SKYTROUGH OPTICAL EVALUATIONS USING VSHOT MEASUREMENT

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Abstract

SkyFuel has developed a new parabolic trough collector, the SkyTrough™. This collector has a 6 meter aperture width, with field-installed mirror panels made from a silvered polymer film laminated to aluminum sheets. This design departs from the use of rigid silvered glass mirrors that are each factory pre-shaped to a parabolic contour and fastened to an underlying support structure using four bolts. The lightweight SkyTrough mirrors do not come from the factory with a pre-defined contour. Instead, they are flat reflector sheets which are assembled onto shape-forming ribs attached to the underlying space frame. This design approach speeds field installation and enables compact transportation from the factory to the site.

Our development effort was designed to determine whether this approach to mirror design could achieve the required optical accuracy. NREL's VSHOT optical instrument measured prototype mirror panels at several stages during the development process. VSHOT measured deviation of the mirror panels from the ideal shape and provided diagnostic information used to improve the mirror through successive refinements. Further, VSHOT data were used in a ray-tracing analysis to estimate mirror panel intercept factor at normal incidence, including the effect of sun shape. The SkyTrough achieved an overall RMS slope error of 1.8 mrad, with a normal incidence intercept factor greater than 99%.

Keywords: parabolic trough, mirror, metrology, SkyTrough, VSHOT

1. Introduction

This paper reviews the development of the mirror for the SkyTrough parabolic trough collector and VSHOT's role in measuring its shape. The following sections provide an overview of the SkyTrough mirror design, describe the basic features of the VSHOT, review key steps in the mirror development process, and discuss resulting SkyTrough mirror performance.

2. SkyTrough Mirror Design

Figure 1 shows the SkyTrough, a new parabolic trough collector with a 6 m aperture width. Figure 1 shows a solar collector assembly (SCA), comprised of eight modules linked together and driven by a central hydraulic actuator. Each module is 13.9 m long, and is comprised of nine mirror panels, each of which is formed by a single sheet of reflective film laminated onto an aluminum substrate. The SkyTrough module aperture area is 83.4 m^2, more than twice as large as the modules at the most recent U.S. utility scale trough installation, Nevada Solar One.

Figure 2 shows the construction of each module. The primary structure is a space frame (a), an efficient truss structure made from aluminum tubing with joints enabling rapid assembly. Next a series of ribs are attached (b), which provide parabolic guide rails for holding the mirror sheets. These ribs hold nine mirror panels (c), completing the mirror. Several patents have been filed to cover the SkyTrough design.

Figure 3 shows an individual mirror panel, both as an assembly (a), and exploded view (b). The mirror reflective surface is ReflecTech® Mirror Film laminated to an aluminum sheet [1]. The resulting laminated sheet is quite flexible, and is mounted to ribs which define the desired parabolic curve. The remaining linear free edges at the trough rim are supported by rim stiffeners.

Figure 1. The SkyTrough Solar Collector Assembly (SCA), comprised of eight modules actuated by a central drive.

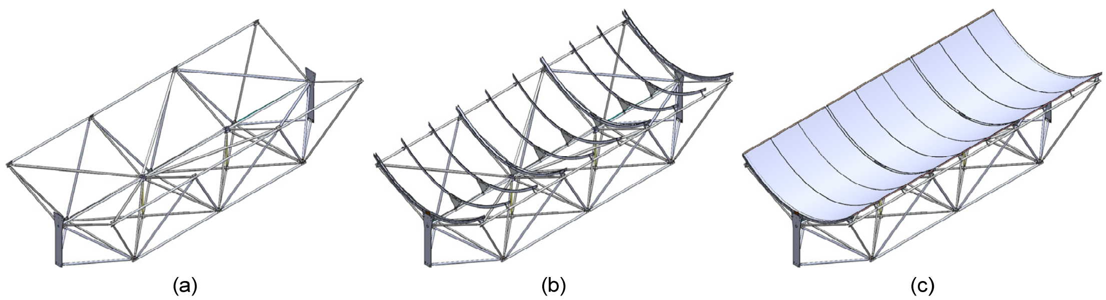

Figure 2. SkyTrough module construction.

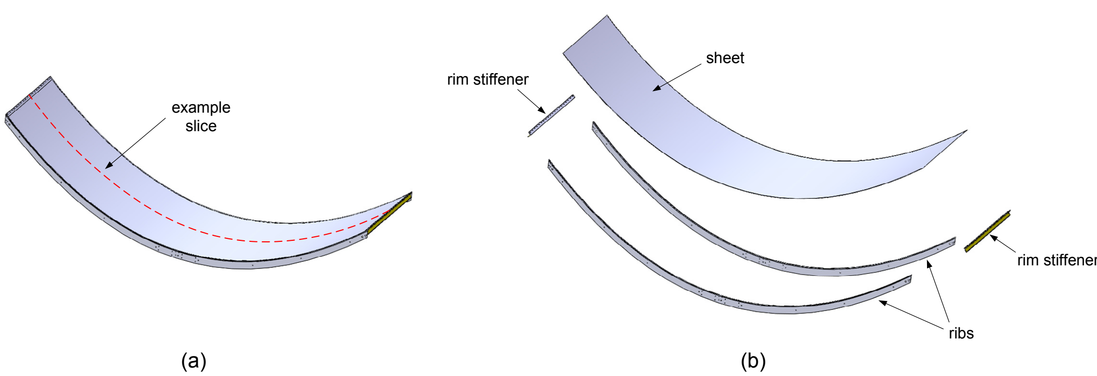

Figure 3. Mirror panel construction.

The construction method shown in Figure 3 enables compact SCA transport and rapid mirror assembly. Three complete SCA's (over 2000 m^2 aperture area) including mirrors, space frames, receivers, pylons, drive units, etc, may be transported to the site using only two standard truck trailers. Installing the mirror sheets is rapid: A single panel providing 9 m^2 aperture area may be inserted and stiffeners attached in a few minutes.

3. Optical Measurement

At several stages in SkyTrough development, NREL's VSHOT optical measurement instrument was used to characterize reflector panel surfaces. This versatile instrument can be used to characterize both linear and point focus optical surfaces [2]. Figure 4 shows a schematic of this device.

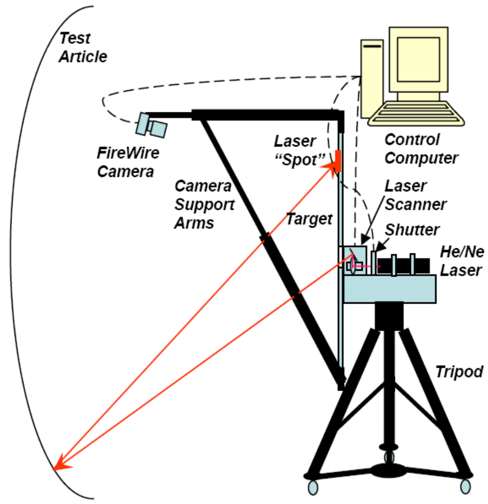

Figure 4. VSHOT instrument.

A helium/neon laser is directed at the reflective surface or test article as shown in Figure 4. The test article reflects the laser back onto a flat optical target. A digital camera views the reflected laser spot, and the software determines the spot position on the target. This measured position is then compared to the ideal expected position to compute slope error. A galvanometer controls laser direction, allowing the laser to scan across the mirror surface in a predefined pattern, measuring slope error for a multitude of points. The instrument has an accuracy of ±0.1 mrad [3]. VSHOT can characterize any reflective surface, but it cannot determine specularity.

To measure a SkyTrough mirror, the mirror module faced the horizon, and the VSHOT was placed in front of the mirror. The VSHOT laser scanned vertically, thus measuring a "slice" of the mirror, as shown by the red dashed line in Figure 3(a). After measuring a given slice, the VSHOT was moved laterally to measure an adjacent slice; this process was repeated until a series of slices across the mirror panel was recorded. The resulting ensemble of slice data was rendered in plots such as shown in Figures 10 and 11, allowing visualization of errors across the mirror surface. Although multiple data slices were obtained as described above, Figures 5-9 show data from only a single slice, due to space limitations.

The width of the mirror panel, the width of VSHOT's target, and the desire to obtain measured slope error data in uniformly spaced vertical slices required lateral translation of VSHOT along the mirror panel between tests. This approach captured slope error in the plane transverse (perpendicular) to the focal line, which the literature [4] and ray-tracing show is primarily responsible for the intercept of reflected beam radiation by the receiver at the collector focus. However, slope errors that tend to reflect light in the direction along the focal line (and that can affect the direction of reflected light in the tranverse plane at non-zero incidence), are not captured by this approach. Therefore all slope error references in this report refer to transverse slope error, and all intercept factor calculations were performed at normal incidence (zero angle between the normal to the collector aperture and the line to the center of the sun's disk).

4. Design Evolution

The VSHOT was used at several points in SkyTrough development to characterize optical performance. Figures 5 - 11 show key measurements obtained at various steps in this process, each of which helped direct subsequent work to improve mirror performance.

As shown in Figure 3, a SkyTrough mirror panel is comprised of a reflective sheet attached to parabolic ribs. The ribs define the optical curve, and thus determine a lower bound on optical error. Early in the project the VSHOT was used to measure ribs directly. A rib was mounted on a mirror test fixture, a thin strip of metal with reflective film was adhered to the rib, and the VSHOT measured the reflective surface. An example result is shown in Figure 5.[1]

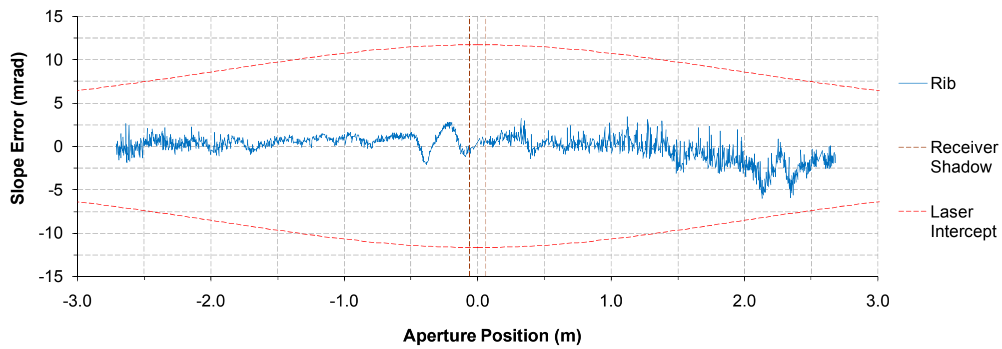

Figure 5. Early prototype rib measurement.

This figure contains many features seen in subsequent plots. The primary data curve indicates slope error as a function of position across the mirror aperture; for a perfect mirror, this plot would be a constant zero value. The domain of the plot is from –3 m to +3 m, the full SkyTrough aperture. The data in Figure 5 spans less than this domain, due to limited VSHOT aperture capacity at the time. The vertical dashed lines on either side of the domain zero position indicate the extent of the receiver shadow when the SkyTrough is in use; errors within this region are not important. The dashed curves above and below the data line correspond to slope errors that would cause a laser beam normal to the collector aperture at the indicated aperture position to miss an 80 mm diameter receiver located at the collector focus after reflection from the imperfect parabolic mirror panel. Therefore, the region bounded by the laser intercept lines gives a simple estimate of acceptable collector slope errors assuming perfect specularity, perfect tracking, perfect receiver alignment, and perfectly collimated incident rays. The percentage of laser rays equally and finely spaced along a slice's aperture that are predicted to hit the receiver is the laser intercept factor for that slice. The influence of the sun-shape on slice and mirror panel intercept factor is discussed in Section 5.

The data of Figure 5 indicate that rib accuracy is very good, with a total RMS slope error of 1.4 mrad. These data and other similar scans confirmed that rib fabrication was of sufficient precision, settling several outstanding questions at the time surrounding machining precision, material stress relaxation, deformation due to mounting, and so on.

Mirror panels were inserted, and VSHOT was used to measure the resulting optical surface. The final mirror panel design shown in Figure 3 shows a continuous single mirror sheet, spanning the full parabola arc length. In early prototypes, the design instead used two sheets, each sheet extending from the parabola vertex to the rim. A simple stiffener design was used at the sheet free edges (both vertex and rim) to reduce panel deflection between ribs. These half-mirror panels closely followed the rib curvature in the vicinity of the rib, but large slope errors developed at the center of the panel, or panel midplane, at both the vertex and rim free edges (see Figure 6). The large slope errors seen at the parabola vertex and rim in Figure 6 indicated that our initial simple stiffener design at free edges was not adequate.

Because VSHOT could not measure the full SkyTrough aperture width at the time of these tests, we focused on improving slope errors at the parabola vertex. Several different vertex stiffener designs were implemented and measured; Figure 7 shows an especially illuminating example. In this test, the vertex stiffener firmly constrained both the sheet position and tangent angle, while an adjustment screw enabled fine tangent angle

[1] The original data set for Figure 5 contained several noise data points due to imperfections in our manual application of the reflective film onto the rib; the worst of these are removed from the figure.

adjustment. Although such an adjustment would not be included in the production SkyTrough, this special stiffener design allowed us to explore the effect of varying the tangent angle at the vertex while holding other parameters constant.

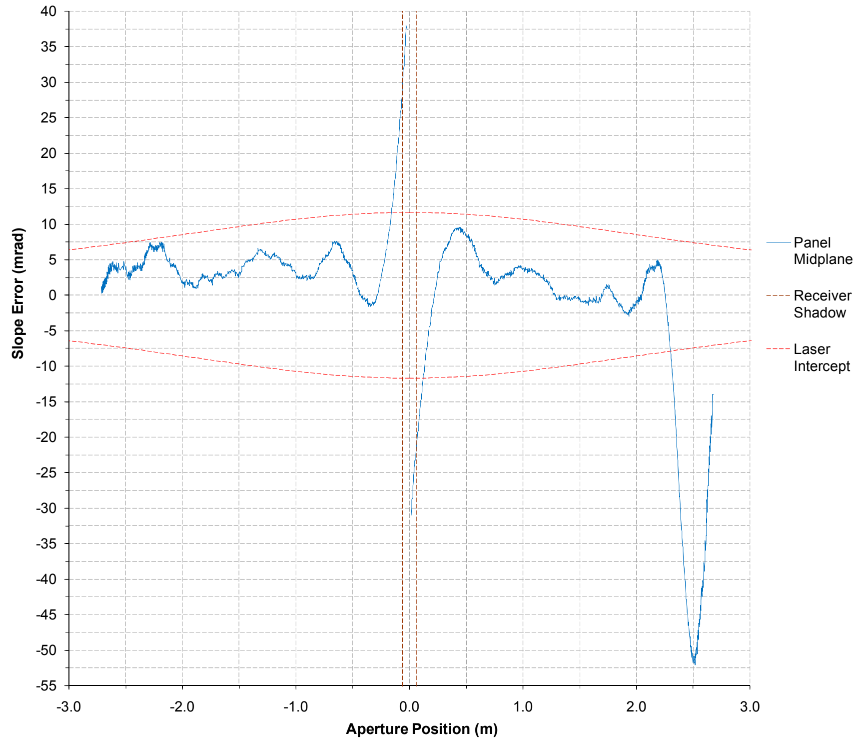

Figure 6. Early prototype, with split mirror panels and simple edge stiffeners.

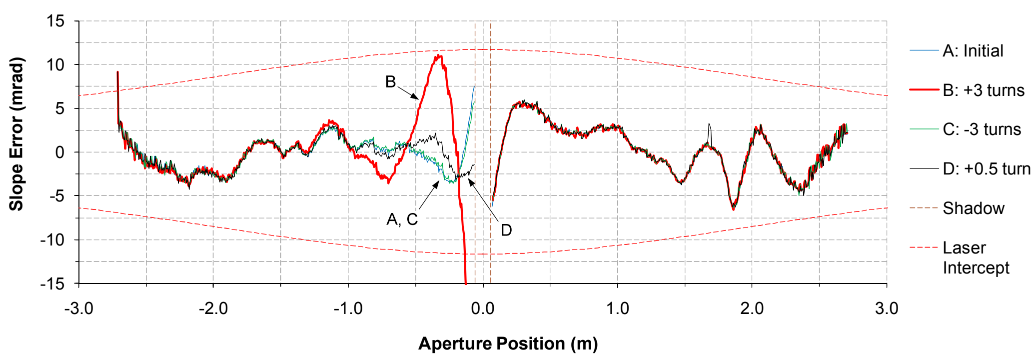

Figure 7. The impact of free edge tangent angle adjustments at the parabola vertex.

Figure 7 shows the effect of tangent angle adjustment on the midplane slice of the mirror panel. The initial mirror shape is shown by curve A. For the lower panel (corresponding to negative aperture positions), the sheet initially had a slope error of roughly +7 mrad at the receiver shadow boundary. After imposing a large adjustment of +3 turns on the lower panel adjustment screw, the slope error reversed sign, producing a radically different shape as indicated by curve B, with a slope error at the receiver shadow in excess of –15 mrad. Relaxing this adjustment by –3 turns, the mirror returned to its original shape, as indicated by the nearly superimposed curves A and C. A final adjustment of +0.5 turn produced a better optical shape, as indicated by curve D. Note that the upper panel did not vary throughout all of these adjustments.

A key insight gained from this experiment is the criticality of controlling tangent angle at the mirror free edge. Note that adjusting the tangent angle at the parabola vertex affected mirror shape as far as 1 m away!

The experimental data indicated that an improved stiffener design, with features to hold the free edge close to the corresponding parabola tangent angle, was required. An improved vertex stiffener was designed, resulting in the midplane slice measurement shown in Figure 8. Mirror shape in the vicinity of the parabola vertex was improved.

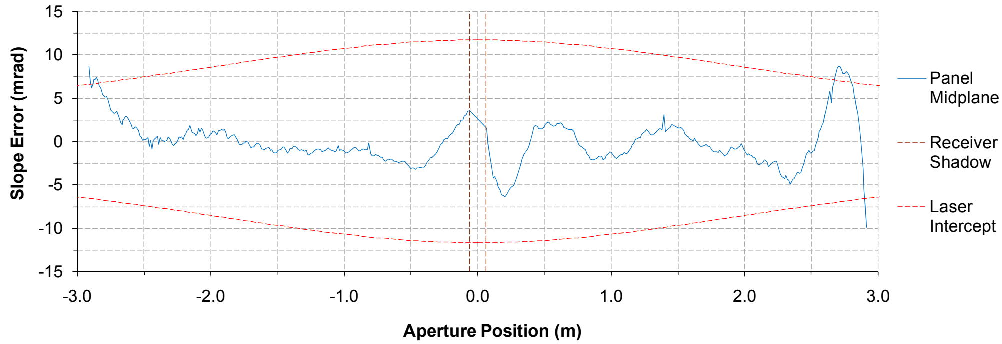

Figure 8. Prototype with improved vertex stiffener.

Although slope errors near the vertex were reduced, they were still large relative to slope errors farther away from the free edges at the vertex and rim. Consequently, the design was modified to eliminate free edges at the vertex, using instead a single monolithic mirror sheet which spanned the full parabolic arc. This modified design offered the advantage of fewer parts, as well as simpler and faster assembly. The single-sheet design also produced better optical results, as shown in Figure 9. It was therefore chosen for the production SkyTrough mirror.

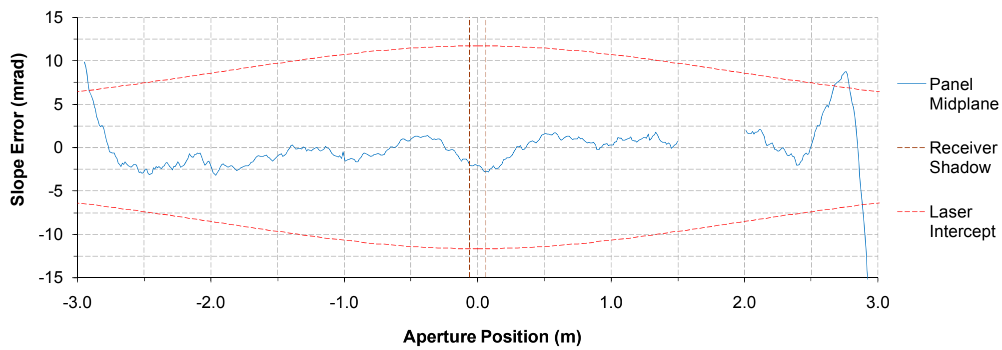

Figure 9. Prototype with a single monolithic sheet.

Control of the parabola rim remained an open issue, as seen by the large slope errors at each end of Figure 9. Several candidate rim stiffener designs were tested to reduce the remaining error at the rim. These tests included rim stiffeners with different structural properties, as well as edge position and angular adjustment capability. Information provided by these series of examinations ultimately led to an effective, non-adjustable rim stiffener design that provided high laser intercept factors required for optical efficiency.

The resulting VSHOT measurement data are shown in Figures 10 and 11. In these figures, all of the measured slices are shown. Slice index numbers correspond to inches from the panel edge; thus slice 30 corresponds to the midplane slice. In Figure 10 all slice data curves are drawn; while it is difficult to identify individual curves, comparison of the curve ensemble against the dashed laser intercept curves above and below indicate that this mirror will provide excellent optical performance. The legend shows the RMS slope error for each curve; the mean of these RMS values for the entire mirror panel is 1.78 mrad.

Figure 11 shows each curve offset by a uniform amount, allowing individual curves to be distinguished and visualization of the propagation of errors across the mirror surface. (This plot format was very useful during mirror development, but omitted above due to space limitations.)

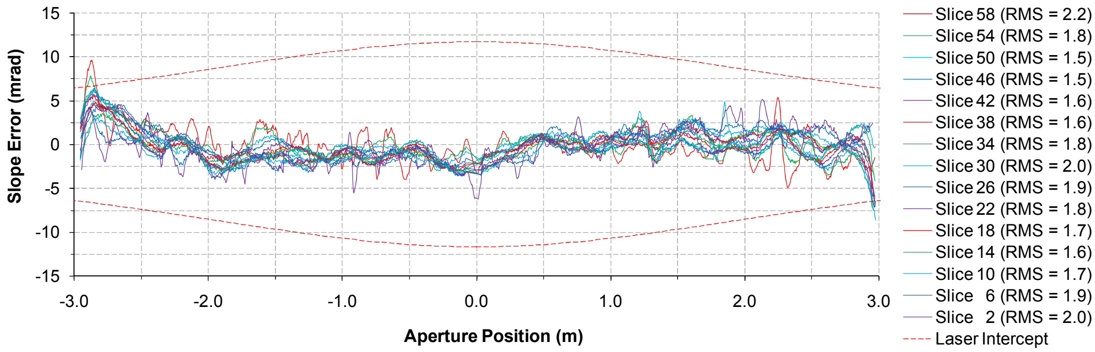

Figure 10. Mirror panel with improved rim stiffener (all slices).

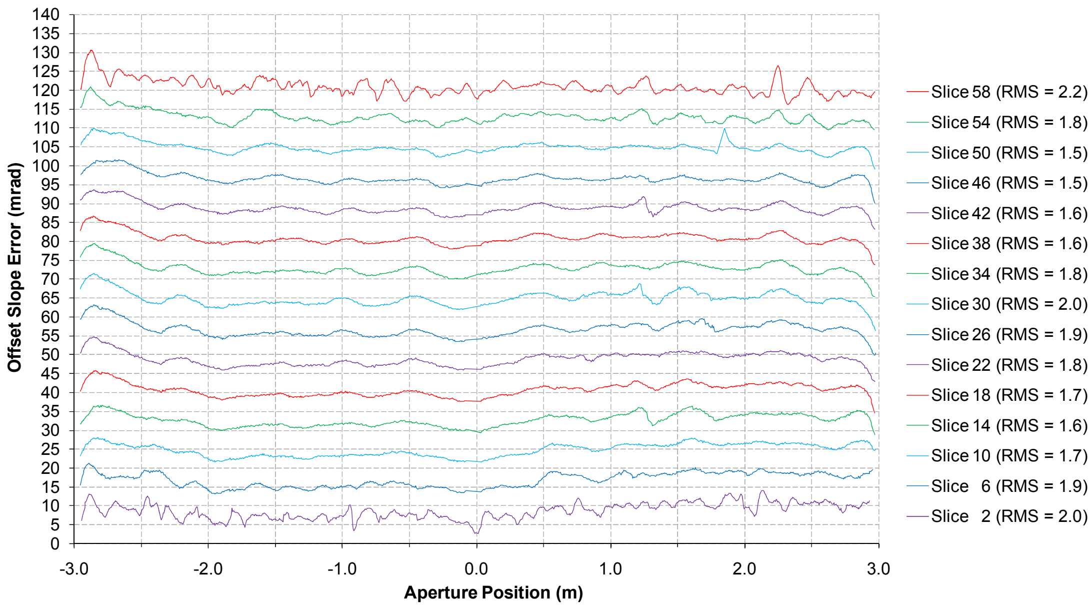

Figure 11. Data from Figure 10, with slice curves offset for clarity.

Note the high-frequency effects seen for edge slices 2 and 58. These effects are attributed to our means of fastening the sheet to the ribs, and were seen throughout testing. These high-frequency effects influence the outer few inches of the mirror panel, and the magnitude of errors for these effects were within the laser intercept curves shown in Figure 10. The relatively thin mirror panel functions as a membrane with moderate bending resistance, and damps these high frequency effects across the span between ribs. Slope error at the rim tends to peak at the midplane slice, and diminishes at the rib boundary. These errors, with the final rim stiffener selection, also remain within the laser intercept limit. Overall surface accuracy is very good, with an average RMS slope error of 1.78 mrad, and a laser intercept of 99.7%, computed over the actual reflective aperture width of 5.8 m. Focal length error is zero, since a fixed focal length was assumed for all fits.

Figures 10-11 show mirror data across the full aperture, with no data gaps. The VSHOT has a limited view angle that cannot measure the entire 6 m aperture with a single scan. This limit was overcome by taking VSHOT scans at two different distances from the mirror and combining measurements to obtain a full-aperture contiguous data set.

5. Normal Incidence Intercept Factor Calculation, Including Sun Shape

A two-dimensional ray tracing program based on [4], which accepted measured VSHOT data as input, calculated slice intercept factor. The intercept factor is defined as the percentage of beam radiation incident on the slice aperture that intercepts the receiver after reflection by the mirror, assuming perfect mirror reflectance, perfect specularity, perfect absorber absorptance, and perfect receiver position. The algorithm generates rays according to the sun shape proposed by Neumann et al. [5] and flattens the sun shape for 2D ray tracing using the methodology presented by Bendt et al. [4]. For a given ray from the sun, the algorithm uses the ideal parabola to determine the point where the ray strikes the mirror, then defines the actual mirror surface normal at that point by adjusting the nominal surface normal by the slope error indicated by the VSHOT data. The algorithm then constructs the reflected ray, and determines whether it intercepts the receiver. By repeating this analysis for a large number of rays (42,000), the algorithm estimates intercept factor for a given slice, taking into account measured slope error and sun shape. The mirror panel intercept factor is approximated as the average of all the slices. As mentioned earlier, all intercept factor calculations were performed at normal incidence.

Figure 12 shows example output from the algorithm. Rays that intercept the 80 mm SkyTrough receiver are drawn green; rays that miss the receiver are drawn red and extend past the receiver. Only a fraction of the rays traced were plotted. The examples shown correspond to slices 2 and 54 of the mirror data presented in Figures 10-11. For slice 2, all rays intercept the receiver. For slice 54, rays at the extreme $-x$ rim miss the receiver. This analysis was also performed for earlier prototypes, producing output that clearly showed regions of the mirror needing improvement.

The ray-tracing algorithm was applied to all of the slice data shown in Figures 10-11, computing an intercept factor for each slice. The intercept factor for slices 2 through 58 were 100%, 100%, 100%, 100%, 99.9%, 99.7%, 99.2%, 99.3%, 99.2%, 99.6%, 99.9%, 99.9%, 99.9%, 99.2%, and 98.9%. The average intercept factor for the full panel is 99.7%.

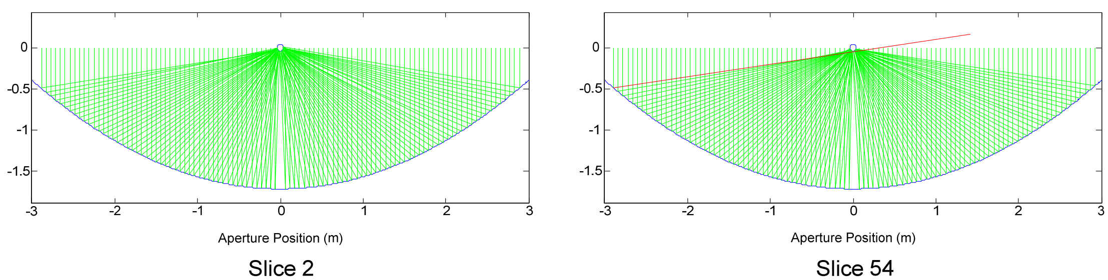

Figure 12. Ray trace intercept calculation, including sun shape.

6. Conclusion

The VSHOT instrument provided indispensable information during development of the SkyTrough mirror. Measurements at various prototype stages helped diagnose problems and identify mirror components requiring further improvement. As a result, the current SkyTrough mirror has achieved an average RMS slope error of 1.78 mrad with no radical slope errors at mirror edges, a laser intercept factor of 99.7%, and intercept factor including sun shape of 99.7%.

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