COMPACT RANGE ROLLED EDGE REFLECTOR DESIGN, FABRICATION, INSTALLATION AND MECHANICAL QUALIFICATION[†]

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ABSTRACT

This paper describes the methodologies and processes used for the development, installation, alignment and qualification of a Compact Range Rolled Edge Reflector purchased by the MIT Lincoln Laboratory and installed at their test facility located at Hanscom Air Force Base. The Ohio State University, under contract to MIT Lincoln Laboratory, performed the electromagnetic design and analysis to determine the desired surface shape and required mechanical accuracy of various zones of that surface. The requirement for operation over a very broad frequency range (400 MHz to 100 GHz) resulted in a surface specification that was both physically large (24 ft × 24 ft) and included extremely tight tolerance requirements in the center section.

The mechanical design process will be described, including the generation of a solid "Master Surface" created from the "cloud" of data points supplied by The Ohio State University, verification of the "Master Surface" with The Ohio State University, segmentation of the reflector body into multiple panels, design, fabrication and factory qualification of the structural stands, panel adjustment mechanisms, and panels. Results of thermal cycling of the reflector panels during the fabrication process will be presented.

The processes used for installation of the reflector and the alignment of each panel to the "Master Surface" will be presented and discussed. Final verification of the surface accuracy using a tracking laser interferometer will be described. Color contour plots of the reflector surface will be provided, illustrating the final surface shape and verifying compliance to the surface accuracy requirement.

Keywords: Antenna Measurements, Compact Range Reflector, Rolled Edge Reflector, Range Alignment, Tracking Laser Interferometer

1.0 Introduction

A 24 ft × 24 ft rolled edge reflector was developed and installed by MI Technologies based on surface shape and accuracy requirements established by MIT Lincoln Laboratory. Additional criteria addressed thermal stability, surface conductivity, and final orientation within the RF chamber.

The mechanical design and fabrication processes were primarily influenced by the following conflicting criteria:

- Operation at high frequency ranges (up to 100 GHz) required a very high surface accuracy in the center, parabolic portion of the reflector.
- Operation at low frequency ranges (down to 400 MHz) required a large physical size, including rolled edges with complex, curved surfaces.

Manufacturing processes that could achieve the high accuracy in the center section were impractical and cost prohibitive to apply to the entire reflector as a single piece. Furthermore, a single piece reflector would be too large to transport.

These considerations drove the principal mechanical design decisions; including segmentation into multiple panels, choice of surface manufacturing process, requirement for precision adjustment mechanisms for each panel, final installation and alignment process, and method of surface accuracy verification.

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2.0 The Rolled Edge Reflector

The rolled edge reflector is a nominally 24 ft × 24 ft offset fed parabolic reflector, the outer 7 ft section of which is a cosine blended rolled edge. The predicted usable frequency range is 400 MHz to 100 GHz. The reflector surface is defined in three sections:

- Paraboloid section (center 10 ft × 10 ft) defined as:
  - A horizontal line 84 inches above the parabola vertex and a horizontal line 204 inches above the parabola vertex
  - Two lines parallel to and 60 inches to either side of, a vertical line through the parabola vertex
- Transition rolled edge section defined as:
  - Termination of the parabola and transitions to the outer rolled edge section that occurs at the reflector surface "shadow" boundary
- Outer rolled edge section defined as:
  - Beginning at the reflector surface "shadow" boundary and continues around to the backside of the reflector structure

The parabola focal length is 288.0 inches with the vertex located 84.0 inches above the facility floor. The required surface tolerances are listed in Table 1.

	RMS Error (one sigma)	Peak to Peak Error
Paraboloid section	0.0015 inches	0.004 inches
Transition rolled edge section	0.0015 to 0.005 inch varying linearly from the parabolic section out to the outer rolled edge section	0.004 to 0.014 inches varying linearly from the parabolic section out to the outer rolled edge section
Outer rolled edge section	0.005 to 0.0125 inches varying linearly from the transition rolled edge section to the far end of the outer rolled edge section	0.014 to 0.035 inches varying linearly from the transition rolled edge section to the far end of the outer rolled edge section

Table 1. Surface Tolerance Specifications

3. 0 Reflector Surface Development

The first step in the physical design and manufacturing of the reflector structure was the creation of a solid model of the reflector surface. The Ohio State University supplied a "cloud of points" that approximated the desired surface. Although the center portion of the reflector system was known to be parabolic and easily surfaced, the transition into the rolled edge treatment and the complex curvatures in each of the four corners required a specialized surfacing tool to assure smooth surface transitions and the prevention of surface ripples and irregularities. To accomplish this task, Imageware Surfacer was chosen. Imageware Surfacer is a surface creation tool used for the direct creation of free form surfaces from curves, surfaces or measured data. Imageware is utilized in the automotive and aerospace industries and, for the reverse engineering of complex curvature components.

The solid surface model was validated by extracting a set of random data points from the model and sending them to The Ohio State University for confirmation via their mathematical equations. Once the surface model was validated a "Master Surface" file was created providing the standard for the surface machining operations, inspection and certification of the machined surface and alignment of the surface within the test facility.

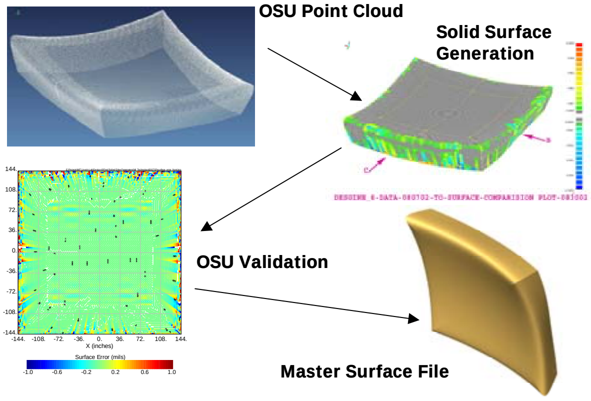

Figure 1 – Surface Definition Process

4. 0 Reflector Design and Fabrication

After the master surface was defined the surface was segmented into 7 main panels to facilitate manufacturing, shipment and installation. The surface segmentation is illustrated in Figure 2.

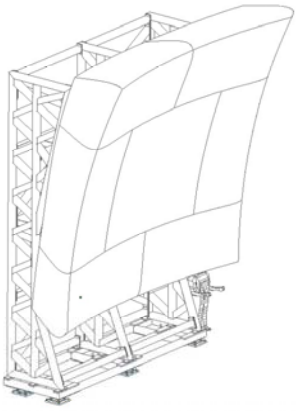

Figure 2 - Surface Segmentation Plan

There is one center panel, four corner panels and two wing panels. The particular segmentation was chosen for several reasons:

- The full parabolic area is contained within a single center panel, eliminating panel seams within the highest tolerance region of the reflector
- The complex shape on each corner is contained on a single panel, eliminating the need for seams and difficult panel alignment in the corners.
- The resulting size of individual panels was within constraints dictated by milling machine size, handling limitations, and shipping limitations.

Each panel was designed with an "egg crate" backbone structure fabricated of aluminum honeycomb panels interlocked for rigidity. The surface structure was constructed of a fiberglass laminate bonded to the backbone and then covered with a machineable epoxy paste.

Thermo couples for remote monitoring of the actual reflector material temperature were embedded in the epoxy surface and mounted in numerous locations within the egg crate structures. The thermo couples were used to monitor the reflector during initial thermal cycling, and are available to monitor the chamber and reflector temperatures during normal operation.

Prior to the final machining of the epoxy surface, each panel was thermally cycled to relieve residual fabrication stresses, and to prove the thermal stability of the individual panel sections. Panels were heated from 70 °F to 120 °F and then allowed to cool. Figure 3 illustrates panel behavior during the cool-down cycle.

The graph illustrates the epoxy and honeycomb temperatures lagging the fall in oven temperature, as expected. The graph indicates a 5 hour cool-down period is required for the reflector to change by 20ºF.

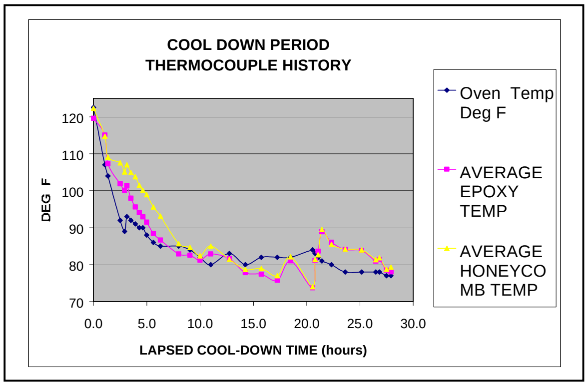

Figure 3 – Thermocouple Readings during Cool-down

Surface shape was measured using a tracking laser interferometer: 1) prior to heating, 2) at maximum temperature, and 3) after cooling. Measured expansion at maximum temperature agreed with calculated (theoretical) expansion within 4%. Permanent deformation present after the first cool-down led to the decision to thermally cycle each panel section multiple times.

After thermal cycling, the panels went through a multi-stage machining process to produce the desired surface contours. The CNC milling machine software generated tool path instructions directly from the "Master Surface" definition file. Each panel went through a series of individual surface inspections using a laser tracker interferometer. Measured data was compared to the "Master Surface" and each panel was reworked until its surface tolerance was within acceptable limits.

A structural steel frame assembly supports the individual panels. The frame is mounted on a base to facilitate the initial reflector alignment to the chamber coordinate system both in translation and rotation. A work platform was integrated into the frame assembly for workman access during panel alignment. A finite element analysis was performed on the frame assembly for static loads and for earthquake conditions. Figure 4 illustrates the frame assembly.

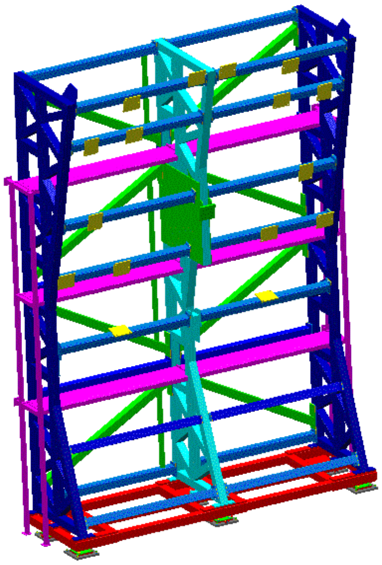

Figure 4 - Structural Stand Assembly with Work Platform

The panels are aligned and supported on the frame assembly by a kinematic support system, specifically intended to allow the reflector panels to expand and contract under temperature change without providing redundant constraints for the mechanical reaction loads. The outer panels are allowed to translate relative to the center panel kingpin without distortion, and without losing alignment.

In the following description, the coordinate system is defined with its origin at the reflector vertex (centered along the lower edge of the reflector), Y-axis vertical and Z-axis downrange (coincident with the focal axis). Z' and Y' are in a system with the same origin, except the system is rotated approximately 20º about the X-axis so that Z' is perpendicular to the panel attachment plane (See Figure 4).

There are two major mechanisms for supporting and aligning the seven panels:

- One king pin mechanism (see Figure 5 and Figure 6) that is centered on parabolic center panel and allows for rotation in pitch, yaw and roll by means of a spherical bearing arrangement.

  The king pin constrains 3 translations (X, Y' and Z').

- Twenty-two adjustment mechanisms (see Figure 5 and Figure 6), four on parabolic center panel and three each on each outside panel, that allow rotation in pitch, yaw and roll by means of a spherical bearing arrangement, and allow for fine adjustments in X, Y' and Z'.

  The adjustment mechanisms facilitate (and constrain) all translations (X, Y' and Z') during initial alignment process. Constraints in X and Y' are released on 21 mechanisms after alignment and inter-panel bonding. On the 22nd mechanism, only the X constraint is released and the remaining Y' constraint prevents rotation about the Z' axis.

  The final result is a single piece reflector in which translations are constrained only by the single kingpin.

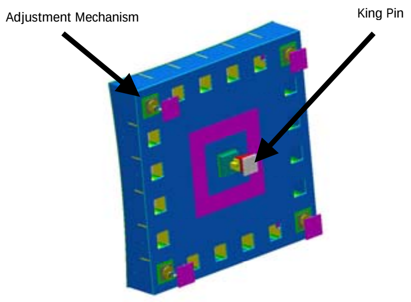

Figure 5 - Support & Alignment System on Center Panel

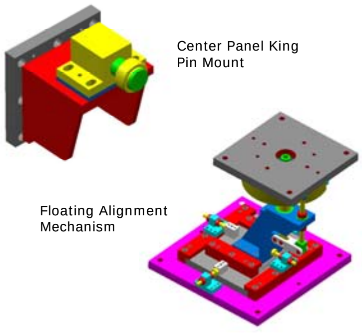

Figure 6 - Support and Alignment Mechanisms

After alignment, the individual panels are fastened to each other and the relevant X and Y' restraints are released, transferring the outer panel's weights to the center panel eggcrate structure. At this point, the reflector consists of one surface rather than seven individual surfaces.

4.0 Installation and Alignment Process

An initial survey of the compact range chamber was performed using a tracking laser interferometer, to establish the chamber coordinate system. A jig transit was used for establishing the gravity vector. The reflector base location and orientation was established and the frame assembly and adjustment mechanisms were installed.

Figure 7 shows the installation of the kingpin onto the center panel.

Figure 7 - Kingpin Installation On Center Panel

Figures 8 and 9 illustrate two stages during the panel installation process.

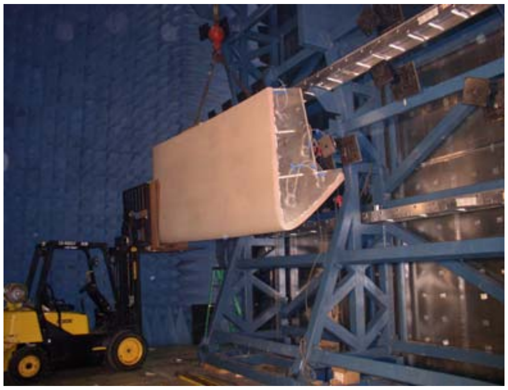

Figure 8 - First Panel Section Lifted Into Place

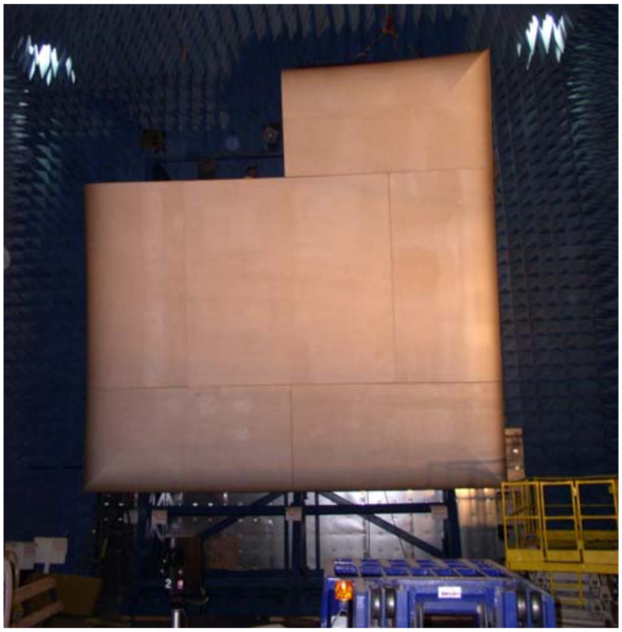

Figure 9 - Next To Last Panel Installed

After installation of all seven panels, the tracking laser and panel adjustment mechanisms were used to bring the seven panels into alignment with respect to each other and with respect to the chamber coordinate system. The design details of the frame, adjustment mechanisms, and work platform were intended to decoupled the effects of movement of one panel on the others, thereby reducing the number of iterations in the alignment process.

After satisfactory alignment, the seven panels were locked together as described above. The seams between panels were filled using an epoxy intended to bond chemically with the base surface epoxy. The conductive coating was applied to seams.

This completed the installation of the rolled edge reflector.

5.0 Final On-Site Qualification

5.1 Verification of Surface Resistivity

The conductive coating on the reflector surface was verified using two instruments, a four-pin Surface Resistivity Meter and a standard ohm-meter.

The four-pin Surface Resistivity Meter was used to determine localized values of sheet resistivity at approximately 30 points per panel. The four-pin meter operates by impressing a known current across two outer pins and measuring the resulting voltage drop across two inner pins, which have a fixed separation distance. The four-pin meter is highly accurate; however the small distance between inner pins (approximately 1/8 inch) limits it to localized measurements.

A standard ohm meter with 3 ft leads was used to measure surface resistivity across seams, around the corners, and generally over numerous 6 foot areas of the reflector surface.

Actual performance of the surface coating was significantly better than the specification of Surface Resistivity ≤ 1.0 Ohms per square.

5.2 Verification of Accuracy of the Surface Shape

The accuracy of the final surface shape was measured using an SMX Model 4000 tracking laser interferometer. The “Master Surface” file was the geometric baseline. Approximately 4000 individual points on the reflector surface were measured. The cloud of measured points was best-fit to the Master Surface and an error was determined for each point. The errors determined (labeled dN) were the deviation of the measured point from the Master Surface, in a direction normal to the surface, at the point of closest approach of the measured point to the Master Surface.

During the measurement process, the temperature in the compact range chamber was controlled to the intended operating temperature range of 70 ± 2°F. Permanent reference monuments were embedded in the foundation, in order to provide a reference system for combining measurements made over multiple days and over multiple locations of the tracking laser.

Measurements of the “top” surface of the rolled edge were made at ground level, due to the difficulty of measuring the top surface after assembly. Temporary tooling ball references were installed in the upper panels to enable top surface data to be combined with the surface data on the balance of the reflector.

The front surface of the reflector was measured on an approximately 5 inch × 5 inch grid. The side, top and bottom surfaces were measured on an 8 inch × 8 inch grid.

The front surface measurement consists of 3200 measured points. An additional 800 measured points comprise the data on the other surfaces. Figure 10 illustrates the distribution of the actual measured points on the front surface.

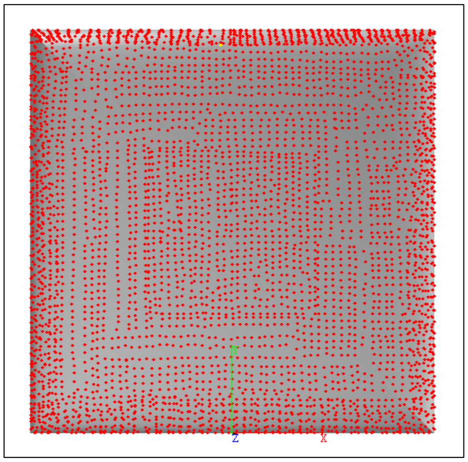

Figure 10 - Distribution of Measured Points on Front Surface

The final measurement results for the front surface are presented below. The color contour plots illustrate dN, the deviation of the measured surface from the Master Surface, in the Normal direction.

Figure 11 is a contour plot of dN on the front surface. Areas within ±0.002 inch of the Master Surface are shown in gray. Contour lines are 0.002 inches apart. Green represents areas that are high (i.e., an excess of material on the surface). Red represents areas that are low (i.e. a deficiency of material). This figure illustrates that the parabolic zone (the center 120 inch × 120 inch area) falls within its specification of 0.004 inch peak-to-peak error.

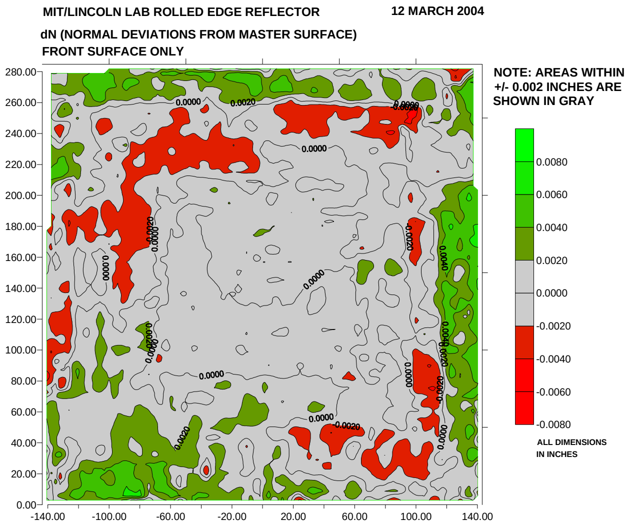

Figure 11-Surface Accuracy Plot With 0.002 Inch Contours

Figure 12 illustrates the front surface accuracy with all areas within ±0.004 inches shown in grey. This plot illustrates that the vast majority of the front surface is within ±0.004 inches of the Master Surface definition.

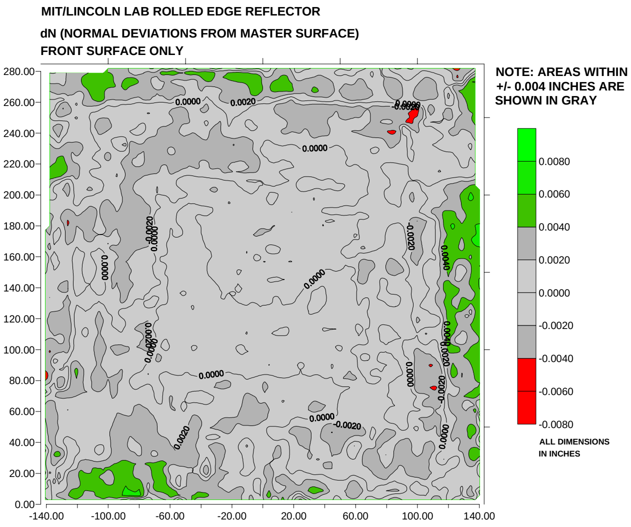

Figure 12 - Surface Accuracy Plot With Areas Within ±0.004 Inch Shown in Grey

6.0 Conclusion

MI Technologies delivered and installed a custom rolled edge compact range reflector for MIT Lincoln Laboratory.

The specifications for final, installed surface profile accuracy were met by incorporating mechanical design considerations including multiple panel sections, thermal cycling of panel sections, panel alignment mechanisms, and a floating suspension. Verification of the final on-site surface profile and orientation were successfully performed using a tracking laser interferometer.

7.0 References

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8.0 Acknowledgements

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