Predicting the Performance of a Very Large, Wideband Rolled-Edge Reflector

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Abstract—**Achieving a very large quiet zone across a wide frequency band in a compact range system requires a physically large reflector with a suitable surface accuracy. The size of the required reflector dictates attention to several important processes such as how to manufacture the desired surface across a large area and the practicality of transportation and installation. This inevitably leads to the segmentation of the reflector into multiple panels; which must be fabricated, installed, and aligned to each other to conform to the required geometry. Performance predictions must take into account not only the surface accuracy of the individual panels, but also their alignment errors.**

This paper presents the design approach taken on a recent project for a compact range system utilizing a blended rolled-edge reflector that produces a 5 meter quiet zone across a frequency range of 350 MHz to 40 GHz. It discusses the physical segmentation strategy, the fabrication methodology, the intermediate qualification of panels, the panel alignment technique, and the laser-based metrology methodology employed. Performance analysis approach and results will be presented for the geometry as conceived, and then for the realized panelized reflector as machined and aligned.

Keywords: Rolled-Edge Reflector, Compact Range, Surface Metrology, Quiet Zone

I. INTRODUCTION

The size of a reflector depends on the required size of quiet zone as well as the low frequency of operation for which it was designed to perform. Rolled-edge reflectors typically provide better RF performance at lower frequencies in a physically smaller size when compared to serrated-edge reflectors. In order to produce a cylindrical quiet zone that is 5m in diameter and 5m in length that operates at a low frequency of 350 MHz, the required size of the reflector is 9.5m x 9.5m. The geometry of the reflector is determined using a physical optics model. Once the required theoretical surface geometry is designed, the physical realization of this surface becomes a major challenge. Consideration must be given to available manufacturing processes for achieving the required surface accuracy as well as the feasibility of transportation via standard commercial avenues and handling during installation. Hence, this leads to segmenting the reflector into multiple panels, which are easier to fabricate, transport, handle, and install. However in order to achieve the proper quiet zone, the panels must be aligned relative to each other and conform to the required surface geometry.

The design and analysis of the required geometry of the reflector are discussed in detail in the next section. RF performance analysis of the quality of the 5m quiet zone at frequencies as low as 350 MHz is shown. The mechanical design of the reflector, including the physical segmentation, fabrication methodology, and panel alignment technique are briefly presented. Since, it is impractical to align the panels perfectly to conform to the theoretical surface geometry, analysis tools are required to predict the RF quality of the quiet zone based on surface accuracy of the panels as well as the misalignments in the panels. The analysis tool used for this purpose is discussed in a later section. The tool is used to qualify panels after they are individually machined. It is also used to predict the quality of the quiet zone when there is some misalignment between the panels. Basically, this tool is used to determine when the required level of panel alignment has been achieved.

II. RF PERFORMANCE ANALYSIS

As we examine the propagating electromagnetic fields radiating from the compact range reflector we examine the properties within the planar equiphase wavefront as it simulates the far field condition. The phase, of course, varies by 2π radians every wavelength (λ) as the wavefront propagates downrange. We can, however, talk about planar wavefront amplitude and phase variation within a cross-section of the quiet zone.

The required quiet zone size is 5m x 5m (diameter x length) over 1-40 GHz with reduced performance below 1 GHz. Typical quiet zone plane wave performance expected are 1dB amplitude taper, ±0.5 dB of amplitude ripple and 10° of phase.

The reflector concept being evaluated to meet these requirements is a rolled-edge center offset-fed reflector design as shown in Figure 1. The design parameters for this particular reflector are as follows:

- Overall Size: 9.5m x 9.5m (31’x31’)
- Parabola in concave rim: 4.6m x 4.6m (15’x15’)
- Rolled-edge Size: 2.4m (8’)
- Focal Length: 12.2m (40’)
- QZ Illumination Angle: 22.6˚
- Amp Taper - Loss (Az,El): 0.09 dB, 0.66 dB
- Feed Tilt: 21.9˚ center, 25.9˚ compensated

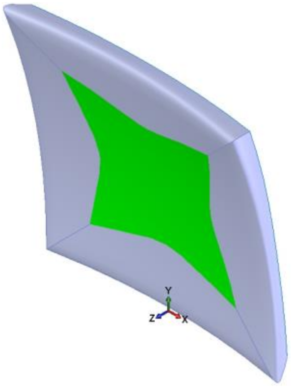


Figure 1. Rolled-Edge Reflector Geometry

The analysis performed is a physical optics, high frequency approximation computation. The model includes the offset-fed rolled-edge reflector geometry [1, 3] being fed by a typical field pattern of an MI-233 compact range feed. The code used to perform these computations is a modified Ohio State University Code for Blended Rolled-edge Compact Range Reflectors (BRCRRC) [2]. The total co-pol field amplitude, and phase, and total cross-pol amplitude were computed for 10, 1, 0.5, and 0.35 GHz. Contour plots and horizontal and vertical cuts illustrate these fields for each case at the center of the quiet zone. The contour plots are normalized relative to the center of the GO field.

A. *X-Band Free Space Analysis*

Figures 2a to 2c illustrate the total amplitude and phase variation at the center of the quiet zone at 10 GHz (X-band). Viewing first the horizontal cut in Figure 2a, the smooth curve is the geometrical optics (GO) fields (Geom EX and Geom EY) or reflected-only field including no diffraction. The GO field, therefore, represents the theoretical limit for the propagating field from this reflector system geometry including the feed pattern. So the amplitude taper in the GO field is as good as it gets. Note that the total EY and EX fields deviate from this GO field only slightly. This is expected since reflector surface imperfections are not represented in this model which would otherwise cause the high frequency results to be disturbed. Therefore simulation results from 10 to 40 GHz are essentially equivalent.

The total computed amplitude variation observed here within the 5m x 5m quiet zone is from -21.4 to -22.14 dB, which includes a maximum of 0.64 dB of taper and ±0.05 dB of ripple. The center quiet zone phase variation is 1.64˚. The cross-pol fields are well below -30 dB on axis.

B. *1.0 GHz Free Space Analysis*

Figures 3a to 3c illustrate the total amplitude and phase variation within the quiet zone at 1 GHz at the center of the quiet zone indicating amplitude, phase and cross-pol.

The total computed amplitude variation within the 5m x 5m quiet zone is from -21.41 to -22.3 dB, which includes a maximum of 0.65 dB of taper and ±0.2 dB ripple. The phase variation is < 5˚ at the center of the quiet zone. The cross-pol fields are well below -30 dB on axis.

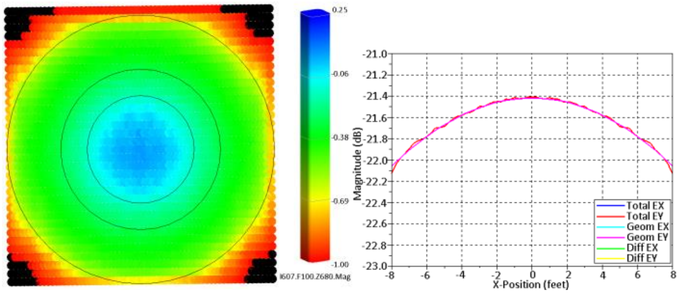


Figure 2a. RF Fields Co-Pol Magnitude at 10 GHz

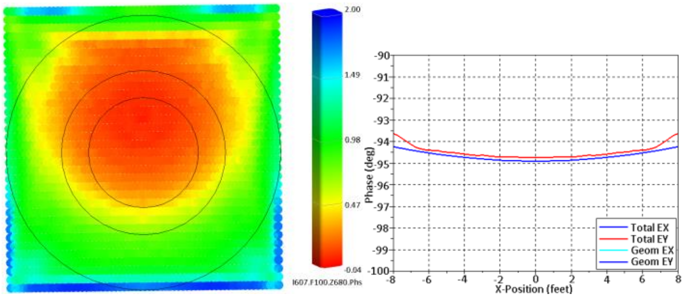


Figure 2b. RF Fields Co-Pol Phase at 10 GHz

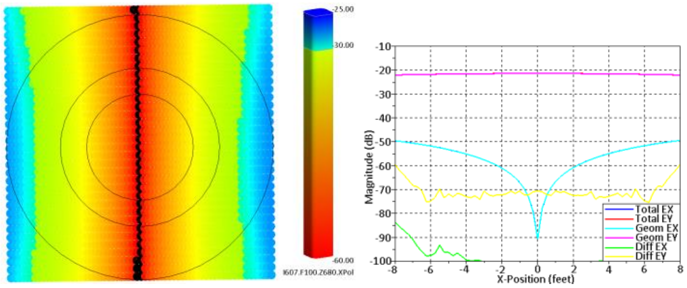


Figure 2c. RF Fields Cross-Pol Magnitude at 10 GHz

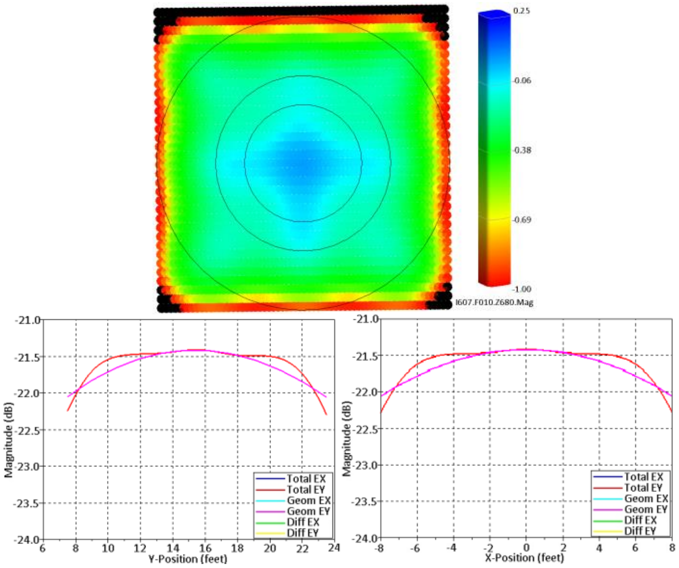


Figure 3a. RF Fields Co-Pol Magnitude at 1 GHz

C. *0.5 GHz Free Space Analysis*

Figures 4a to 4c illustrate the total amplitude and phase variation within the quiet zone at 0.5 GHz.

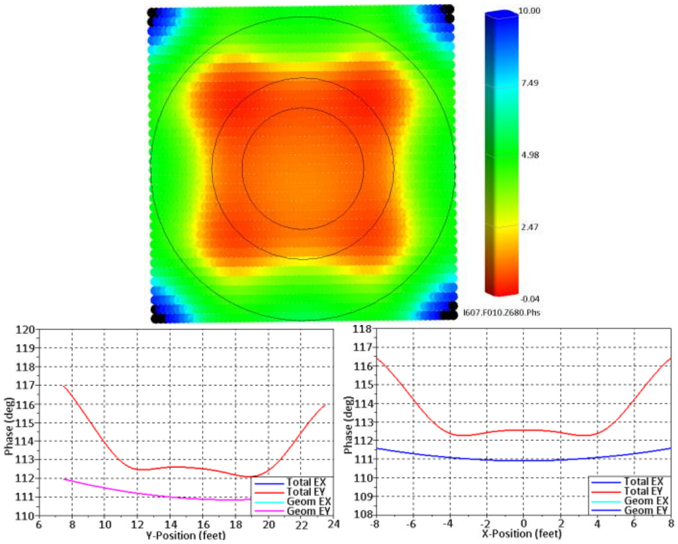


Figure 3b. RF Fields Co-Pol Phase at 1 GHz

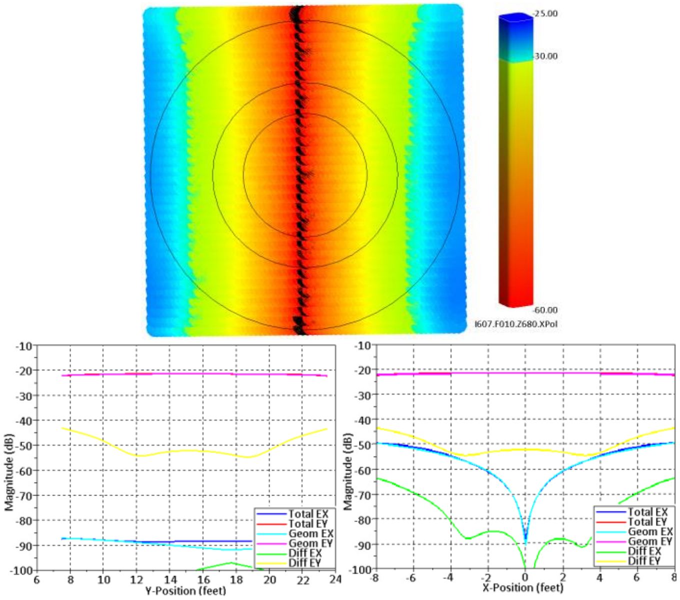


Figure 3c. RF Fields Cross-Pol Magnitude at 1 GHz

The total computed amplitude variation within the 5m x 5m quiet zone is from -21.32 to -22.71 dB, which includes a variation of < 1 dB of taper and ±0.25 dB ripple. The phase variation is < 7˚ at the center of the quiet zone. The cross-pol fields are well below -30 dB on axis

D. 0.35 GHz Free Space Analysis

Figures 5a to 5c illustrate the total amplitude and phase variation within the quiet zone at 0.35 GHz. The fields begin to break down a bit from a planar wavefront at this frequency by the presence of one large lobe across the quiet zone.

The total computed amplitude variation within the 5m x 5m quiet zone is from -20.55 to -22.17 dB, which includes a maximum of 1.5 dB of taper and ±0.1 dB ripple. The phase variation is < 11˚ at the center of the quiet zone. The cross-pol fields are well below -30 dB on axis.

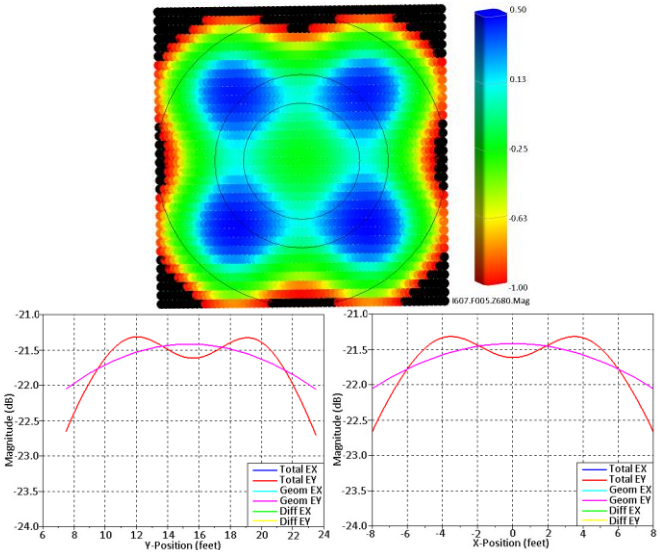


Figure 4a. RF Fields Co-Pol Magnitude at 0.5 GHz

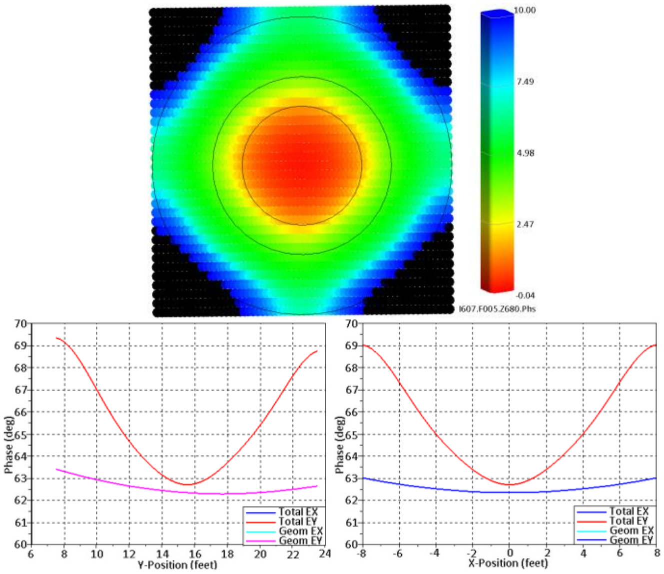


Figure 4b. RF Fields Co-Pol Phase at 0.5 GHz

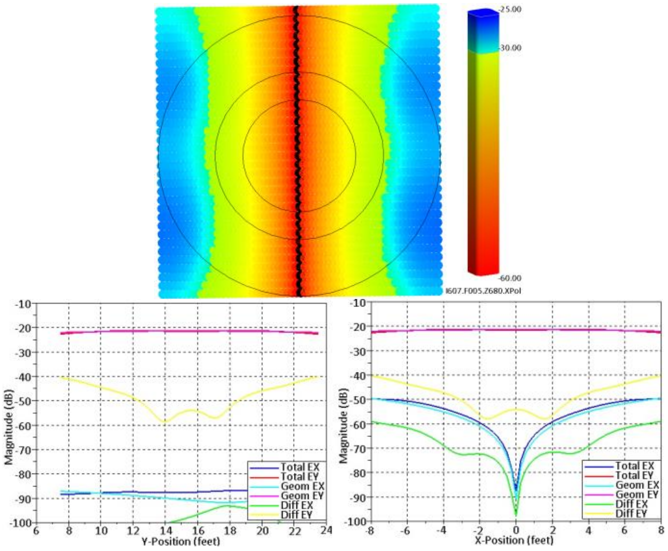


Figure 4c. RF Fields Cross-Pol Magnitude at 0.5 GHz

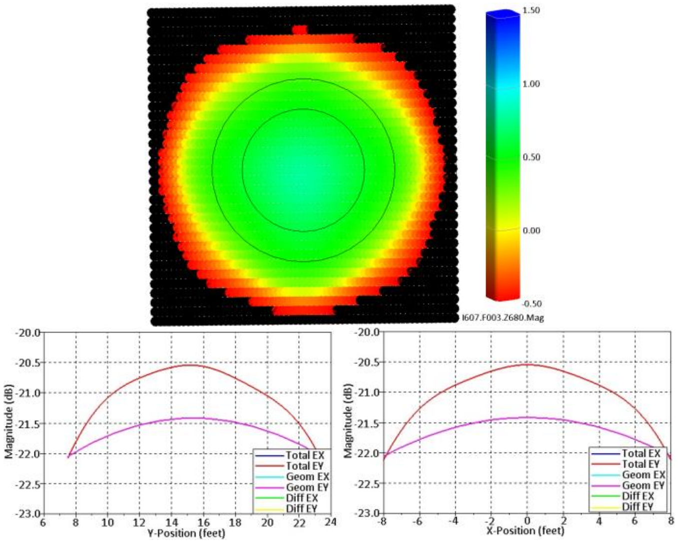


Figure 5a. RF Fields Co-Pol Magnitude at 0.35 GHz

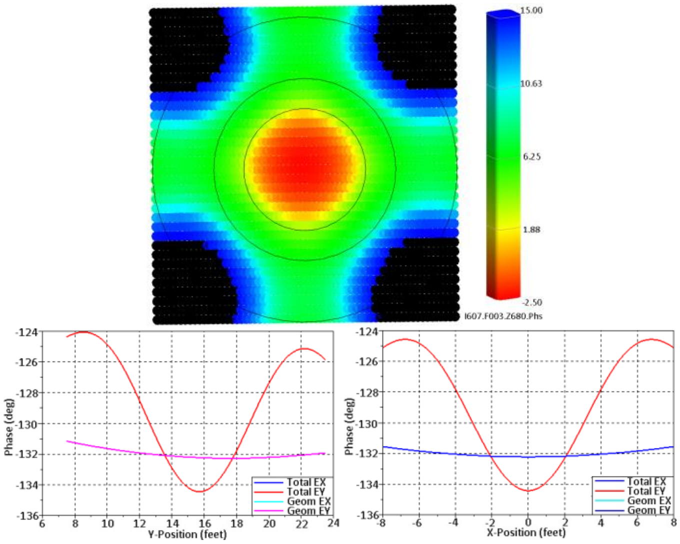


Figure 5b. RF Fields Co-Pol Phase at 0.35 GHz

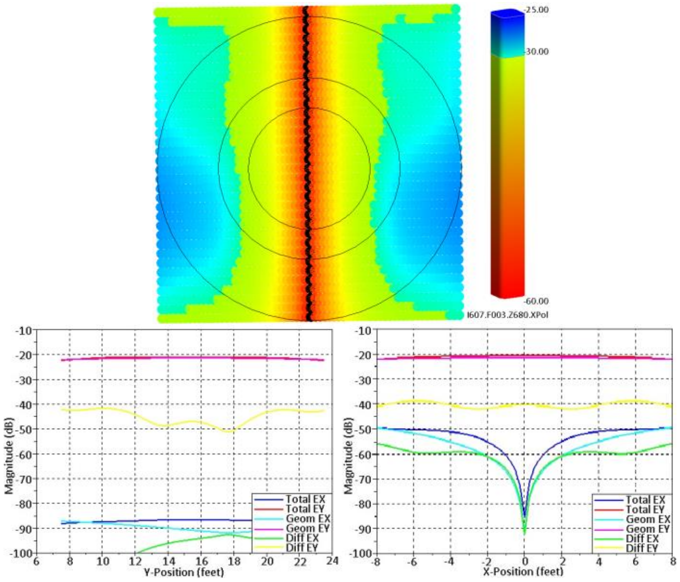


Figure 5c. RF Fields Cross-Pol Magnitude at 0.35 GHz

III. MECHANICAL DESIGN

Based on the reflector geometry, the depth of the rolled edges limits the availability of machining centers capable of machining the reflector as one or two panels. Further, it would be even more limited if machined in the installed orientation, which would be optimal for compensation of gravitational effects. Shipment of a large precision machined reflector would also be of concern as special oversized, temperature-controlled containers would be required to transport and it would become cost prohibitive. Hence, the approach is to segment the reflector surface into 21 panels with precision machined surfaces. The physical segmentation of the reflector is shown in Figure 6. The central lit region of 24 feet by 21 feet in size was made of 9 main panels and the rolled-edge termination on the four sides was made as 12 separate panels. See Figure 7 and Figure 8 for a representative main and roll panels.

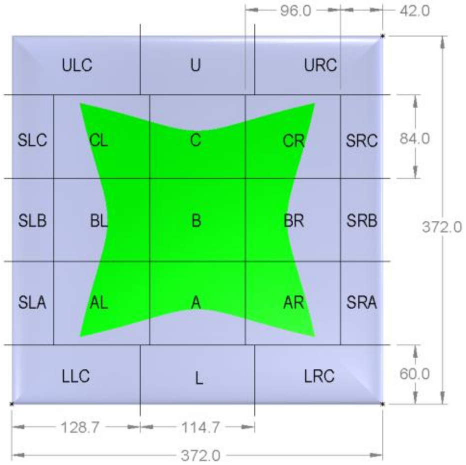


Figure 6. Reflector Segmentation Scheme (Dim in inches)

As with any large structure and especially cantilevered structures such as reflectors, weight is of major concern. If it is not possible to machine the entire surface as one in the installed orientation, deflections caused by weight must be dealt with in the design of the reflector and stand structure. The structure of the panels is designed to have a very high stiffness to weight ratio in order to ensure that the surface does not change appreciably when the panel is moved from the machining orientation to the installed orientation.

Additional concerns of a segmented reflector design are the alignment of the reflector panels and panel to panel seams. The design of the reflector incorporates alignment mechanisms on each panel to allow fine adjustment of all six degrees of freedom (DOF) as shown in Figure 9. Further, high precision metrology tools, such as laser tracker or laser radar systems, are used to accurately measure and analyze the installed surface to the master surface. The mechanism consists of a three-point mount incorporating ball and socket joints, which can be translated in all three axes, independently, without straining the panels. MI Technologies has designed and fabricated reflector units with these types of alignment mechanisms and has aligned the panels using high accuracy spatial geometry measurement systems. Both commercial and internally developed analysis software are used for the surface and alignment evaluations.

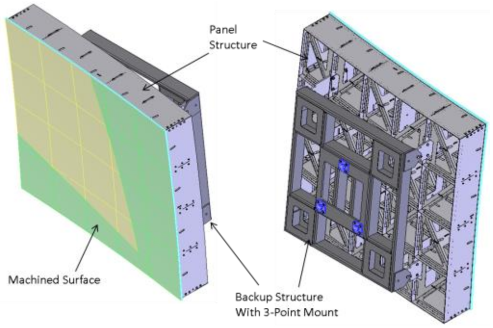


Figure 7. Example of a Main Panel

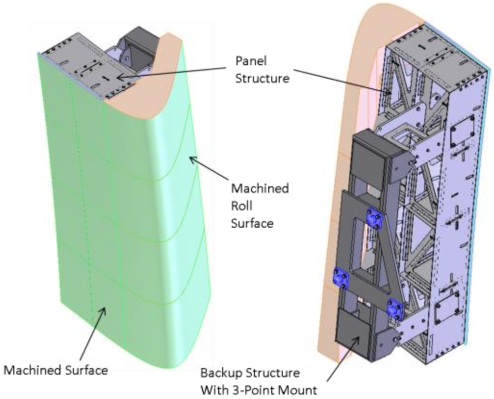


Figure 8. Example of a Rolled-Edge Panel

During installation, the seams between the panels are patched and finished after the panels are aligned. It should be noted that non-structural seams at extreme temperature variations act as a "sacrificial" point that minimizes the possibility of damage to the reflector surface. The seams are much easier to repair than replacing precision panels.

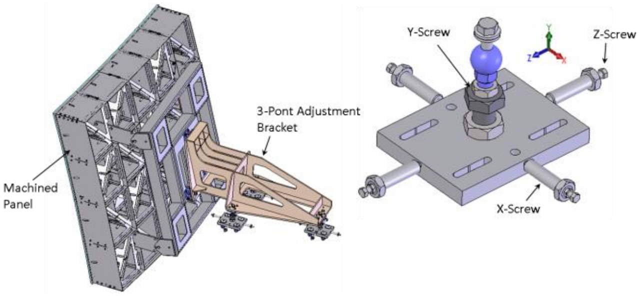
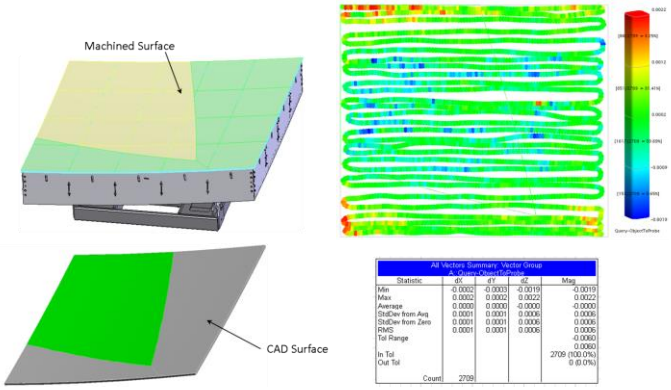


Figure 9. Typical Adjustment Mechanism for the Panels

The design approach is to use material with low coefficient of thermal expansion extensively in the fabrication of the individual panels which will minimize thermal movements and distortions due to temperature instability in the chamber.

At the completion of the machining process, each panel is inspected and the surface characterized in the installed orientation. Once accepted, each panel surface is painted with a thin conductive silver coating. All panels are checked for the proper surface resistivity. An example of surface metrology is shown in Figure 10. The factory installation of the central 9 main panels is shown in Figure 11.



All Vectors Summary: Vector Group
A: Query-ObjectToProbe

Statistic	dX	dY	dZ	Mag
Min	-0.0002	-0.0003	-0.0019	-0.0019
Max	0.0002	0.0002	0.0022	0.0022
Average	0.0000	0.0000	-0.0000	-0.0000
StdDev from Avg	0.0001	0.0001	0.0006	0.0006
StdDev from Zero	0.0001	0.0001	0.0006	0.0006
RMS	0.0001	0.0001	0.0006	0.0006
Tol Range				-0.0060 0.0060
In Tol				2709 (100.0%)
Out Tol				0 (0.0%)
Count	2709			

Figure 10. Surface Metrology of Reflector Panel

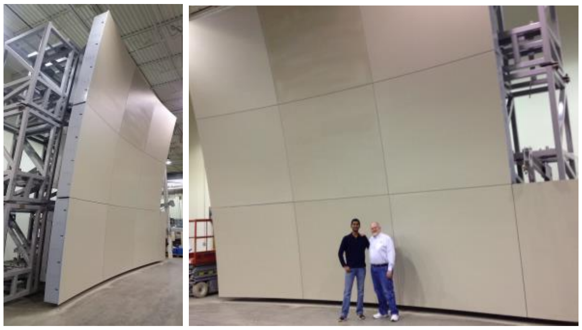


Figure 11. Factory Installation of Main Panels

IV. MICROWAVE HOLOGRAPHY – PREDICTION OF RF PERFORMANCE

A. Introduction

MI Technologies routinely use holographic techniques, in which a planar electric field near the reflector is numerically propagated to the quiet zone, to evaluate laser measurements of its serrated-edge reflectors' surfaces. These holography results have compared favorably with measured field-probe data, and the algorithmic efficiency makes holography a very effective tool for surface-tolerance evaluation.

The modeling of a blended-rolled-edge reflector is slightly more complicated due to the intentional deviation from a paraboloidal surface. A new holographic model was developed to predict the RF performance of the nine central panels, and includes the effects of both panel alignment and surface tolerance. This new model runs in about 30 seconds, so it lends itself well to go/no-go testing of machining and/or alignment.

B. Panel Alignment And Surface Tolerance

Figure 12 shows laser measurements of the central nine panels installed in the factory, but very coarsely aligned. The color scale of the plot is in millimeters relative to a paraboloid of the nominal focal length. At 40 GHz, we would expect this level of surface error to produce large errors in the quiet-zone amplitude and phase.

Figure 13 shows the amplitude-ripple estimate at 40 GHz due to the surface in Figure 12.

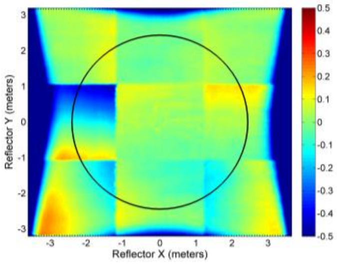


Figure 12. Panels Prior To Alignment

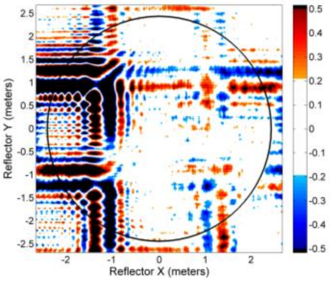


Figure 13. Amplitude-Ripple Estimate for Misaligned Panels

Figure 14 shows the phase-ripple estimate. The color scales in these two plots include a white dead band in the middle to declutter the plot, and out-of-spec points are shown in black. The analysis quantifies the amplitude ripple over the quiet zone as ±2.8 dB, and the phase ripple as ±37°. These large values are no surprise given the Z discontinuities of up to 0.5 mm (0.020") between panels.

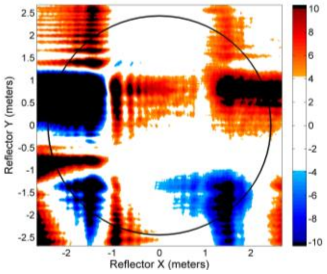


Figure 14. Phase-Ripple Estimate For Misaligned Panels

If we numerically manipulate each panel's as-machined laser measurements to simulate a perfect alignment, then we obtain the best-case results in Figure 15. The results of this analysis can be used to see if further machining is needed on the individual panels.

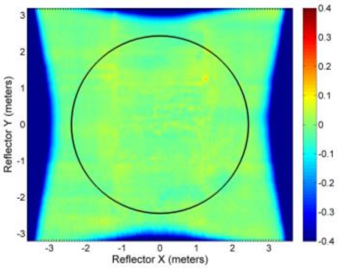


Figure 15. Panels With Perfect Alignment

The holographic quiet-zone prediction at 40 GHz with perfect alignment is plotted in Figure 16, which shows that most of the quiet zone has less than ±0.5 dB amplitude ripple and ±5° of phase ripple.

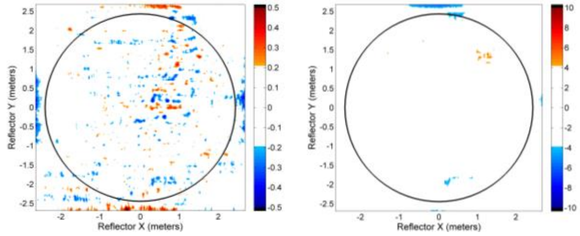


Figure 16. Quiet-Zone Prediction With Perfect Alignment

If we introduce a simple 1σ uncertainty of 0.127 mm (0.005") in our ability to set the Y location of each panel, then we see the slightly degraded performance in Figure 18. However, the amplitude prediction in most of the quiet zone is still well within ±0.5 dB, and the phase prediction is still well within specifications at ±7°. It has been seen that the panels could be easily aligned to a 1σ error of 0.076 mm (0.003”).

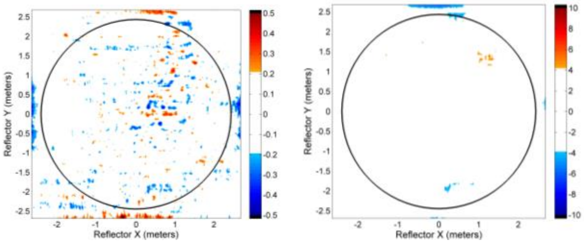


Figure 17. Quiet-Zone Prediction With Perfect Alignment

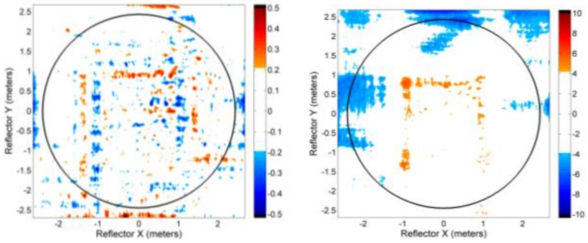


Figure 18. QZ Prediction With Small Alignment Errors

SUMMARY

The design approach taken for realizing a large, segmented rolled-edge reflector capable of producing a 5m quiet zone at frequencies as low as 350 MHz has been described. The predicted RF performance based on the selected geometry was presented. The process and tools needed to realize the desired reflector were discussed including the segmented mechanical design approach, intermediate qualification of panels and efficacy of panel alignment relative to each other using specialized holography tools. Such prediction tools are essential during the manufacturing and assembly phase to ensure acceptable performance of the reflector prior to installation and actual field-probing of the quiet zone. It was shown that the reflector, as machined, and aligned within demonstrated capabilities, should perform well

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