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VSHOT MEASUREMENTS OF DISTAL II DISH CONCENTRATORS

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ABSTRACT

The Video Scanning Hartmann Optical Tester (VSHOT) is a laser ray-trace tool for measuring the slope error of solar concentrator mirrors. The VSHOT measurements made on two, 8.5-m diameter, Distal II dishes represent its first use on a concentrator installed and operating in the field. A number of valuable lessons were learned regarding the use of the VSHOT for outdoor testing. The two dishes were found to have overall figure-of-merit RMS slope errors from an ideal parabola of 2.99 and 3.18 milliradians. The VSHOT measurements compare well qualitatively with distant observer photographs made using a colored concentric ring target.

VSHOT DESCRIPTION

The VSHOT was developed to measure the optical quality of large, point-focus solar concentrators, but is usable on any reflector with an F# (focal length/diameter ratio) greater than 0.45 and a root-mean-square (RMS) optical error in the 0.1-20 milliradian (mrad) range. Jones et al. (1997) and Wendelin et al. (1991) provide detailed descriptions of the VSHOT and its predecessor, the SHOT, so only a brief overview will be provided here. The VSHOT measures the slope of a reflector at many locations on its surface and compares those slope measurements to the values expected from a mathematical fit to the surface shape. Figure 1 is a schematic of the system in use on a medium size reflector. A mirror is typically positioned at a distance slightly greater or less than twice its focal length (f). Then a laser beam is steered by a 2-axis scanner to a point on the mirror. After reflecting off the mirror, the laser beam returns to a location near its source and strikes the target. A computer video board digitizes a CCD camera's image and the centroid location of the reflected spot is calculated. The laser is scanned quickly across the surface of the mirror and this process is repeated many times. The concentrator's slope at each point of reflection and a polynomial surface fit to the measured slopes is then calculated. The magnitude and direction of fit residuals (slope errors) are calculated and can be graphically displayed. The statistical variation between the measured and the ideal slopes from a 2^{nd}-order fit, as represented by the RMS slope error, provides an optical quality figure-of-merit for the reflector. The accuracy of the VSHOT device depends upon the geometry of the test setup (F#, distance, laser spot size, etc.) and the accuracy of input data (distance, scanner calibration, video calibration, etc.), but values on the order of tenths of a milliradian are typical (Jones et al., 1997).

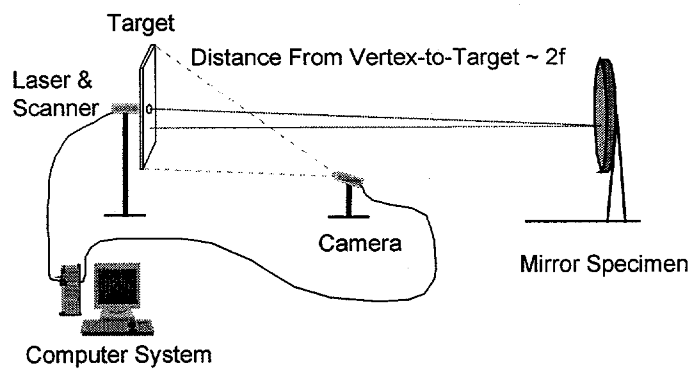

Figure 1. Schematic of the VSHOT

DISTAL II DISHES

There are three Distal II Dish/Stirling systems installed at the Plataforma Solar de Almeria (PSA) in southern Spain. The systems were installed in a line and will be referred to in this paper by their location at the site – south, middle and north dish. The Distal II dishes, built by Steinmueller and Schlaich, Bergermann und Partner GbR (German companies) are 8.5m in diameter and their curvature is achieved by evacuating a drum covered by stretched steel membranes. The mirror-covered front membranes were plastically deformed to achieve their short focal length using a pool of water on the outside of the membrane while the drum was simultaneously evacuated. The systems use a directly-illuminated, Solo V161 Stirling engine to produce electrical power from the heat input. Figure 2 shows a Distal

II dish at the PSA. Schlaich et al. (1994) explains the Distal construction techniques and Stein and Diver (1994) provide general information on dish-engine systems.

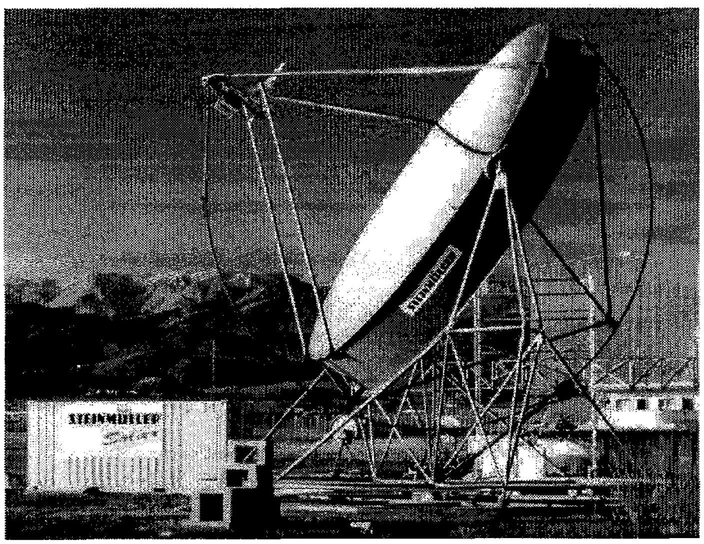

Figure 2. A Distal II dish without the Solo V161 engine.

OUTDOOR MEASUREMENTS, SYSTEM SETUP, AND LESSONS LEARNED

The measurements reported here represent the first use of the VSHOT system outdoors. While there were some difficulties encountered in performing the measurements, as will be described later, the use of the VSHOT on concentrators installed in the field is possible. The largest concern in performing outdoor tests is the effect of uncontrolled environmental conditions on the measurements—most notably the background lighting and the wind.

The VSHOT uses background subtraction and image thresholding to calculate an accurate return spot centroid. The background subtraction corrects for environmental lighting, while image thresholding (the uniform subtraction of intensity from the entire image) eliminates CCD camera readout noise. Image thresholding of eight bits out of 256 was typically required to eliminate the camera readout noise from our system.

Outdoor lighting is a concern for two reasons—it is often brighter than indoor lighting and it changes. The laser return spot must appear brighter to the camera than the target background to calculate an accurate centroid. Since we have imposed an upper limit of 5mW (Class IIIa) on the laser power for safety reasons, the brighter background reduces the signal-to-noise ratio. In addition, changes in background lighting during the test that are greater than the image thresholding value will cause erroneous centroid calculations. Both of these issues were resolved by performing the measurements at night. However, with two modifications to the system—the use of a more Lambertian target and a band-pass filter—daytime measurements should be possible.

The use of a band-pass filter on the video camera should improve measurements performed in daylight by increasing the signal-to-noise ratio and reducing the influence of changes in background lighting. Since the VSHOT uses a HeNe laser, a band-pass filter acting at wavelengths near 633 nm is needed. Additionally, the target surface currently used on the VSHOT is slightly specular. The use of a more Lambertian reflecting target will also help reduce the effects of changes in environmental lighting.

Wind is another uncontrollable environmental condition that can affect VSHOT measurements. This may actually be deemed advantageous to the limited extent that the VSHOT can provide accurate insights in to the dish performance in real-world, windy conditions. For instance, the VSHOT will provide a time-averaged membrane deflection due to wind rather than an instantaneous deflection. A time-averaged membrane deflection may not accurately reflect the true vibration modes, but it still provides some valuable, experimental insights into performance degradation due to wind. Dish tracking is another example where the VSHOT data can reasonably capture the effects of wind. Wind causes the dish to miss-track while the location of the VSHOT, like the sun, is not affected. In optical modeling codes using a numerical convolution approach—such as CIRCE (Romero, 1994) and HELIOS (Biggs and Vittitoe, 1979)—the RMS tracking error is simply combined with the optical surface error using a root-sum-square (quadrature) approach to yield an overall concentrator error for flux predictions. VSHOT measurements taken in windy conditions could be treated as a measure of this overall combined error. But since good tracking accuracy data is often fairly easily obtained, the inaccuracies associated with time averaging may make this approach less desirable.

The wind can also affect the pointing of the VSHOT or deflect its target surface, although this is less likely to occur than with most solar concentrators because of its locking tripod head and smaller area. Should it occur, measurement error will be introduced. The best way to mitigate the effects of wind is to perform outdoor measurements in low wind conditions, as was done with these tests. Another approach is to take many data points and repeat the measurements so that any changes in environmental conditions are sufficiently averaged.

Increasing measurement speed is also helpful for outdoor tests so that a full test can be completed before changes in environmental conditions occur—or at least more data points can be taken for each change in environmental conditions. The VSHOT system performed approximately one measurement every 2 seconds during these tests, but the speed has since been improved to achieve 10 measurements per second. For the ~2000 data points taken in these tests, the VSHOT required over an hour to complete the test. The VSHOT now requires just over 3 minutes to complete the same test. While this time period is often short enough to complete a test without changes in environmental lighting conditions (even in daylight hours), the time constant of changes in wind speed and direction is typically on the order of tenths of a second to seconds. To totally mitigate the effects of changes in wind, the VSHOT measurement speed would have to been increased by a factor of 100, an expensive proposition if technically feasible. Therefore, low wind speeds are likely to remain a preferred condition for outdoor testing with the VSHOT.

The measurement of an installed concentrator has other complications not seen in a laboratory test of a single mirror facet. One example is the gaps in the reflective surface of a multi-faceted concentrator. Even for the single-element Distal II dishes, the engine support arms block the view of part of the dish from the VSHOT. While it would be possible to carefully define the test region to exclude the receiver support arms, this would be difficult to implement in the software and tedious to use. The simple approach used instead was to exclude data points with no measured return beam ("lost" spots) from the fit to the slope measurements.

The problem with this approach is that a few data points were lost not because the beam was blocked, but rather because the concentrator errors were so large that the return beam missed the target. The RS-170 video camera used has a 4x3 aspect ratio between horizontal and vertical field of view. A 1.22-m x 0.91-m (4-ft x 3-ft) target was used for the outdoor measurements to match the video camera aspect ratio. The VSHOT was positioned to maximize the number of return spots on the target. However, a few spots still missed the target. A slightly larger target would be beneficial for the Distal II dishes. The testing of a typical, large (50+ m^2) heliostat would require a much larger target and may be impractical with the current system configuration. Individual heliostat module testing will require at most a target twice the size of the module.

Despite the rectangular target shape, a square grid was used for the video calibration. When return spots fall in the region of the target visible to the camera, but outside the square calibration grid, an extrapolation of the video calibration is used to measure the return spot location. Since a fourth order polynomial is used for each axis of the video calibration, this opens the possibility for errors to be introduced. To fix this problem, targets are now constructed with a rectangular calibration grid to match the aspect ratio of the camera.

Another issue with outdoor testing is the durability of the VSHOT itself. The VSHOT must be resistant to vibration so that it may be moved around outdoors. In one instance, moving the system from the lab to the outdoor test site caused hardware to shift and corrupt the laser scanner calibration. All the hardware must be tightened before moving the system. Additionally, a new laser mount has been incorporated to reduce its sensitivity to system movement. It is also important to protect the VSHOT from adverse weather conditions like rain or blowing dust. For these tests, a plastic tarp was kept handy for this purpose, but a more elegant enclosure could be designed.

MIDDLE DISH MEASUREMENTS

After a long delay in customs, the VSHOT system arrived at the PSA. It was assembled and tested on a reference optic to verify proper operation. The target was modified for wide angle use as required for the Distal II dishes by cutting a roughly 5 cm (2 in) hole in the target and calibrating for a 50 degree cone angle field of view. The error in this wide-angle calibration (0.38 mrad RMS) was much larger than had been seen previously in laboratory work using smaller cone angle calibrations. It is believed the cause of this large error was the placement of the video camera during calibration. The camera lens had a field of view of less than 50 degrees, requiring that it be placed further from the calibration target than the VSHOT and at a large incidence angle so that its view was not obstructed by the VSHOT. Normally during scanner calibration, the video camera is positioned between the VSHOT and the calibration target, which it then views at a small incidence angle. A later analysis of the data uncovered further inconsistencies that were ultimately attributed to an incorrect spot spacing parameter during the laser calibration. The data was corrected for this error and self-consistency was verified.

The middle dish measurements were performed first because there was no engine mounted on that dish. To get an approximate idea where to set up the VSHOT for measurements, a 10 cm (4 in.) diameter red plastic disk with a hole in the middle was used as a "pocket 2f" tester. Looking through the hole in the center of the disk helped locate a point along the dish's optical axis at a distance equal to twice the focal length of the dish—indicated by the majority of the dish appearing red to the observer. Sound reflection (voice, clapping) was also effective in finding the 2f point of the Distal dishes. The dish was pointed below the horizon and rotated in an azimuth direction until the focal point was at an appropriate height for the VSHOT to be positioned on a concrete walkway to the east of the dish. Then fine adjustments were made in the dish pointing and the location and pointing of the VSHOT to align their optical axes. This was achieved by drawing a test pattern to fill the dish and the number of return spots that missed the target. A measurement of the distance from the VSHOT to the dish vertex, made with a laser range finder, was 11.02 m (434 in.). The equipment setup and alignment process required 2-3 hours. An initial test with only 240 points was performed to insure proper system operation and setup, then a test with 2129 data points was performed over roughly 1 hour. As mentioned earlier, many data points were obstructed by the receiver support structure. A few missed the target due to large slope errors at their point of reflection, and some were "lost" for another reason[1]. These lost points were omitted from the analysis. Of the 2119 points tested, 523 were lost. leaving 1606 points for analysis.

The results of the middle dish measurements are shown in Table 1 for different polynomial fit orders. Typically, the figure of merit used when discussing the optical quality of a concentrator is the RMS of the slope residuals from a 2^{nd}-order fit since this represents the deviation from the ideally shaped concentrator of the same focal length. However, if the best-fit focal length differs from the desired value, this also can be considered an error. The optical quality of stretched-membrane facets for multi-faceted dishes have been measured by others - Wendelin and Grossman (1995), Grossman (1995), and Davenport and Oshmyansky (1995) to fall between roughly 1 and 3 mrad for facets ranging in size from 1.5 to 3.5 m in diameter. When comparing these results with the 3.18 mrad optical quality of the Distal II middle dish, it is important to remember that multi-faceted dishes also suffer from alignment and focal length mismatches in addition to the slope errors of the individual facets quoted above. However, Grossman (1995) found a total dish error of only 2.3 mrad for the SAIC multi-facet dish by comparing CIRCE predictions with flux mapping done at the focal plane with all facets aimed at one location (an aiming strategy not often used because it creates a very peaked flux distribution).

As the fit order is increased, the slope errors from the fit decrease because the fit more accurately accommodates local variations in mirror shape. Additionally, the slope errors become less deterministic and more random. This can be seen in the last column of Table 3 that lists the difference between the slope error of all points and the slope error excluding the outlier points that have error magnitude greater than 3 standard deviations. This fact is even better illustrated by the error vector plots for the 2^{nd}-order and 10^{th}-order fits shown in Figures 3 and 4 respectively. In these figures, the measurement point is indicated by a small square, and the slope residual vector (fit-measured slope) magnitude and direction is shown as a line originating from that point. The different scales of each plot are show at the bottom of the figure. The blank areas without a square dot are lost spots. The 2^{nd}-order fit residuals are highly deterministic in nature, showing specific "bubbles" near the rim. The 10^{th}-order fit residuals are more random in nature because the fit more closely matches the slopes in the "bubble" regions. The gaps in the error vector plots are due mostly to

[1] A number of points (mostly from areas near the middle of the dish with small slope errors) were also "lost" when their return spots landed in the middle of the target where the scanned laser beam originates. This small (~5 cm diameter) region of the target is blocked from video analysis so that the outgoing laser beam does not cause errors in calculating the return beam centroid.

obstructions caused by the engine support members and the counterweight used in place of the engine. Conversely, the focal length shows less dependence on fit order. A 2nd-order fit provides a very accurate estimate of the focal length. Jones et al. (1997) also showed that very few data points are needed to calculate a good estimate of the focal length.

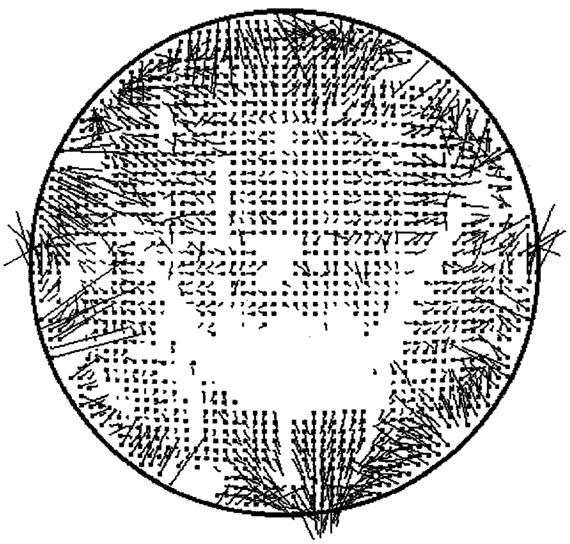

Figure 3. VSHOT residuals for 2nd-order fit of middle dish.

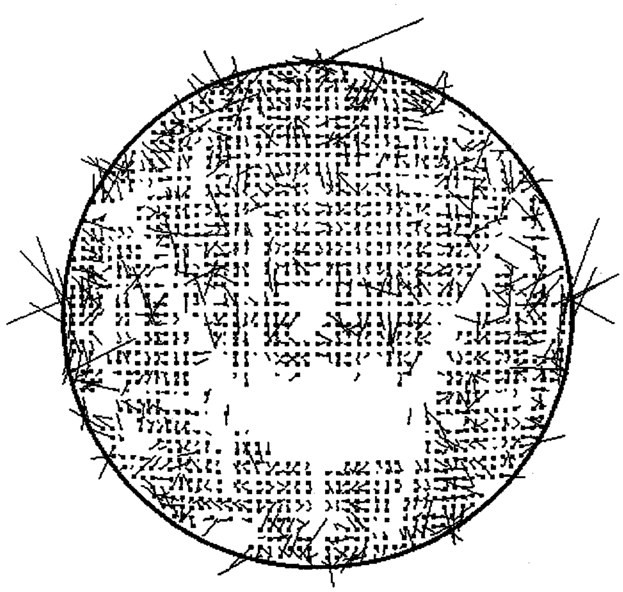

Figure 4. VSHOT residuals for 10th-order fit of middle dish.

Table 1. VSHOT results on the Distal II middle dish

Fit	Focal Length				RMS Slope Error (mrad)		
Order	X (in)	Y (in)	Avg. (in)	Avg. (m)	All points	<3 Sigma	Diff.
2	204	203	203	5.17	3.18	2.49	0.69
4	208	205	206	5.24	2.55	2.00	0.55
6	204	201	202	5.14	2.13	1.67	0.45
8	207	205	206	5.22	1.57	1.21	0.37
10	206	203	204	5.19	1.37	1.14	0.24

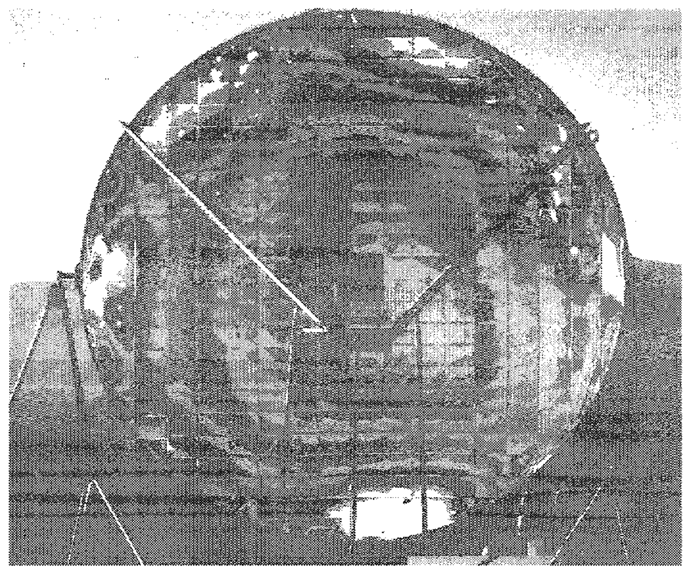

Figure 5. Distant observer measurements of the middle dish with a colored, concentric-ring target.

The "bubbles" seen near the rim are believed to be caused by non-uniformity in the membrane's attachment to the rim as well as its mechanical properties. The membrane is made of strips of stainless steel welded to each other and then welded to the support ring while under tension. A distant observer photograph taken by the PSA using a colored, concentric-ring target shows agreement with the VSHOT measurements. Figure 5 shows a grayscale image of the distant observer photograph of the middle dish. The image contrast and brightness have been adjusted to improve readability.

The PSA distant observer photographs provide only a qualitative, rather than quantitative, assessment of the dish optical quality. The Sandia Color 2F system (Grossman and Edgar, 1996) provides some quantitative analysis of optical quality using a similar colored, concentric-ring target viewed from twice the focal length (2f), rather than a distant location. This device has been used only on optics that are spherical (f/d ≥ 3) because use on parabolic reflectors like the Distal II dishes (f/d = 0.6) makes a numerical analysis of optical quality nearly impossible. The problem is that it is very difficult to know the exact location on the colored ring that is seen reflected in each part of the dish. For a spherical mirror, this means the directions of slope errors are unknown, but the magnitude of slope errors are bounded by the width of the rings. By assuming all errors are of a magnitude halfway between the bounds, an overall optical quality figure can be estimated (Grossman, 1994). However, for an ideal parabolic mirror, not all rays converge to the center of the concentric ring target. Consequently, both the direction and magnitude of slope errors are unknown and a numerical value of optical quality is unobtainable.

The regions of the dish that appear white in Figure 5 have large, albeit unknown optical errors since they are reflecting the white background of the target outside the colored concentric rings. The distant observer photograph shows the same "bubble" locations as the VSHOT 2nd-order fit residuals- a qualitative confirmation of the VSHOT results. The bubble at the mirror's bottom, just right of center is too steep, rather than too flat like some of the other bubbles. This information is available from the VSHOT results and is not available from distant observer photographs or 2f measurements. The VSHOT results may also be used for highly accurate, ray-trace computer modeling of flux distributions. For these reasons, and since the VSHOT measurement time is comparable, the Color 2f system is not routinely used anymore.

NORTH DISH MEASUREMENTS

The north dish measurements were performed a few nights after the middle dish using a similar procedure for setup. However, during alignment, it was discovered that the scanner calibration was incorrect because the hardware had shifted on its mounting rail. Apparently it was not tightened enough for the somewhat bumpy trip from the control building to the dishes. In order to complete the test in the time slot available, a new calibration had to be done quickly, precluding a wide-angle calibration. A 13-degree cone angle calibration was performed outdoors where the VSHOT had been positioned for measurements. The 13-degree calibration was extrapolated out to 48 degrees during the testing. While the RMS fit errors of 0.07 mrad for the 13 degree scanner calibration were much lower than for the 50 degree calibration, this fit did not accurately model the pincushion distortion present in the x-axis of the scan heads at large angles. Additional uncertainty is present in the results for the north dish listed in Table 2. A total of 2537 data points were taken and 496 were "lost", leaving 2041 points used for analysis. Fewer points were lost in this test because there was less equipment on the receiver platform to obstruct the view. The RMS fit errors again decrease with increasing order of fit and the focal length varies little with fit order. Strangely, the difference in RMS slope error between using all points and excluding those with error more than 3 times the standard deviation did not consistently decrease with increasing fit order. The 4th-order fit had a larger difference than the 2nd-order fit and is an anomaly of unknown origin. Figure 6 shows the VSHOT fit results for a 2nd-order fit, and Figure 8 shows the VSHOT fit results for a 10th-order fit. As expected, these errors appear more statistically random than Figure 6. Figure 7 shows the distant observer measurements made at the PSA in contrast-adjusted grayscale. Again, the results match very closely those shown in Figure 6, although the VSHOT shows the problem areas more quantitatively than the distant observer approach. It appears that around the rim of the dish, the errors alternate between regions that are too steep and too flat compared with the ideal shape. Imperfect tensioning of the membrane or attachment to the support rim may be causing these errors. Variations in mechanical properties of the membrane or any non-circularity or non-planarity in the support rim are also possible causes of the bubbles.

Table 2. VSHOT results on the Distal II north dish

Fit Order	Focal Length X (in)	Y (in)	Avg. (in)	Avg. (m)	RMS Slope Error (mrad) All points	<3 Sigma	Diff.
2	196	195	195	4.96	2.99	2.78	0.22
4	198	194	196	4.98	2.07	1.79	0.27
6	195	192	194	4.92	1.55	1.37	0.18
8	198	194	196	4.98	1.42	1.26	0.16
10	197	193	195	4.95	1.23	1.11	0.12

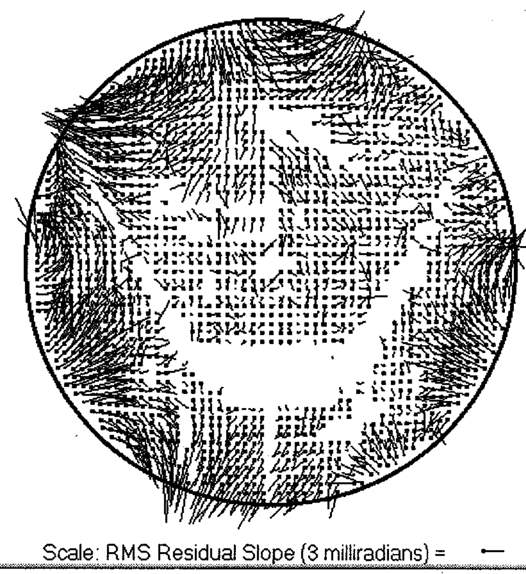

Figure 6. VSHOT residuals for 2nd-order fit of the north dish

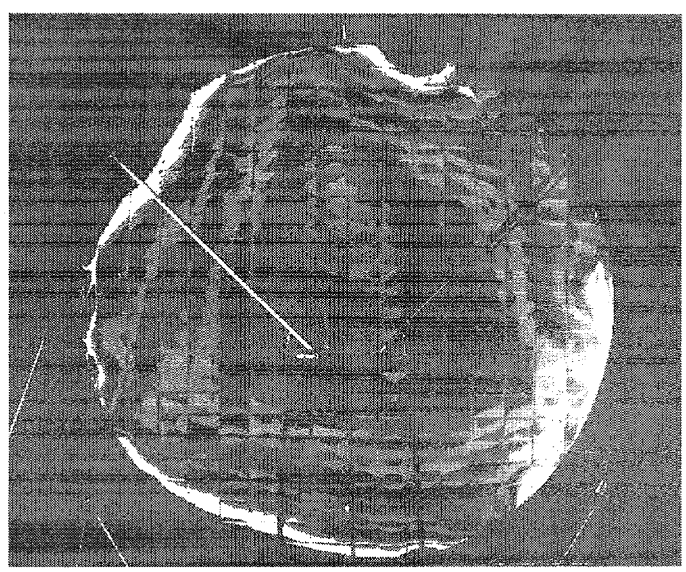

Figure 7. Distant observer measurements of the north dish with a colored, concentric-ring target

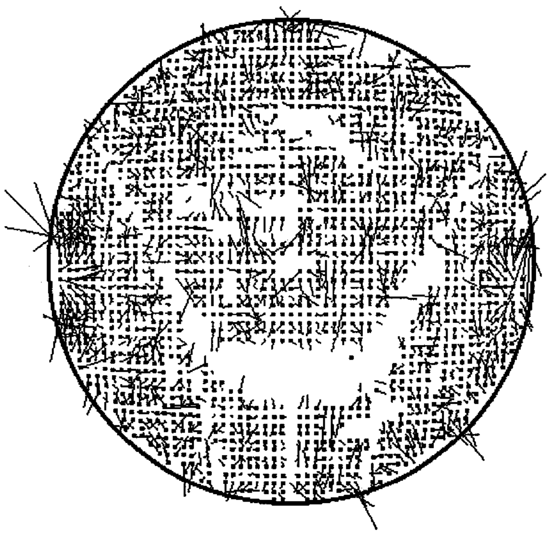

Figure 7. VSHOT residuals for 10th-order fit of the north dish

CONCLUSIONS

The figure of merit RMS slope error from an ideal parabola of 3.18 mrad for the middle dish and 2.99 mrad for the north dish are good considering the value represents the total dish error and are free of focal mismatch and alignment errors typically found on multi-faceted dishes. The VSHOT measurements of the Distal II dishes match the qualitative distant observer photographs taken at the PSA. A number of "bubbles" near the rim of the Distal II dishes have reduced their optical performance and may be due to imperfect membrane tensioning or attachment, variations in the mechanical properties of the membrane, or non-circularity or non-planarity of the support rim.

The outdoor testing of concentrators installed in the field appears feasible. A number of suggestions to improve the VSHOT capabilities in outdoor testing have been provided, such as the use of a 633 nm band-pass filter on the video camera. Many of the improvements have been implemented since these tests were performed. For instance, the measurement speed has been increased by a factor of 20 to 10 measurements/second and new targets have been constructed that have better designed video calibration patterns and are more Lambertian reflectors.

The testing of multi-faceted concentrators installed in the field is a logical next step, but has additional complications over these single-element tests because the data from each facet should ideally be analyzed separately. This is because multi-faceted dishes typically use spherical (F >3) facets with different aim points, and may have piston-type offsets between different facets. All of these factors support fitting each facet individually rather than doing all as one unit. This leads to another potential use of the VSHOT—Alignment. The VSHOT fitting routine can calculate the angle of each facet and be used to aim them as desired.

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