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DETERMINATION OF ACCURACY OF MEASUREMENTS BY NREL'S SCANNING HARTMANN OPTICAL TEST INSTRUMENT

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ABSTRACT

NREL's Scanning Hartmann Optical Test (SHOT) instrument is routinely used to characterize the surface of candidate dish concentrator elements for solar thermal applications. An approach was devised to quantify the accuracy of these measurements. Excellent reproducibility was exhibited and high confidence established in the absolute error related to individual characterizations.

The SHOT instrument was designed to allow the surface figure of large optical test articles to be accurately specified. Such test articles are nominally parabolic shapes with an f/D ratio (in which f = focal length and D = aperture diameter) in the range of 0.5-1.0. Recent modifications of SHOT have extended the characterization range out to about f/D = 3.0.

A series of experiments was designed to investigate and quantify the uncertainties associated with optical characterizations performed by SHOT. This approach involved making a series of measurements with an arbitrary test article positioned at a number of locations transverse to the optical axis of SHOT.

KEYWORDS

Optical measurements; optical characterization; surface figure; large optics; dish concentrators.

INTRODUCTION

A reliable and accurate means of quantifying the surface figure of large-aperture dish concentrators is required to allow optical performance to be predicted. Such a capability would allow comparison of candidate prototype designs, suggest improvement of fabrication techniques during the manufacturing process, and provide quality control of mass-produced modules. An instrument has been developed at the National Renewable Energy Laboratory (NREL) and has been used to test a variety of concentrators fabricated for the U.S. Department of Energy's Solar Thermal Program (Wendelin, Jorgensen, and Wood, 1991).

The standard test configuration is shown in Fig. 1. A laser beam emanating from the center of a screen is sequentially directed toward a user-specified number of points located on the test article. To minimize the time required to process each point, a regularly spaced test grid pattern is used as a first-approximation sampling scheme. To avoid biasing the data by any periodic features that may be present whose size or spatial frequency is of the order of the sampling grid, each point is located randomly about its nominal regular grid coordinate.

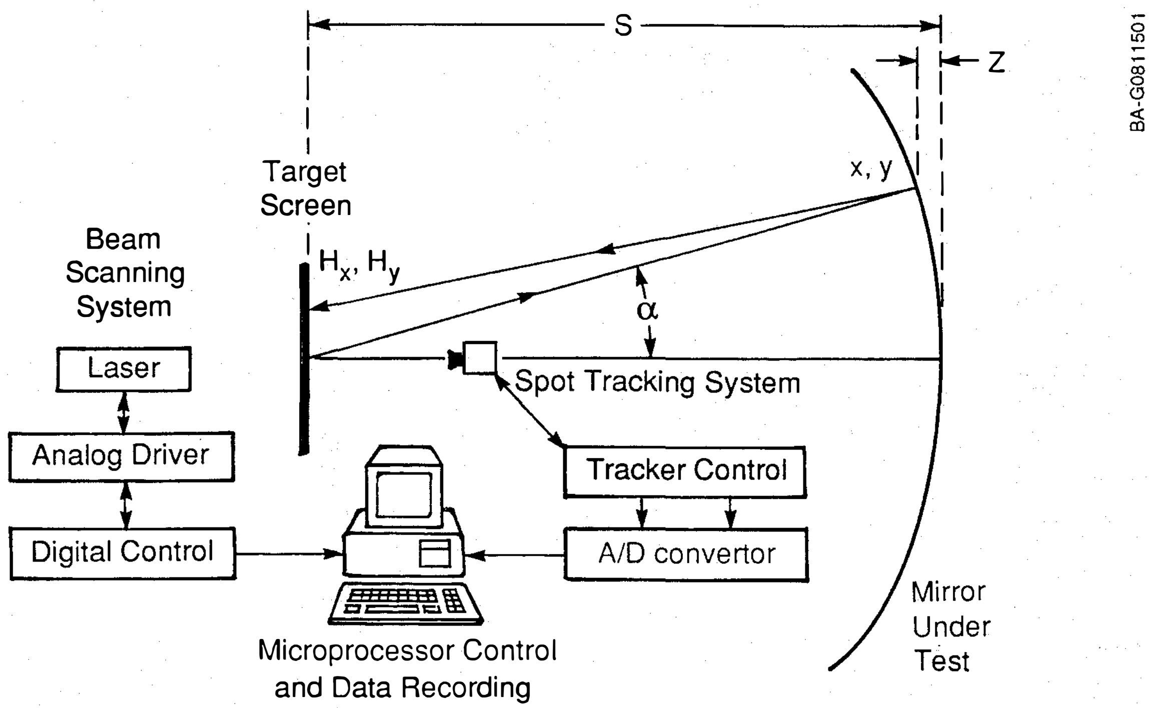

Figure 1. Standard SHOT test configuration

The intersection of the reflected spot with the screen is detected by a phase-locked quad-cell tracking unit. By knowing the distance from the screen to the vertex of the test article (s, typically chosen to be slightly greater than 2f) and the direction angles (α_x and α_y) of the scanned laser beam, the position at which the laser beam intersects the surface can be estimated, and the slope of the surface (ϕ_x and ϕ_y) can be determined from the measured position (H_x and H_y) of the return spot on the screen.

A Zernike monomial equation (Malacara, 1978) is used to represent the surface of the test article. This representation is non-axisymmetric, and the various terms of the expansion can be related to standard optical errors such as tilt, coma, etc. Measured data points are used to fit a surface equation expressed as

$$z(x-\Delta_x/y-\Delta_y) = \sum_{i=0}^{k} \sum_{j=0}^{i} B_{i-j} * (x-\Delta_x)^{i-j} * (y-\Delta_y)^j \qquad (1)$$

where Δ_x and Δ_y are the transverse distances (decenter) a given test article is displaced from the optical axis ($\alpha_x = \theta$ and $\alpha_y = \theta$) of the scanning laser in the x and y directions, respectively. A best-fit least-squares approach is used that minimizes the root mean square (RMS) of the sum of the differences between the measured and calculated slopes. These residuals are given by

$$r_x = \Phi_x - \frac{\partial z}{\partial x} \quad \text{and:} \quad r_y = \Phi_y - \frac{\partial z}{\partial y} \qquad (2)$$

The RMS residual slope is defined as

$$\sigma = \sqrt{\frac{\sum_{m=1}^{n} (r_x^2 + r_y^2)}{n}} \qquad (3)$$

with n being the number of measured data points. The magnitude of σ is an indication of how well the monomial representation defines the surface of the test article; it compares the fit curve to the measured slope data.

In practice, the procedure is to align the test article with the optical axis of the scanning laser, measure s and D, specify the number of data points desired and the designed focal length (f) of the (assumed parabolic) test article, and acquire data. Given the order of the fit (k), the number of desired iterations (I) to be performed during the fitting process, and the offset positions (Δ_x and Δ_y), the surface equation (1) can be fit to the data. Results from SHOT measurements can be input to the OPTDSH program (Balch and coworkers, 1991) to obtain optical and thermal performance information.

Ideally, the number of iterations and the order of the fit should be chosen to maximize the significance of regression (as determined by an F-test). If too many terms are included in the fit, the confidence in higher-order terms may be low. Such higher-order terms may be applied to fitting experimental errors in the data rather than contributing to a description of "true" surface shape. Typically, σ is monitored until convergence (in terms of changes in σ after each iteration during the fitting process) is obtained.

When the fitting process has been carried out, the amount of tilt of the test article with respect to the optical axis will be given by

$$\theta_x = \tan^{-1}(B_{10}) \quad \text{and:} \quad \theta_y = \tan^{-1}(B_{11}) \qquad (4)$$

The focal lengths in the x (horizontal) and y (vertical) directions are given respectively by

$$f_x = \frac{1}{4B_{20}} \quad \text{and:} \quad f_y = \frac{1}{4B_{22}} \qquad (5)$$

EXPERIMENTAL APPROACH

A series of experiments was carried out to investigate and quantify the uncertainties associated with optical characterizations performed by SHOT. The ideal way to validate an instrument such as SHOT would be to obtain a standard test article having a surface figure that is well known a priori. A measured characterization could then be carried out using SHOT, and the results could be compared with the known standard surface. Unfortunately, no such standards exist having the applicable size and geometry required. Consequently, an alternate means was devised to verify the operation of this instrument in an absolute sense. This was accomplished by characterizing the surface figure of a particular test article a number of times without changing any of the test parameters and then comparing these results with those for the same test article moved transverse to the optical axis. By moving the test article orthogonally to the optical axis a known distance, the degree of internal consistency could be derived for the measurement system. Although the fitting process allows an unknown surface to be represented in terms of the offset parameters Δ_x and Δ_y, the measurement system independently characterizes the surface of each new test article. The measurement system does not discriminate between one test article positioned exactly along the optical axis and another that has been shifted relative to that axis. Therefore, if an identical test article is characterized both on axis and at some displaced position, and the same surface is predicted to within the accuracy of the measurement/repositioning process, then the surface figure as predicted by SHOT is correct and valid. A summary of these experiments and their results is presented in Table 1.

Table 1. Results of SHOT Verification Experiments

Run #	Δ_x (cm)	Δ_y (cm)	B_{20}	B_{22}	σ* (mrad)	# of Pts.	P (Pa)	Remarks
1	-0.99	1.63	0.1274	0.1318	5.018	2000	1900	1st replication
2	-0.96	1.58	0.1272	0.1316	4.930	2000	1900	2nd replication
3	-0.95	1.61	0.1273	0.1316	5.023	2000	1900	3rd replication
4	-1.02	1.57	0.1271	0.1315	4.871	1000	1900	1/2 × # of points
5	-0.96	1.57	0.1273	0.1314	4.917	4000	1900	2 × # of points
6	-17.35	0.88	0.1265	0.1313	5.025	2000	1900	Moved 15.24 cm to left
7	-24.62	1.17	0.1259	0.1309	4.857	2000	1900	Moved 22.86 cm to left
8	13.98	1.02	0.1269	0.1313	5.080	2000	1900	Moved 15.24 cm to right
9	-1.77	0.81	0.1269	0.1313	4.903	2000	1900	Recentered (0 cm)
10	-0.88	0.92	0.1269	0.1313	4.876	2000	1750 to 2250	Moved 18.29 cm forward
11	-0.89	0.88	0.1269	0.1315	4.933	2000	1900	Moved 18.29 cm forward
12	-1.01	1.09	0.1258	0.1307	5.378	2000	1900	Recentered; $R=R_{Dish}$
13	-1.14	0.70	0.1259	0.1308	5.225	2000	1900	Relocated tracker
14	-0.18	1.34	0.1266	0.1315	5.141	2000	1900	Moved SHOT and test article to new lab

* All RMS residual slopes are after fifth iteration of a fourth-order fit. The tracker calibration coefficients were the same for experiments 10-12; for all other runs, the tracker calibration procedure was explicitly performed.

The test article used for these experiments was a fiberglass composite membrane dish having a 3-m diameter and a designed parabolic shape with f/D = 0.6 at a stabilization pressure (required to maintain the desired parabolic shape during operation) of about 1900 Pa. For each experiment (Run #), the decenter terms (Δ_x and Δ_y) were determined as the values that minimized the root mean square (RMS) of the residuals between measured slopes and a second-order least-squares fit. For Runs 1–5, the actual values of Δ_x and Δ_y that were used during the fitting process were the averages obtained from the first three "identical" replications. The monomial terms related to the focal length in the x (horizontal) and y (vertical) directions are also tabulated, along with the RMS residual slopes for a fourth-order fit and five iterations. Additional distinguishing information associated with each run is also provided in Table 1.

A figure of merit for comparing various experimental effects was defined as the RMS difference between the monomial coefficients used to describe the surface for different runs. Tilt terms (B_{10} and B_{11}) were not included because they are not integral to the surface being tested but rather are an artifact of positioning. The figure of merit that was used is

$$\varepsilon = \sqrt{\frac{\sum_{i=2}^{k=4} \sum_{j=0}^{i} [B_{ij}(\mu) - B_{ij}(\nu)]^2}{\eta}} \qquad (6)$$

where the number of coefficients excluding the two tilt terms, η, is given by

$$\eta = \frac{[(k+1)\ (k+2)\ -2]}{2} \qquad (7)$$

and B_{ij} (μ or ν) are the monomial coefficients associated with run #'s μ or ν. The average monomial coefficients from the first three experiments are denoted as $B_{ij}(0)$. Key comparisons that isolated various experimental effects are summarized in Table 2.

RESULTS

The effect that exhibited the largest uncertainty was that of sampling a greater number of data points near the outer perimeter of the test article (Table 2, comparison 9, 12). This is the region where it is most difficult to maintain a desired surface figure during fabrication.

Very close agreement was found between the calculated lateral displacements and the measured position of the test article (Δ_x vs. movement reported in "Remarks" in Table 1). Errors associated with small movements transverse to the optical axis (±15.24 cm, comparisons 9,6 and 9,8) are close to those related to simple repositioning of the test article (comparisons 0,9 and 0,14). For larger movements (22.86 cm, comparison 9,7), an appreciable area along half of the outer perimeter of the test article is moved into SHOT's scannable range (Fig. 2). Data points from this region can introduce errors as discussed above. Based upon these results, the description of the laterally shifted surface of the test article is identical (to within the uncertainties related to other experimental factors) to the description of the unshifted surface. This result verifies the SHOT measurement process. Random variation in stabilization pressure (roughly 10% to 20% for the particular test article under consideration) and longitudinal movement of the test article along the optical axis introduce minor uncertainty into the measured surface figure. Such effects are barely more significant than the inherent error associated with the measurement process itself (as represented by the first three entries of Table 2.

Table 2. Surface Figure of Merit for Various Experimental Effects

Comparison Run #'s (μ, ν)	ε (×10[5])	Effect Being Computed
0, 1	0.533	Average for replications vs. replication #1
0, 2	0.455	Average for replications vs. replication #2
0, 3	0.375	Average for replications vs. replication #3
0, 4	1.448	Decrease number of points by half
0, 5	1.129	Double number of points
0, 9	2.160	Move and reposition test article
0, 14	2.553	Relocate SHOT and test article
9, 6	1.906	Move 15.24 cm left
9, 7	4.747	Move 22.86 cm left
9, 8	1.350	Move 15.24 cm right
9, 11	0.559	Move 18.29 cm forward
9, 12	5.319	Sample closer to outer perimeter
9, 13	5.291	Move tracker
11, 10	0.721	Variation of nominal stabilization pressure

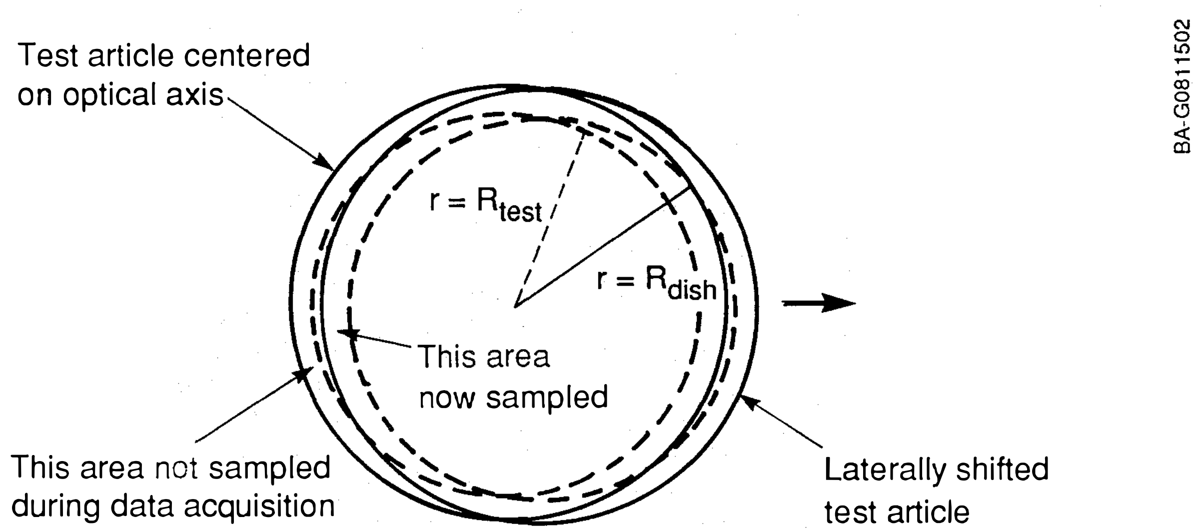

Figure 2. Perimeter area is sampled when test article is moved laterally

CONCLUSIONS

An approach was devised to quantify the accuracy associated with optical characterization of the surface of dish concentrators by NREL's SHOT instrument. This approach was independent of the details of the surface figure of the test article. Excellent reproducibility was exhibited, and high confidence was established in the absolute error related to individual measurements.

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REFERENCES

Balch, C., C. Steele, G. Jorgensen, T. Wendelin, and A. Lewandowski, (1991). *Membrane Dish Analysis: A Summary.* SERI/TP-253-3432, Solar Energy Research Institute, Golden, Colorado.

Malacara, D., (1978). *Optical Shop Testing.* John Wiley and Sons, New York.

Wendelin, T., G. Jorgensen, and R. Wood, (1991). "SHOT: A method for characterizing the surface figure and optical performance of point focus solar concentrators." *Proceedings 13th Annual ASME Solar Energy Conference*, Reno, Nevada.