NREL/TP-471-7296 • UC Category: 1300 • DE95000282

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Prepared for the ASME/JSME/JSES International Solar Energy Conference, Maui, HI, March 19-24, 1995

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
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October 1994

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COMPARISON OF THREE METHODS FOR OPTICAL CHARACTERIZATION OF POINT-FOCUS CONCENTRATORS

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ABSTRACT

Three different methods for characterizing point-focus solar concentrator optical performance have been developed for specific applications. These methods include a laser ray trace technique called the Scanning Hartmann Optical Test, a video imaging process called the 2f Test, and on-sun testing in conjunction with optical computer modeling. Three concentrator test articles, each of a different design, were characterized using at least two of the methods and, in one case, all three. The results of these tests are compared. Excellent agreement was observed in the results, suggesting that the techniques provide consistent and accurate characterizations of solar concentrator optics.

INTRODUCTION

Standard methods for validating and benchmarking optical test methods typically utilize some type of reference article whose surface is either well characterized or "known." In most situations where solar optics are tested, such a reference article is impractical given the large size of both the solar concentrator and the scale of optical errors considered acceptable for solar power applications [1]. Three different methods have been used by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories to test solar point-focus concentrators. These methods were developed independently for different applications. The Scanning Hartmann Optical Test (SHOT) was developed at the NREL [2]. On-sun testing and the 2f Technique were both developed at Sandia National Laboratories. SHOT was developed early in the Department of Energy's dish concentrator development program and is used to mathematically characterize optical surfaces. Data obtained with SHOT can be used to identify the nature and size of optical errors present in a solar concentrator and are, therefore, useful in the concentrator engineering and design stages. The method is thorough, but time-consuming, and SHOT is considered to be a good research and development tool.

The capability to test facets on-sun was developed to obtain real solar performance including image flux maps and power [3]. When used in conjunction with the CIRCE2 computer codes [4], values for overall optical performance (uniform slope errors) can be derived.

In response to industry's need for a quality control tool for large-scale manufacturing, Sandia National Laboratories is developing a video imaging process called the 2f technique [5]. This method has the potential to quickly assess optical surface quality and determine whether products that come off of the assembly line meet certain accuracy requirements. It provides a less quantitative assessment of the optical surface than SHOT but is better suited for quality assurance testing.

DESCRIPTION OF TEST METHODS

SHOT

The SHOT test configuration is shown in Figure 1. A He/Ne laser beam is directed toward the concentrator test article from a known location relative to the test article. This location is usually on the concentrator optical axis and is approximately twice the concentrator focal length away from the concentrator vertex. The beam strikes the reflective surface of the concentrator and is reflected back to a white target screen. An electronic detector viewing the screen locates the centroid of this return spot. The slope at the origination point of the reflected beam is determined from the position of this centroid on the target. Once the slope of the origination point is determined, the laser beam is directed to a new point. The process is repeated until the entire concentrator surface has been characterized.

Typically, 2000 datum points are acquired using this automated computer process. Experience has shown that this number is optimum for most concentrators. Sampling more points yields little additional information. These slope data are then fit to a

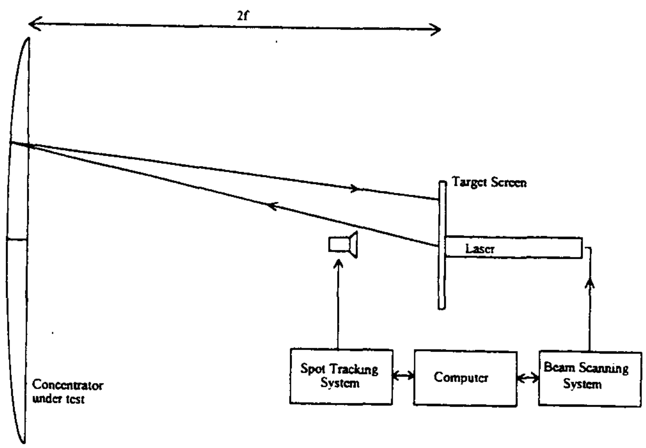

FIGURE 1. SHOT TEST CONFIGURATION

special mathematical series known as the Zernike monomial expansion [6]. This fit is fully asymmetric and therefore can accommodate circumferential errors as well as radial errors. A useful feature of this process is that optical parameters such as focal length, coma, astigmatism, spherical aberration, and piston error fall immediately out of the expansion. Thus the focal length does not have to be known a priori; it is actually determined afterwards by the SHOT data processing system.

If one chooses to fit the data to a second-order series (i.e., perfect parabola), the resulting root-mean-square (RMS) difference between the fit and the actual data provides the RMS slope error typically used to characterize the quality of solar concentrator surfaces. The "raw" slope information can also be input to an optical ray trace code, OPTDSH [7], to generate maps of the concentrator surface slope error as well as predict solar flux maps at user-specified target planes. An earlier independent study helped to establish confidence in the SHOT procedure and results [8].

2f Test

Figure 2 illustrates the 2f Test. The 2f Test is based on a standard distant-observer look-back technique and is an optical performance measurement system for use with parabolic point-focus concentrators that have focal length to diameter ratios (f/D) greater than 3.0. The method views a target of concentric rings at the radius of curvature (twice the focal length, hence the name 2f) by looking back at the facet from the center of the target. A computer with a frame-grabber and image digitizer acquires and stores the data. The contribution of a given ring to the uniform slope error is a function of the facet geometry, the ring size, and the number of pixels from the ring in the digitized image of the target. The inner and outer diameters of a ring define the range of slope errors within the ring, but the method does not measure the pixel distribution within the ring. A single arbitrary radius (the radius that divides the ring into two equal areas) is used to provide a single slope error value for each ring. This value is combined with the corresponding value from each ring to provide a single number for the facet. This number is called the Facet Figure of Merit (FFM). This is not considered a true slope error because it is based on an arbitrary value. A monochrome version of this system has been demonstrated [5] and development is proceeding on a color-based system intended to reduce test and analysis time. This method is designed to be used as a quality control tool in a production scenario. It does not have the sophistication or information capability of the SHOT system, but results do correlate with the SHOT results.

On-Sun Testing

On-sun testing in conjunction with the CIRCE2 computer code has been used to determine optical performance for different types of facets and solar concentrator systems [3]. A typical on-sun test configuration is shown in Figure 3. The primary tool for these measurements is the Beam Characterization System (BCS) that employs an image digitizer and a commercially available software package that is enhanced for this application. The output of the system is an array of image intensities, a peak flux value, and the total power incident on the target.

CIRCE2 [4] is a computer code for modeling the optical performance of solar concentrators. The code will predict flux distribution and total power on a target surface using statistical methods to evaluate the directional distribution of reflected rays based on sunshape, receiver geometry, and concentrator characteristics. One of these characteristics, concentrator slope error, is iterated until the calculated peak flux matches the measured peak flux, providing a single-point comparison. A more rigorous comparison begins by determining the intensity difference between elements of the normalized measured intensity array and the elements of a normalized calculated array using CIRCE2. The slope error in CIRCE2 is again iterated to generate calculated flux arrays. The goal is to minimize the square root of the sum of squares (RSS) of the differences between measured and calculated. In this way, the flux distributions are volumetrically matched as opposed to the single-point peak-flux approach. This is more time-consuming, but it provides a more accurate comparison.

CONCENTRATOR TEST ARTICLES AND RESULTS

A variety of concentrator designs have been tested using combinations of the three techniques just described. Comparative results are presented in this paper for three specific concentrator designs.

Prototype Stretched-Membrane Facets

The first concentrator characterized using both the SHOT and on-sun testing was the stretched-membrane facet designed for the Faceted Stretched-Membrane Dish Project [9]. Two facets were tested with the SHOT and on-sun systems. One of these facets was fabricated by Science Applications International Corporation (SAIC) and the other by Solar Kinetics, Inc. (SKI). Both facets are approximately 3.5 meters in diameter with a focal length that can be adjusted to be between 9.0 and 11.0 meters. The SAIC facet uses a vacuum to elastically form the front membrane while

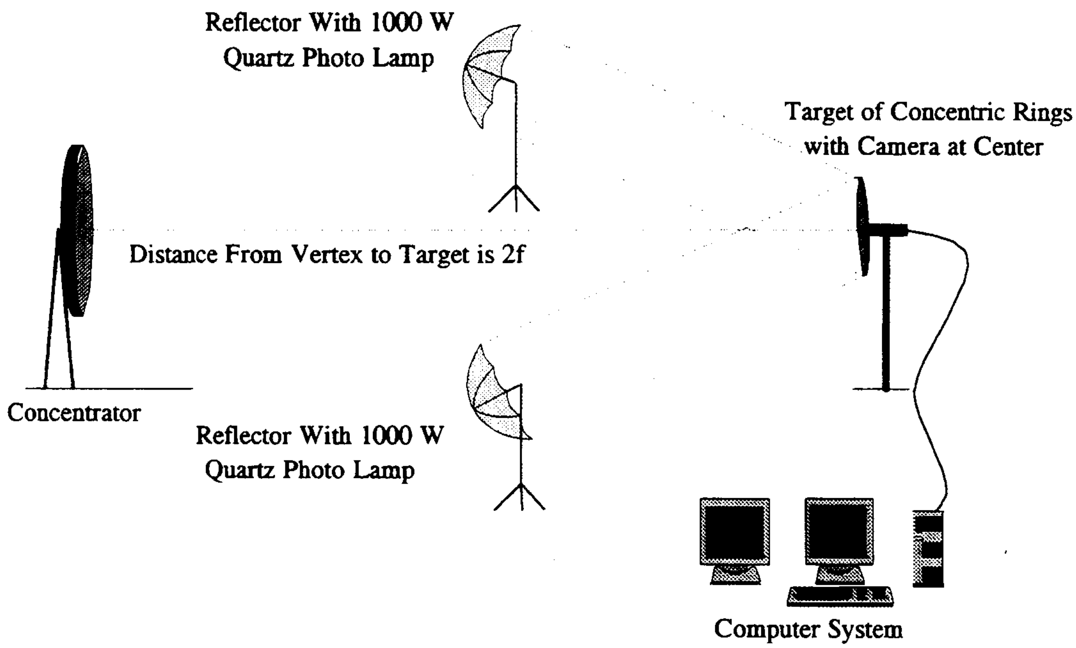

FIGURE 2. 2f TEST CONFIGURATION

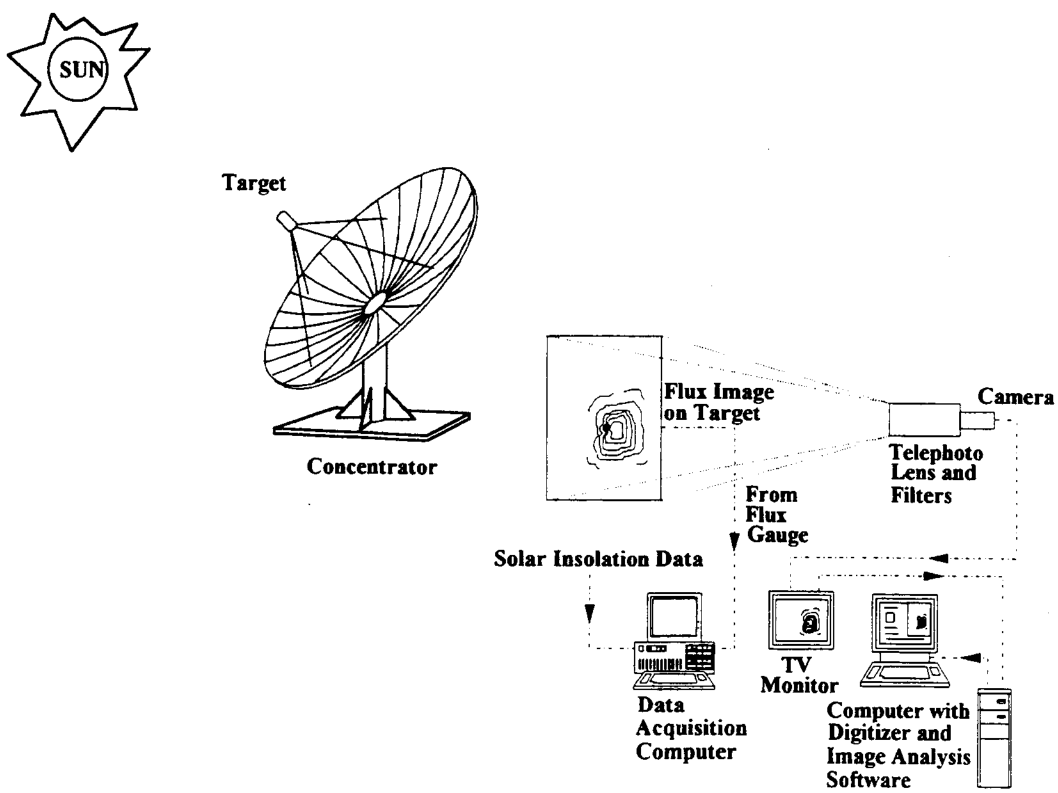

FIGURE 3. ON-SUN TEST CONFIGURATION

the SKI facet is initially plastically deformed, and the vacuum serves to keep the membrane taut so that wind will not affect the surface shape. The comparable results of the on-sun testing and the SHOT characterization are presented in Table 1. In both cases, the comparable results are reported as RMS slope errors. The discussion of how these results are generated for each test can be found in the technique descriptions above. The SHOT testing was done first at NREL and then the facets were sent to Sandia for on-sun testing. The on-sun testing was done as closely as possible to the SHOT focal lengths. Because these are long-focal-length concentrators (i.e., $f/D \geq 3.0$), the surface contours of these facets were fairly axisymmetric, but not perfectly so. The fit used by the SHOT can account for this, but the flux distribution fit used in the on-sun testing does not account for this. Thus, some minor differences in the results are expected. The uncertainty in the SHOT results would be on the order of $\pm$ 0.2-0.3 milliradians. The on-sun values have similar uncertainties. The major sources of uncertainty are the measured distances and orientations in the test set-up configurations. Also, the computer modeling used to predict the flux distribution introduces uncertainty in the final results.

The results compare favorably for all of the tests with the exception of the SKI facet at the shortest focal length. The SHOT measured an RMS error of 1.3 mrads while on-sun testing measured 1.9-2.0 mrads depending on the fit method. This difference is attributed to a dual focal zone effect produced by the concentrator surface at this short f/D (i.e., high vacuum, deep contour). This was discovered by Sandia during on-sun testing. At the longer f/Ds (i.e., lower vacuum, flatter contour) the focal zones converge into one. The results indicate that the on-sun testing was performed at one of the two focal zones, whereas the SHOT testing yielded an average value for the surface as a whole.

Test Bed Concentrator Facets

The Test Bed Concentrators at Sandia National Laboratories provide high-flux solar radiation for a variety of experiments and engineering demonstration projects. Recently, an effort was undertaken to increase the delivered thermal solar power by improving the reflectivity of the foam glass facets [10]. This was accomplished by refurbishing their surfaces with thin glass tiles. To determine how well the glass tiles would conform to the facet contours, both the SHOT and the 2f Test were used to characterize the facet optical performance before and after refurbishment. The original spherical surfaces of the glass facets are substantially more accurate than those required or expected for solar thermal electricity applications. Each facet has a different radius of curvature depending upon its specific location on the multi-faceted dish structure. Two facets were tested, one from the center of the dish where the facet focal length is shortest, and one from the edge of the dish where the facet focal length is longest. The results of the 2f Test and SHOT are shown in Table 2. The SHOT values again are RMS slope errors in milliradians. The 2f results as described above are Facet Figures of Merit (FFM), which give an indication of the range of possible slope error in milliradians. The facet numbers shown in the first column are identification numbers for specific facets. Although the same facets were not tested with the 2f Test and SHOT, the facets tested have nominally the same radius of spherical curvature.

The results of both the 2f Test and SHOT show that the laminating of the glass tiles to the facet contours increases the surface slope error slightly. This would be expected as the glass tile does not conform perfectly to the surface curvature underneath it. The increase in slope error for the long radius of curvature facets was approximately 0.16 milliradians as measure by the 2F

TABLE 1. CIRCE2 AND SHOT RESULTS FOR THE PROTOTYPE STRETCHED-MEMBRANE FACETS. RMS SLOPE ERROR IN MILLIRADIANS, FOCAL LENGTH IN METERS

SHOT System		On-Sun System		
Focal Length	*Slope Error*	*Focal Length*	*Peak Flux Method Slope Error*	*RSS Difference Method Slope Error*
SAIC Facet				
10.45	2.6	10.5	2.2	2.2
9.9	2.7	10.0	2.8	3.0
9.6	2.8	9.5	2.8	3.0
SKI Facet				
10.45	1.5	10.5	1.5	1.6
9.9	1.2	10.0	1.3	1.2
9.6	1.3	9.5	2.0	1.9

TABLE 2. 2f TEST AND SHOT RESULTS FOR THE TEST BED CONCENTRATOR FACETS

	Radius of Curvature	2f Facet Figure of Merit (FFM) (mrads)					
		Before Refurbishment			After Refurbishment		
Facet #	*m*	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*	*Max.*
TB030A	12.9	.31	.62	.79	.61	.911	.11
TB128B	16.0	.33	.63	.78	.55	.790	.94

		SHOT RMS Slope Error (mrads)	
		Before Refurbishment	After Refurbishment
Facet #	*m*		
TB024	13.0	.50	.64
TB190	15.7	.38	.51

TABLE 3. SHOT, 2f AND ON-SUN TESTING RESULTS FOR THE CUMMINS POWER GENERATION STRETCHED MEMBRANE FACETS

SHOT Tests	Focal Length in meters	2 X F.L	RMS Slope Error (mrads)
CPG Facet #1 (Best)	5.23	10.4	1.73
CPG Facet #2 (Worst)	5.44	10.6	2.20

		2f Facet Figure of Merit (FFM) (mrads)		
2F Tests	*2f Distance in meters*	*Min.*	*Avg.*	*Max.*
CPG Facet #1 (Best)	10.4	1.21	1.41	1.56
CPG Facet #2 (Worst)	10.5	2.32	2.65	2.92

On-sun Tests	*Focal Length*	*Peak Flux Method slope error (mrads)*	*RSS Difference Method slope error (mrads)*
CPG Facet #1 (Best)	10.4	1.32	1.5
CPG Facet #2 (Worst)	10.5	2.25	4.2

Test and 0.13 milliradians as measure by SHOT. The slope error for the shorter radius of curvature facets increased by 0.29 milliradians (2f Test) and 0.14 milliradians (SHOT). The measure SHOT RMS errors fall into the range measure by the 2f Test in all cases except the long-radius-of-curvature facet after refurbishment. Because different facets were measured by each instrument, some minor differences would be expected.

Cummins Power Generation 5 kW Dish/Stirling Engine Stretched-Membrane Facets

The final concentrator test articles to be discussed are the stretched-membrane facets used by Cummins Power Generation (CPG) in their 5 kW Dish/Stirling engine design. Similar to the SAIC and SKI facets discussed earlier, these facets are focused using an evacuated plenum. The focal length is adjustable by changing the vacuum pressure. The facets are approximately 1.5 meters in diameter. Two such facets were tested for CPG. One was qualitatively judged by CPG to have a worse surface shape than the other when focused. Testing was done to quantitatively compare the performance of the facets. In this "round-robin" test, the same two facets were tested with all three techniques: SHOT, 2f, and on-sun. The results are shown in Table 3.

As can be seen, the focal lengths could not be matched exactly for all three testing processes. Given this fact, good agreement is noted in all cases with the exception of the on-sun test of CPG Facet #2 using the RSS difference method. As mentioned previously, the CIRCE2 code is used to generate flux profiles matching those measured on-sun at the target plane. Either the peak flux is matched or the volume under measured distribution is matched to the volume under the distribution predicted by CIRCE2. CIRCE2 cannot model asymmetric surfaces. However, the support ring for the membrane in CPG Facet #2 was warped slightly out of plane, and thus the surface shape contained significant asymmetry about the optical axis. The data from the on-sun and SHOT tests indicate that this asymmetry may not be accounted for correctly in on-sun analysis.

CONCLUSIONS

The agreement observed in "round-robin" testing of three different concentrator test articles with SHOT, 2f Test, and on-sun testing provides increased confidence in the use of each method independently. Each technique has particular advantages for its specific application and provides useful and complementary information to the other two. These data provide increased confidence in the capability of each method and pave the way for future developmental and quality control testing of concentrator designs using either these techniques or variations of them.

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The work at Sandia National Laboratories, Albuquerque, New Mexico, is supported by the U. S. Department of Energy under contract DE-AC04-94AL85000.