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Comparison of Predicted Optical Performance with Measured Results for Dish Concentrators

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COMPARISON OF PREDICTED OPTICAL PERFORMANCE WITH MEASURED RESULTS FOR DISH CONCENTRATORS

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ABSTRACT

Several optical design tools have been developed at the National Renewable Energy Laboratory (NREL) during the past two years. These have been used extensively both in-house and by industry to analyze dish concentrator systems and to optimize performance of such designs. The first program, OPTDSH, models single-element dish concentrators. The second code, ODMF, allows multifacet dish arrays to be modeled. The accuracy of performance simulations by these programs has been established by comparing predicted results with measured on-sun data.

ODMF evolved from NREL's High-Flux Solar Furnace (HFSF) design tool, SOLFUR, and in fact is a special case of SOLFUR in which the primary facet array is "on sun." Consequently, confirmation of the accuracy of SOLFUR would verify the results from ODMF as well. Furthermore, because OPTDSH can be viewed as a single-facet case of ODMF, determination of the precision of SOLFUR/ODMF would also substantiate OPTDSH. Thus, the approach to verifying the correctness of all three codes was to compare flux patterns as predicted by SOLFUR with those actually measured at NREL's HFSF.

Measured vs. calculated data have been compared on the basis of flux distribution (in terms of contour plots) and peak flux for both single-facet and multiple-facet cases. Agreement in measured vs. predicted peak flux values has been obtained within the uncertainty associated with the measurement/calibration process. Excellent agreement has also been demonstrated by comparing contour maps of measured vs. computed flux levels.

KEYWORDS

Optical performance modeling; measurement of optical performance; dish concentrators.

INTRODUCTION

A computer model named SOLFUR was written at the National Renewable Energy Laboratory (NREL) to serve as a design tool during the development of a High-Flux Solar Furnace (HFSF), also at NREL (Lewandowski, 1989). Because ODMF evolved from this solar furnace design tool and in fact is a special case of SOLFUR in which the primary facet array is "on sun," validation of SOLFUR would effectively validate ODMF as well. Furthermore, because OPTDSH (Balch and coworkers, 1991) can be viewed as a single-facet case of ODMF, validation of SOLFUR/ODMF would also validate OPTDSH. Thus, the approach to validating all three codes was to compare flux patterns as predicted by SOLFUR with those actually measured at NREL's HFSF.

All these programs use a three-dimensional ray-trace procedure as described by Spencer and Murty (1962). Rays are generated at infinity either on a uniform (Cartesian) grid or in a random fashion. The intersection of each ray with the appropriate optical surfaces (heliostat, dish facet, target plane for SOLFUR; dish facet and target plane for ODMF; and dish surface and target plane for OPTDSH) is sequentially computed, and optical errors are incorporated into the reflected ray directions. The target plane is divided into a two-dimensional grid, and a tally is kept of the number of rays that intersect each grid area. The concentration ratio (C_g) within each grid is then proportional to the ratio of the number of rays per grid area to the number of rays per dish area:

$$C_g = \rho_h * \rho_d * \left(\frac{N_g}{A_g}\right) * \left(\frac{N_d}{A_d}\right) \tag{1}$$

where
- ρ_h = the solar-weighted reflectance of the heliostat
- ρ_d = the solar-weighted reflectance of the dish array
- N_d = the number of rays that strike the dish array
- A_d = the projected area of the dish array
- N_g = the number of rays that intersect the grid element
- A_g = the area of the grid element.

Given the concentration ratio and the value of the direct solar irradiance [I, for example, as provided by a Normal Incidence Pyrheliometer (NIP) reading, in W/m^2], the flux within a given grid (F_g) can be calculated as:

$$F_g = I * C_g \tag{2}$$

Calculated results have been compared to measured data on the basis of flux distribution (in terms of contour plots) and peak flux for both single-facet and multiple-facet cases. Agreement in predicted vs. measured peak flux values has been obtained within the uncertainty associated with the measurement/calibration process. Excellent agreement has also been demonstrated by comparing contour maps of measured vs. computed flux levels.

EXPERIMENTAL APPROACH

The basic approach to verifying the optical performance codes was to compare measured flux profile data obtained at NREL's HFSF with results calculated by SOLFUR in simulating the geometric configuration and optical specifications of the various elements of the HFSF. With the use of a commercial beam analysis software package named BEAMCODE (1990), which has been integrated into the HFSF data acquisition and control system (Bingham and Lewandowski, 1991), the following flux profiles were measured:

- Two flux maps at the optimum target distance (i.e., at the focal plane) taken over a fairly short time period (several minutes or less between each measurement) to demonstrate the variability associated with the measurement process.

- Two flux maps, each at a distance +8 cm (away from the dish array) and -8 cm (closer to the dish array) along the optical axis from the ideal target plane. This was carried out to verify the angular distribution of rays at the target; if a series of flux profile "snapshots" taken along the optical axis agrees well with predicted results, then confidence in the direction of rays at the target plane is high.

- A flux map for the central facet only (i.e., all other dish facets covered). This corresponds to a single-facet "on-axis" dish concentrator as modeled by OPTDSH.

Results of these experiments are presented in Table 1. NIP readings provide the direct-normal irradiance required to convert between flux and concentration ratios. The scale factors listed in Table 1 vary because the video camera remained stationary during the measurement process, while the target flux plate (and its intercepted flux profile) was moved about the focal plane, resulting in differences in the projected size of the image at the camera sensor array.

Values for the following optical parameters were used as input to the SOLFUR model:

$\rho_h = 0.879$ = reflectance of heliostat facets
$\rho_d = 0.904$ = reflectance of dish facets
$\sigma_h = 0.1$ mrad = specularity of heliostat facets
$\sigma_d = 0.1$ mrad = specularity of dish facets
$s_h = 0.5$ mrad = slope error associated with heliostat facets
$s_d = 0.2$ mrad = slope error associated with dish facets

Heliostat and dish reflectances were measured after cleaning the mirror surfaces prior to the set of experiments discussed herein. The sun was modeled as a pillbox distribution having a characteristic size of 4.65 mrad. Additional design parameters required to model the HFSF are given by Lewandowski (1989) and by Lewandowski and coworkers (1990).

A common format was desirable in order to readily compare predicted results with measurements. Such an arrangement is provided by a program named SURFER (1989). This program allows three-dimensional information (for example, flux level as a function of x and y coordinates) to be graphically represented as topological contour maps (TOPO feature) and as three-dimensional isometric projections (SURF option). This program was used to accept both measured and calculated data.

RESULTS

A number of SOLFUR simulations were run corresponding to the measurements taken for the various configurations specified in Table 1. The results predicted by SOLFUR fluctuate, based on several factors including the number of rays traced and the size of the grid pattern used to tally rays in the target plane. The predicted peak flux is a strong function of the size of the grids used to compute concentration ratios (and hence flux levels). This can be seen from the results presented in Table 2. In general, for a large number of rays, the greater the number of grids, the more accurate will be the predicted peak flux. The reason for this is that the grouping of rays will tend to be more uniform, and jagged features of local peaks will be smoothed into a more rounded distribution.

Figure 1 is a contour map of the measured flux levels for 23 dish facets with the target plane located at the focal plane. The flux levels predicted by SOLFUR presented in Fig. 2 have been scaled so that the peak flux agrees with measured values. As suggested above, the calculated peak flux can be made to artificially agree with measured values (Table 1) by varying the number of grids used in the simulation (Table 2). The scaling process was within the uncertainty of measured peak flux levels reported by BEAMCODE; calibrated values are generally 7%-10% higher than expected, based upon measured direct

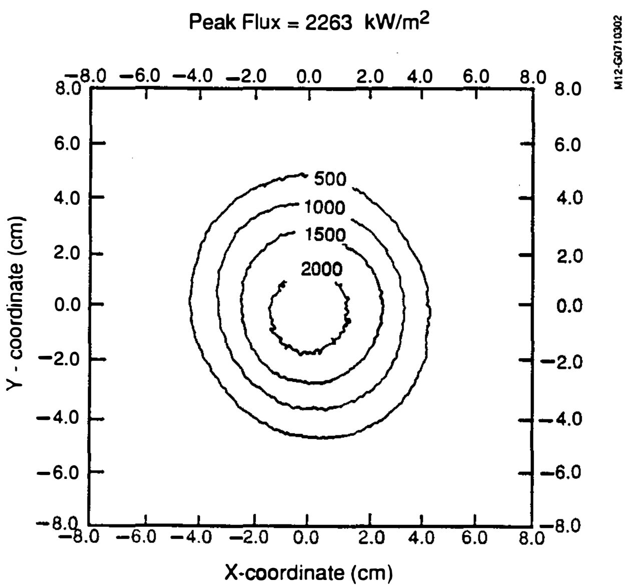
Table 1. Measurement Parameters at SERI's High-Flux Solar Furnace, 8/3/90

Run/ Flux File Name	Time	# of Facets	Distance of Target Plate from Focal Plane (cm)	Peak Scale Factor	Direct Peak Normal Flux (kW/m)^2	Irradiance (W/m^2)	Concen-tration Ratio (suns)
G1B	10:54	1	0	35.8	106	890	119
G2A	11:56	23	-8	34.6	1873	957	1957
G2B	11:58	23	-8	34.6	1868	957	1952
G2C	12:00	23	0	35.8	2263	954	2372
G2D	12:03	23	0	35.8	2249	954	2357
G2E	12:04	23	+8	37.0	2085	950	2195
G2F	12:05	23	+8	37.0	2091	950	2201

Table 2. Simulation Results Predicted by SOLFUR*

Run/Ray File Name	1-D # of Rays	# of Grids	# of Facets	Distance from focal plane (cm)	Peak Flux (kW/m^2)
B05K0000	5000	16	1	0	86
B12K0000	12500	25	1	0	93
B25K0000	25000	35	1	0	98
B50K0003	50000	25	1	0	87
B50K0004	50000	50	1	0	96
B50K0006	50000	25	23	0	2091
B50K0005	50000	50	23	0	2306
B50K0008	50000	25	23	-8	1767
B50K0012	50000	35	23	-8	1852
B50K0007	50000	50	23	-8	1948
B50K0010	50000	25	23	+8	1817
B50K0011	50000	35	23	+8	1891
B50K0009	50000	50	23	+8	1986

For comparison with the various measurement configurations enumerated in Table 1; the random number generator seed was held fixed for all runs.



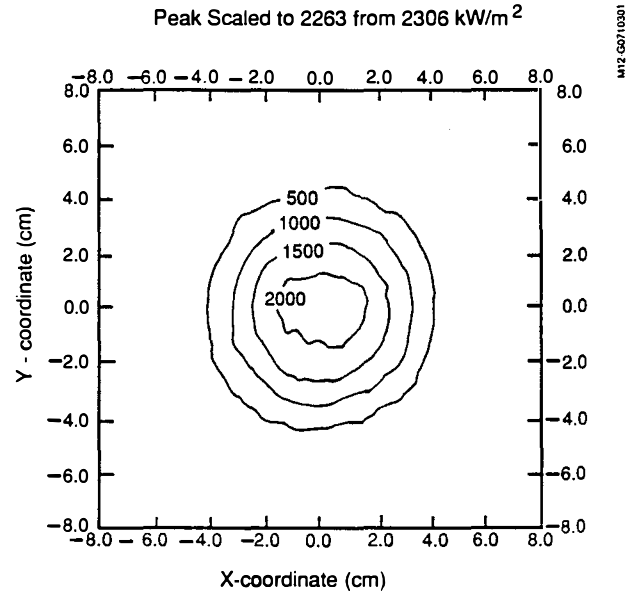


Figure 1. Contour map of measured flux levels for 23 facets with target plane located at focal plane

Figure 2. Contour map of flux levels predicted by SOLFUR for 23 dish facets with target plane located at focal plane

normal irradiance. Comparison of measured results (Fig. 1) with calculated flux levels (Fig. 2) indicates excellent agreement.

Figures 3 and 4 present the measured and predicted contour maps for 23 dish facets with the target plane located -8 cm from the focal plane. Although some structure appears in the measured data (Fig. 3) that is not evident in the calculated pattern (Fig. 4), the spacing between lines of constant flux in both plots gives a superb match. The pattern associated with the measured data may be due to the fact that the primary dish array was aligned so that the centroids of each facet coincided at the focal plane. This is in contrast to the optical models, in which the aim points that are specified for each dish facet refer to the central ray rather than to the centroids of the resulting flux patterns. Similar results are obtained when the target plane is positioned +8 cm from the focal plane. These results suggest that the angular distribution of rays at the focal plane is correctly predicted by the optical models.

To validate the single-facet model (OPTDSH), a simulation was run for just the central facet of the primary array. The measured data are presented in Fig. 5; the corresponding predicted results are given in Fig. 6. Outstanding agreement can readily be seen in terms of both the shape and the orientation of the contour lines.

CONCLUSIONS

The performance simulations of several optical ray-trace programs have been validated by comparing predicted results with measured on-sun data. Comparison of flux patterns measured at NREL's HFSF and those predicted by SOLFUR reveal excellent agreement for both peak values and distribution profiles.

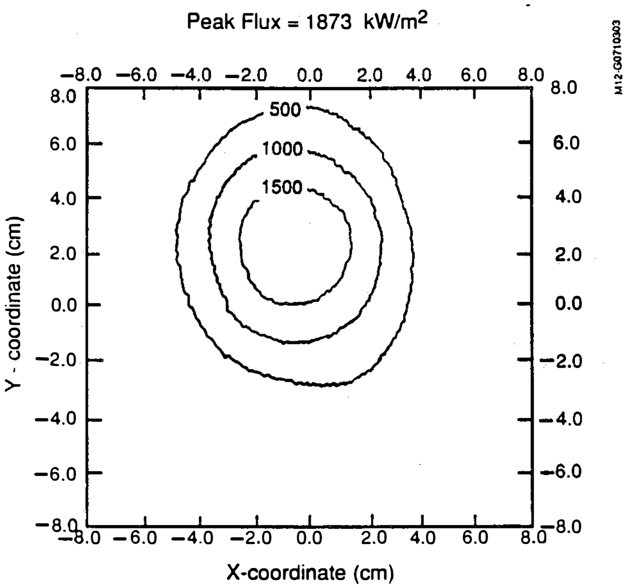


Figure 3. Contour map of measured flux levels for 23 dish facets with target plane located -8 cm from focal plane

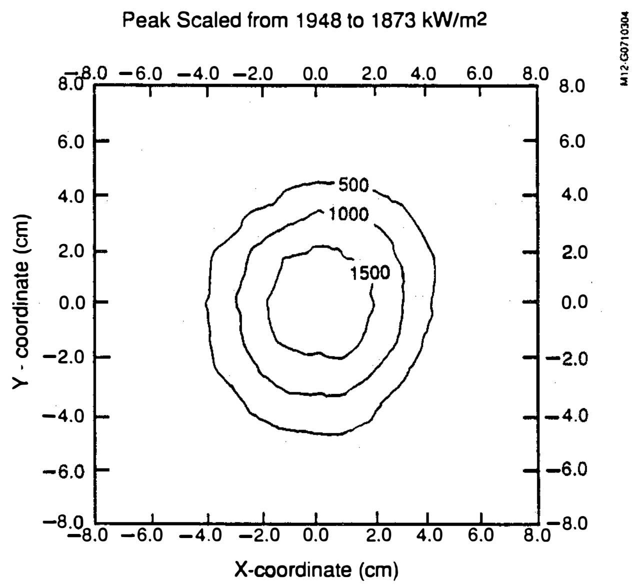


Figure 4. Contour map of flux levels predicted by SOLFUR for 23 dish facets with target plane located -8 cm from focal plane

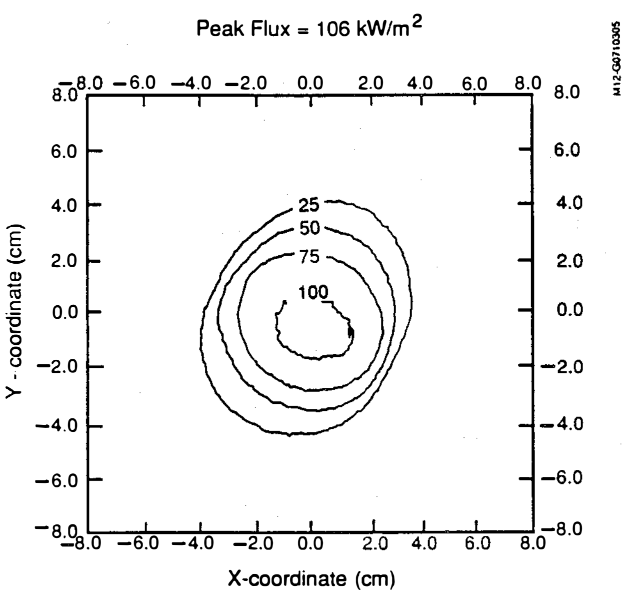


Figure 5. Contour map of measured flux levels for single (central) dish facet with target plane located at focal plane

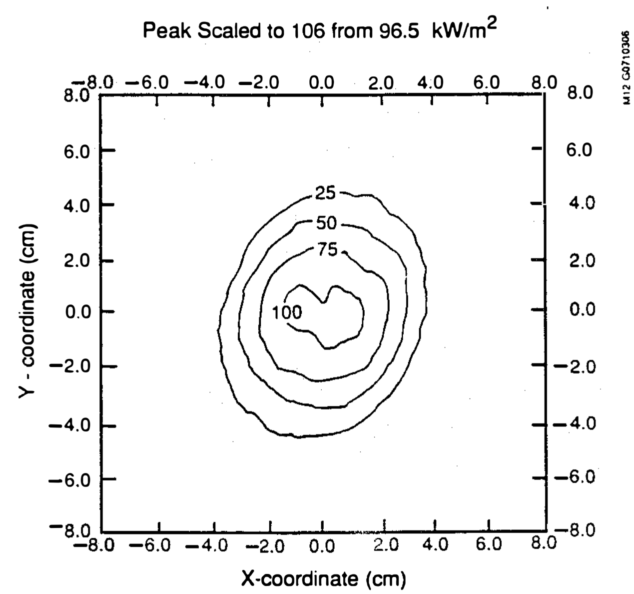


Figure 6. Contour map of flux levels predicted by SOLFUR for single (central) dish facet with target plane located at focal plane

Concordance between measured peak flux values and those predicted by the model has been obtained within the uncertainty associated with the measurement/calibration process. Comparison of contour maps of measured vs. computed flux levels demonstrates the validity of NREL's optical ray-trace codes for both the single-dish element case and the multifacet case. Strong evidence for the accuracy of the predicted angular distribution of rays at the focal plane has also been shown by comparing measured vs. predicted results for target planes offset on either side of the focal plane.

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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.

BEAMCODE 6.0 Rev. 19, (1990). Big Sky Software Corp., Bozeman, Montana.

Bingham, C., and A. Lewandowski, (1991). "Data acquisition and control of NREL's high flux solar furnace." American Society of Mechanical Engineers, paper to be presented in Reno, Nevada.

Lewandowski, A., (1989). "The design of an ultra-high flux solar test capability." *Proceedings 24th IECEC Meeting*, Washington, D.C.

Lewandowski, A., C. Bingham, J. O'Gallagher, R. Winston, and D. Sagie, (1990). "Performance characterization of the SERI high flux solar furnace." Presented at the International Energy Agency 5th Symposium on Solar High-Temperature Technologies, Davos, Switzerland.

Spencer, G. H., and M. V. R. K. Murty, (1962). *J. Opt. Soc. Am., 52*, 672-678.

SURFER Version 4 Reference Manual, (1989). Golden Software, Inc., Golden, Colorado.