is reduced by a maximum of 0.11dB at 15° elevation under gravity, all other cases being less. There is also a scan offset at 15° elevation of 0.0325° but this would be corrected by the pointing table. Wind has very little effect, which is one of the strong points of this design (wind plots are not shown due to space constraints). Temperature also has little effect due to a very clean dish structure and the low CTE of carbon fibre.

Load Case	Peak Gain	Scan Offset	Scan Ortho-gonal	On-axis Gain	Peak Sidelobe	Peak X-pol	Beam Width	
	(dB)	mdeg	mdeg	(dB)	(dB)	(dB)	X (deg)	Y (deg)
Undistorted	63.27	0.51	0	63.27	20.857	41.954	0.133	0.133
25C Temp increase	63.253	-2.97	-0.18	63.247	20.317	42.196	0.133	0.133
Gravity 15 degrees	63.162	32.49	0.17	62.482	19.076	43.2	0.134	0.132
Gravity 55 degrees	63.25	12.82	0.12	63.145	20.674	42.092	0.134	0.133
Gravity 90 degrees	63.107	-9.29	0.03	63.052	19.501	41.046	0.134	0.134
Wind 15 degrees	63.268	5.09	0.15	63.251	20.689	42.014	0.134	0.133
Wind 55 degrees	63.27	0.23	0.03	63.27	20.834	41.951	0.133	0.133
Wind 90 degrees	63.27	1.3	-0.11	63.269	20.804	41.954	0.133	0.133

Table 2: Tabular data of beam performance for thermal, wind and gravity at 10GHz

5 SUMMARY

As expected the DVA-1 prototype telescopes gravitational, thermal, and wind performance are very good, due to the rim-supported design and the use of low CTE materials. We expect that the DVA-1 prototype telescope will be a high performance, high dynamic range instrument fully compliant with SKA specifications. Testing will begin with a number of different feed types when the telescope is complete in 2013.

Acknowledgements

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References

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