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Design and Test of a 2m x 4m DART system

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ABSTRACT

A 2meter by 4meter DART (dual anamorphic reflector telescope) system has been designed and fabricated using thin stretched mesh reflectors. The system concept consists of a pair of single curvature reflectors with curvature in orthogonal directions relative to each other and is being developed for future ultra-lightweight space applications. The current design is an extension of a successful 1m system previously prototyped and tested. The 2m x 4m system is a laboratory prototype with areal density of less than 10kg/m2 for each reflector. The new design demonstrates the advantageous scaling properties of the single curvature reflector concept. The 2m x 4m system was configured and tested in the RF over several frequencies from 5.8 - 8.2 GHz. This report documents the structural configuration, test preparation, test results, and analysis correlation. Test results show the DART system to be a high directivity antenna (46.5 dB), and very low cross-polarization (-33 dB) with good off-axis properties. Test results were in good agreement with analytical predictions of the performance. Generally, the DART system easily achieves the surface accuracy requirements at 8.2GHz.

1. INTRODUCTION

The DART system architecture consists of a pair of cylindrical parabolic reflectors oriented with curvature orthogonal to each other, thus producing a single common focal point. The capability of such a system to focus electromagnetic energy and its application to IR imaging was described and demonstrated for a 1m system in Ref. 1 and Ref. 2. We have previously presented the results of a 1m prototype used to image a 10um where we calculated an equivalent diffraction limited performance of 40um over a testable area of the aperture of about 0.5m. We have now built a larger 2m x 4m system to demonstrate the scaling of such a system to very large apertures. The system has been configured and tested in the LMMS Sunnyvale PNTR (Planar Nearfield Test Range) at a set of frequencies from 5.8GHz - 8.2GHz to demonstrate the scalability of this technology and the application to RF systems.

2. SYSTEM DESIGN

The DART hardware tested was the 2m x 4m pair of reflectors. The reflector design is shown in Figure 1. Each reflector assembly weighs approx 135 lbs. The reflectors consist of an assembly of thin 5" aluminum tubes that function as a rigid back-up structure to react the reflector membrane tension. Each back-up structure is a series of parallel tubes that run in the direction that is to be used to tension the membrane reflector. These tubes are sized to resist buckling during operation. Two tubes are welded at the each end of these parallel tubes, forming a rectangular frame. Mounted to the two end tubes are a series of alignment mechanisms, tension application mechanisms, and actuation sites.

Precision flat rails are mounted at opposite sides of the back-up structure through these mechanisms sites and given curvature through a system of moment and force application. The rails were then formed to parabolic shape as required by the system layout Figure 2. The rails were required to be parabolic to with approximately 0.04" in order to achieve desired performance at these RF test frequencies. The DART prototype has the capability for active actuation

along the end rails, but these components were not used in this test as the DART system could easily meet the surface accuracy requirements.

The DART reflectors were made from aluminum mesh 16threads/inch with 0.011" thread diameter. The mesh was stretched between the parabolic edge rails using approximately 10lbs/in of tension corresponding to about 180lbs of tension in each tension cable site. Most of the visible surface inaccuracies were pulled flat with this load application. A tensioned cable was placed in contact with the mesh at the two opposite free edge sides (orthogonal to the tension application sides) in order to stabilize the free edge.

The DART layout consists of placing the two main reflectors approximately 67.6inches away from each other at there centers with an relative angle between them of 43.5degrees. The first, or main-reflector, is section of an offset parabola with center sag on the edge rails of about 0.63 inch. The second, or sub-reflector, is an on-axis parabola with sag at the edge rail center of about 3.55 inch corresponding to an F/2.5. The curvature and alignment of the reflectors was established manually using adjustment mechanisms in the DART design and using a pair of theodolite scopes.

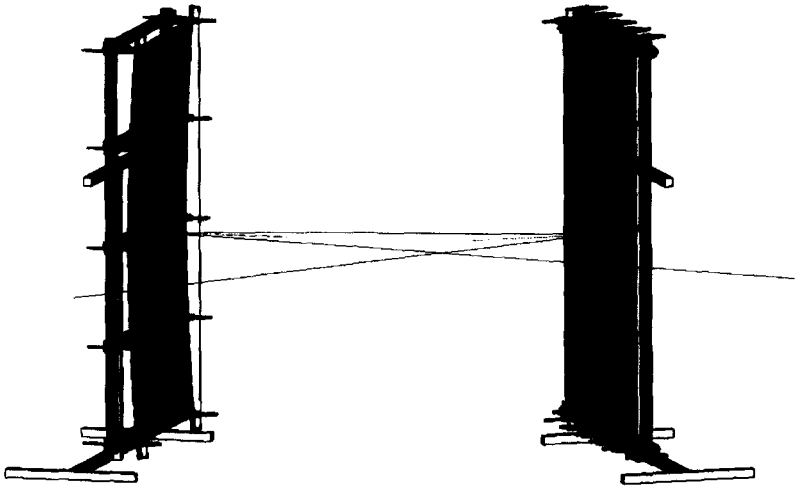

Figure 1. CAD drawing of two cylindrical parabolic reflectors mounted on mobile test stands.

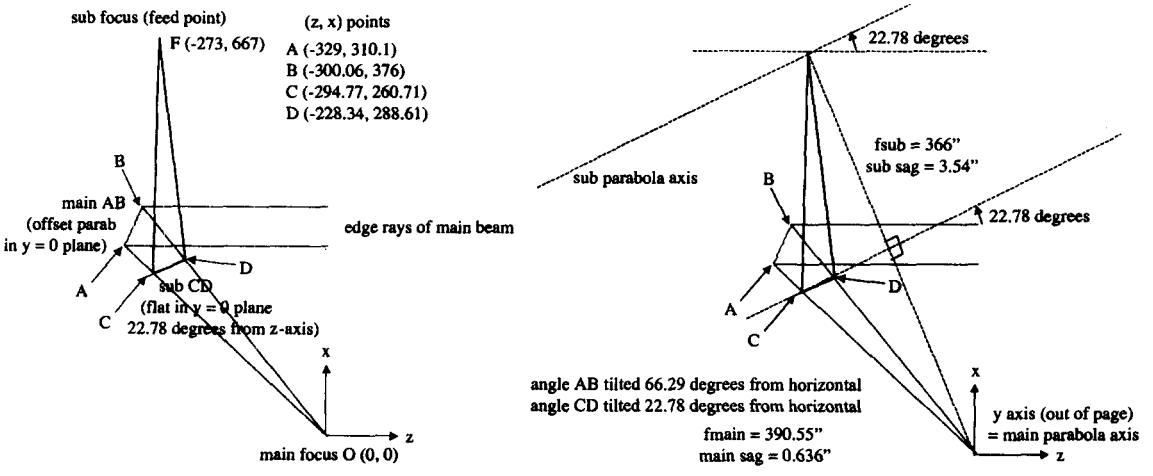

Figure 2. System Layout

3. TEST SETUP

The reflectors were set to proper curvature outside of the PNTR range. A pair of Leica TM5100 digital theodolite scopes were used measure the surface coordinates of the edge rails. The repeatability of these measurements was approximately 0.001 inch. After each curvature setting the data was analyzed by best fitting to the desired parabolic shape using a simple Matlab algorithm, and then iterating on force and moment application to manually adjust the curvature. After a few iterations the proper curvature and sag were established. Each surface was shown to deviate from the desired parabolic by approximately 0.03 inch (0.75mm) spatial RMS. This was satisfactory for the wavelengths being tested (~1.4inch).

The reflectors were mounted to a spacecraft dolly with large spacer rings to bring the center height of the each reflector to 13feet above the ground as shown in Figure 3. This was to ensure an approximately 30degree view from the reflector to the scanner plane in all directions. Figure 3 shows the reflectors mounted and prepared to be pushed into the range. The dolly was position in approximately the middle of the range with the feed 366 inches from the center of the sub-reflector and the probe approximately 120inches away from the main-reflector at center. Final alignment of each reflector position and surface curvature was confirmed within the range as shown in Figure 4. Absorber material was subsequently mounted to the reflector test stands and spacer rings to reduce scatter of RF energy.

The feed horn was located in the range according to the measured curvature of the reflectors approximately 366 inches from the center of the subreflector. This was modified by several inches to best focal location based on preliminary scans of the system and moved to final position shown in Figure 2. A 12inch 2-18GHz qaudridge horn was used as feed. The reflector illumination taper was less than 3dB in the tall direction and 1dB across the width direction. The VAO Planar scanner manufactured by Nearfield Systems Inc. has a scan plane of X (horizontal) = 504", Y (vertical) = 334" with RF measurement capability of 1 to 18 GHz. The acquisition code used is NSI2000 version 3.0.48.

After the test was complete, the spacecraft dolly was pushed out of the PNTR facility. The two reflectors were again shot for alignment to confirm that the figure of the reflectors had not changed during the test.

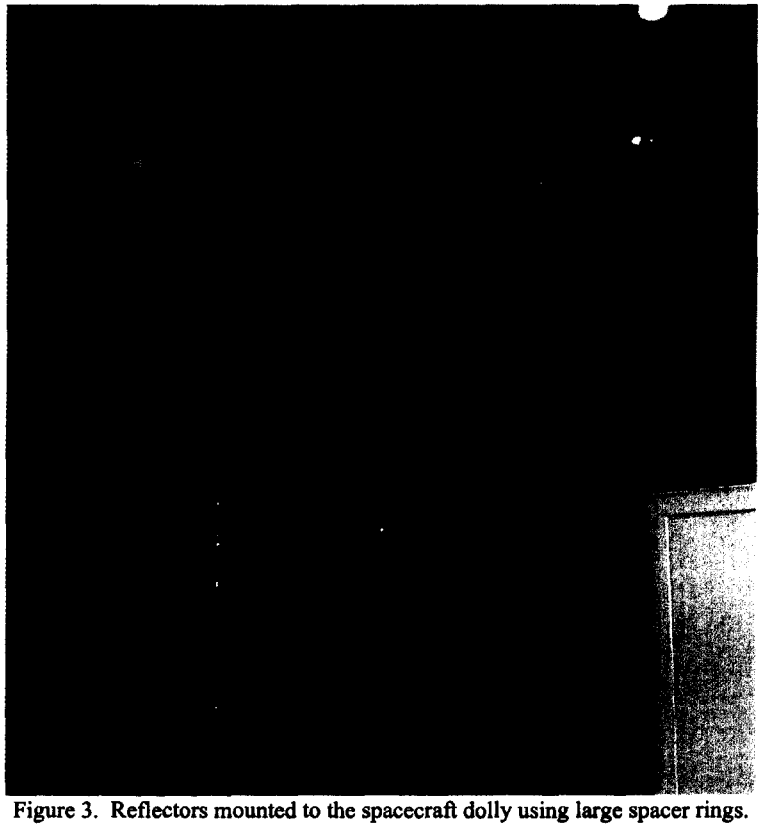

Figure 3. Reflectors mounted to the spacecraft dolly using large spacer rings.

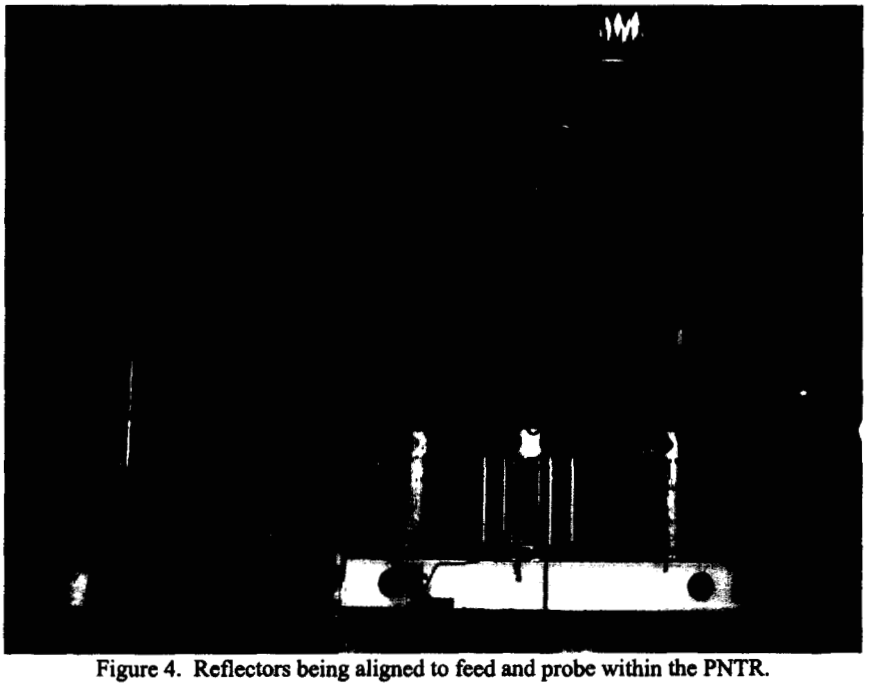

Figure 4. Reflectors being aligned to feed and probe within the PNTR.

4. ANALYSIS & TEST RESULTS

The analysis of the DART system configured for operation in the RF was performed using the physical optics based LMMS software package PO3D. Figures 6-8 show predictions at 8.2 GHz. Directivity was 46.53 dB at 8.2 GHz with no significant change when the feed was offset 6.7 degrees from focal center. Here we present the Directivity rather than system Gain as the most meaningful measurement since we simply used an available horn and no significant effort was made to optimize the feed design to improve Gain. Cross-polarization was below –33dB.

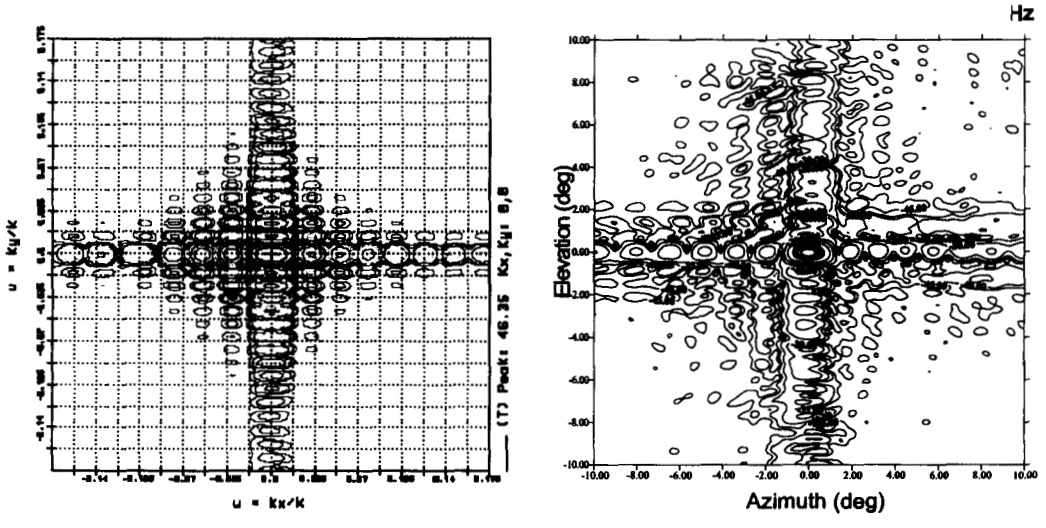

Figure 6. Far-field prediction at 8.2GHz with 47.6dB directivity compared to test results with 46.5dB directivity (right image).

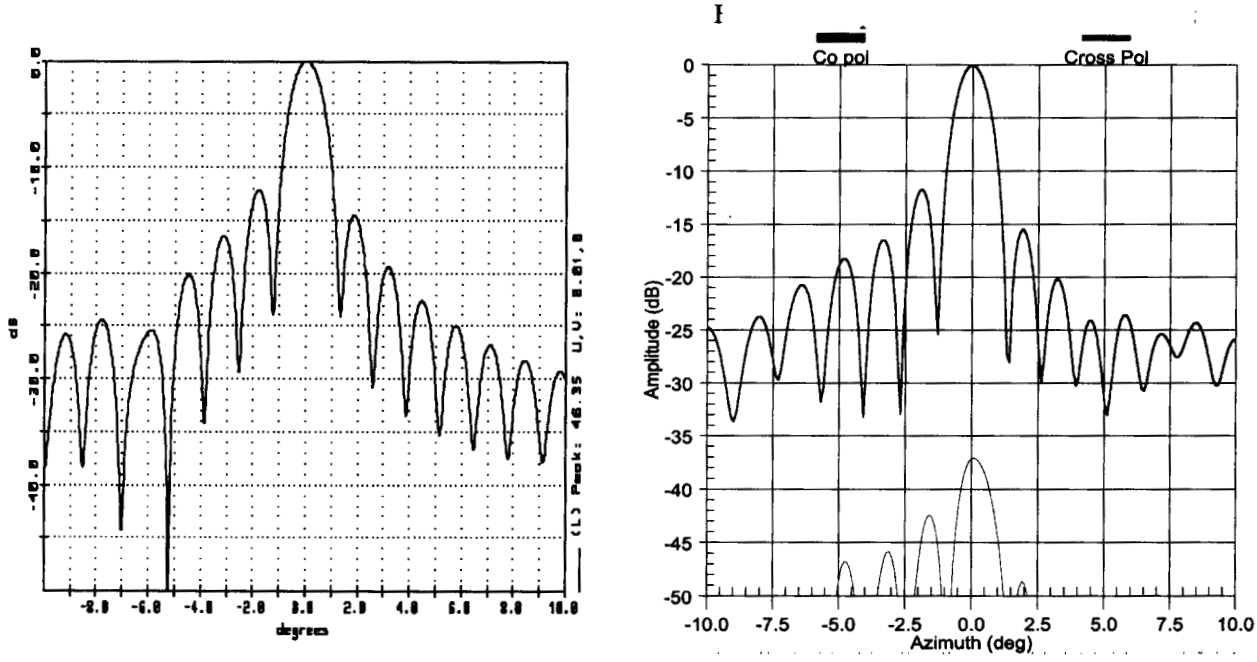

Figure 7. X-Cut (Horizontal) Far-field prediction at 8.2GHz compared to test results (right).

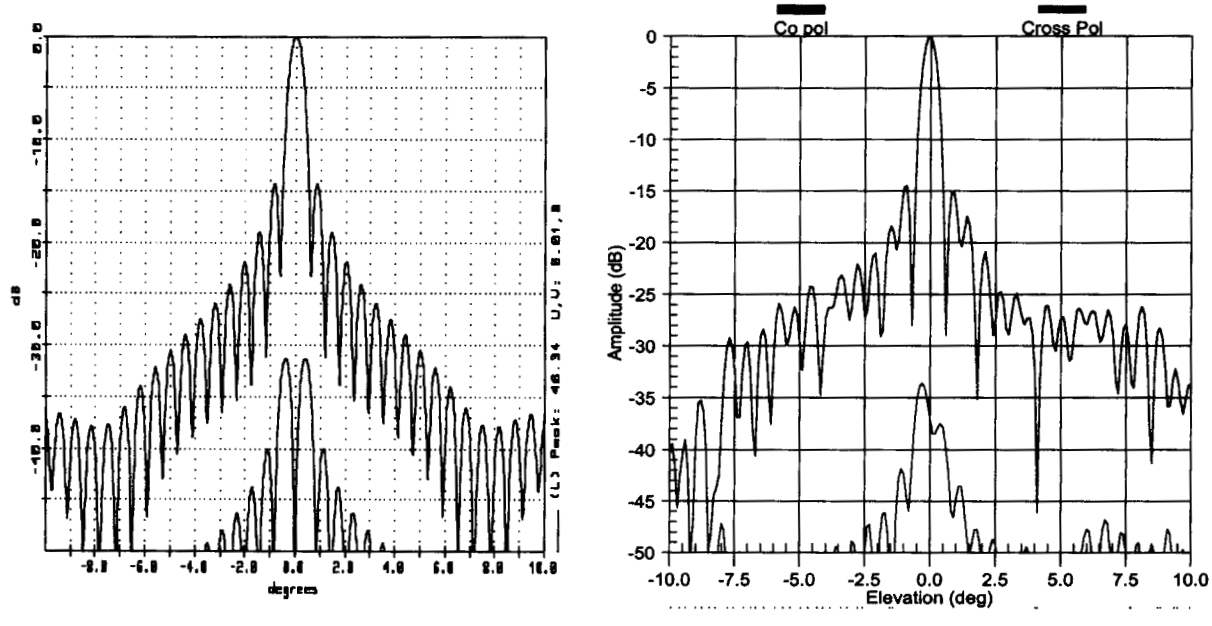

Figure 8. Y-Cut (Vertical) far-field prediction at 8.2GHz compared to test results (right).

6. DISCUSSION

The main reflector is curved over its narrow dimension, compared to the subreflector curved over its tall dimension (sag experimentally determined at approximately 3.54 over 144, or parabola focal length of 366 inches). This arrangement doubles the main reflector focal ratio relative to that of the subreflector. As seen from the relative sag of the two reflectors, the subreflector does five times the "work" of transforming a spherical wavefront into a planar wavefront (transmit mode). The same focusing motion in this geometry produces about five times the phase change across the subreflector as across the main reflector. Therefore, actual determination of the focus depends mostly on satisfying the subreflector. At this frequency range, an excellent focus can be found, as shown in both simulation and measurement.

A preliminary test pattern was taken before the final absorber was attached around the reflector frame. The pointing was good, but the focusing showed need for improvement, since about 60 degrees of quadratic phase error was seen, a positive bulge on a chart, with the exp(-jkz) convention meaning that the wavefront was bulging out from the aperture. The feed was then moved 15 inches farther back in the positive x-direction. The directivity from the range calculation rose from 46.108 to 46.533 dB. The cross-pol also improved in the y-cut. The cross-pol is low in the x-cut because the observer is near the null in the y-cut cross-pol. It can be seen in Fig. 7 to be –37 dB instead of zero because of slight asymmetries. The cross-pol in the y-cut shown in Figure 8 is between –30 and –35 dB as can be predicted. The average quadratic phase was noted to approximately lie within a 10-degree strip.

The horn used in the measurements had a 3-dB beamwidth of about 25 degrees at 8.2 GHz, so the reflector illumination taper was less than 3 dB in the tall dimension and less than 1 dB in the narrow dimension. This causes less than 0.1 dB taper loss, but it also illuminates surface errors anywhere on the reflectors. Linear polarization was chosen in order to more easily identify cross-pol. The feed polarization was horizontal, i. e. the E-field there was normal to the y-axis, because this polarization would not scatter from the vertical tension wires on the edges of the subreflector. The horn was aimed at the center of the subreflector. The focused data transformed to the far field show well-defined nulls indicative of good flatness of phase. The focused far-field pattern cuts at 8.2 GHz, shown in Figures 7 and 8, extended out to 10 degrees with the feed placement shown in Figure 2, which aimed the beam along the z-axis. The contour pattern is shown in Fig. 6 with power contours 5 dB apart, although the cuts give better resolution. Simulated patterns including contours are also shown in Figure 6 - 8, which accurately predict the near sidelobe levels including the high first sidelobe on the left in the x-cut. This is due to the aperture amplitude, not coma, and no attempt was made to lower it. The contour patterns appear cross-like because the transform of the aperture is essentially sinc(ax) times sinc(by).

The optical directivity calculation for a tilted aperture gives 47.6 dB for this system, about 1.1 dB above the processed result. Using the random surface error loss formula $-(\text{rms}/27.5 \text{ degrees})^2$ dB, the total rms phase error through the system is 29 degrees. Evenly splitting the error between the two surfaces gives 21 degrees since the variances add. Knowing that a change in reflecting surface position gives double the change in optical path and taking the incidence angle into account, the maximum normal deviation of each surface would be approximately 0.045 inches RMS. Ohmic and transmission loss would decrease this number, more in agreement with direct surface measurements of 0.030 inches RMS. We did not attempt to align and set curvature of the reflector better than 0.030inch because this was adequate for the frequencies being tested. Subsequent alignment work on the reflectors has improved this figure by approximately an order of magnitude. Further figure improvement is anticipated dependent on the reflector material being used.

Because field of view is important in both RF systems and optical imaging, an off-axis beam was measured in the critical direction where subreflector defocusing comes into play. The feed horn was lowered 46.5 inches, the limit of the mounting tripod and new data was taken. The range transform showed a well-defined beam scanned upward 6.7 degrees, about 11 beamwidths, with no coma-lobe increase on the "inside." From the data, the directivity shows only 0.001 dB loss, too small to measure.

These measurements were made on a near-field range and the processed to the far field, so there is some error introduced by probe noise and the fact that data is taken over a finite area. Since this reflector is of a respectable size (50

by 100 wavelengths), it produces a good approximation to a collimated beam, and most of the power can be recorded since the field drops off quickly outside of the beam. Also, since we are only looking within a few degrees of the beam peak, the radiated power is high compared to the noise even in the sidelobes. The error should be comparable to that of a conventional range, negligible down to around –40 dB from the pattern peak.

7. CONCLUSIONS

Test results of the 2m x 4m DART system showed it to be a high directivity, low cross-polarization antenna at 5.82 – 8.2GHz. The reflector mesh material was assembled onto the DART structure, transported to bldg 159, aligned, and tested in the PNTR in a period of less than 4 weeks. This attests to the simplicity and efficiency of the DART concept. The surface figure of each reflector tested was 0.03 inch RMS and was essentially diffraction limited for the wavelengths that were tested. We have subsequently reduced this RMS error value by an order of magnitude in the lab during a post alignment task. The actuators located along the edge rails have not yet been utilized, and we believe that these will enable us to improve figure by another order of magnitude. We conclude that the current DART prototype design should be applicable to much higher frequencies than the current test in this report. Each reflector weighs about 135lbs, or less than 10kg/m^2. The DART system design is directly scalable to larger apertures without significant modification.

REFERENCES

1. Dragovan, M., DART System for FarIR Applications, Proceeding of the SPIE, Vol 4849, Waikoloa, Hawaii, 2002.

2. Tolomeo, J., Cross, E., Sable, B., Decker, T., Putnam, D., Jamieson, T., Dragovan, M., Chmielewski, A., and Dooley, J., Design and Test of a Prototype DART System, Proceeding of the SPIE, Vol 4849, Waikoloa, Hawaii, 2002.