A PARAMETER STUDY FOR A CENTRAL-RECEIVER POWER STATION*

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ABSTRACT

The interactions between alignment and focusing strategies and heliostat errors are described and illustrated. Some descriptions of astigmatic aberrations are developed and are used to suggest an evaluation criterion for concentrators. Finally, an analysis of measurements for evaluating heliostat reflectors is given.

Introduction

We present some results of parameter studies conducted during the early construction and planning phase of the Solar Thermal Test Facility in Albuquerque, New Mexico. Three different areas of activity are addressed: the interaction between facet alignment and focus strategies and alignment errors, astigmatic aberrations and heliostat size, and the analysis of measurements for evaluating heliostat reflectors (facets). The simulation code HELIOS is used in conjunction with these activities.

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Alignment and Focus Strategy Versus Alignment Errors

This study applies to the 78 heliostats of zone A in the concentrator field. Each heliostat, containing 25 1.22 by 1.22 m glass reflectors, utilizes a two-axis tracking mechanism for keeping the solar image correctly located on the boiler as the sun position ("sun direction") changes. The reflectors (facets) are attached to the heliostat frame so that they can be prealigned (tilted) with respect to each other. Each glass plate, which has a 16-inch diameter plate attached to the center of its back surface, is supported by a ring 46 inches in diameter. A pull-down mechanism can deflect this plate up or down to provide some focusing capability for the facet.

The facet focus is optimized for the slant range from the heliostat to the receiver. The focal length is calculated analytically if a simple shape, such as spherical, is assumed for the facet. When a more complicated shape is assumed (such as that obtained from a stress analysis of the facet) the concept of focal length is not so simple. In this case, an optimization routine in HELIOS calculates the pull-down deflection that will maximize the power concentrated on the receiver aperture by the facet.

The strategy used to prealign the facets with respect to the reference axis of the heliostat can have a significant effect on the performance of the heliostat. The larger the heliostat, the more important this effect becomes. To specify a geometry under which prealignment of the facet is to be optimized, it is necessary to designate a sun direction. Since a date and time of day establishes the sun direction with respect to the heliostat field, an "align time" is supplied as input information. HELIOS then uses a model of the solar system to determine the sun direction corresponding to align time. First in the alignment strategy, the heliostat is aligned, by rotations about the tracking axes, until the central ray from the sun is reflected from the center of the reference facet to intersect the aim point on the receiver. Then the remaining facets are aligned until central rays from the sun reflected from their centers also intersects the alignment point. The align time may be specified independently for each heliostat if desired. The align time selected for the heliostats constitutes
an important part of the alignment strategy. The model provides information for exact alignment of the facets in accordance with the alignment strategy. In practice, however, the facet prealignments, which must be set by measurement techniques, entail some errors. These errors contribute to the error cone.

The facets are also prefocused for optimum performance in the align time geometry. The optimum focus is dependent primarily on the slant range to the reference facet, but the individual-facet slant range changes slightly as the heliostat alignment changes. This is a small effect, however, and optimizing the facet focuses in the align time geometry for the heliostat is sufficient.

Once the prefocus and prealignment information is calculated for a facet in accordance with the alignment strategy, it is stored and used in subsequent calculations. Input information to the code also includes the date and time of day ("run time") for determining the specific sun direction for the geometry to be simulated. The code can, of course, cycle over as many run times as desired.

In analyzing the effects of facet shapes (flat, spherical) and sizes on collection efficiency, one must consider the above calibration strategy and include the effect of the error cone (e.g., the distribution of errors in alignment, surface normals, sun tracking). We use program HELIOS to illustrate the interaction of facet shapes, alignment and focusing calibration strategy, and errors in the calculation of collection efficiencies. Let us consider the power reflected from the 78 heliostats of zone A of the concentrator field that strikes the 1- by 1-m aperture of the Martin Marietta 1-mW thermal bench-model receiver. The aperture faces northward, is centered at an altitude of 44.5 m, and is inclined downward 20° from the vertical. For this example, we assume a constant facet reflectivity (0.90) and calculate the fraction of the reflected power (collection efficiency) that strikes the aperture at 12:00 noon of March 21.

The total concentrator area is \((1.22)^2 \times 25 \times 78 = 2902\ m^2\), but the area projected normal to the central ray from the sun (projected area) is only 2786 \(m^2\) because of the alignment geometry. The power striking the receiver aperture is the product of the collection efficiency, the facet reflectivity, the projected area, and the solar insolation.
The sunshape (angular distribution of incoming sun rays), with a small amount of aureole broadening added, is taken from The Sun\(^1\), edited by G. P. Kuiper. Improved sunshape and aureole information will be available soon, but the present information is adequate for illustrative purposes.

Each row of Table 1 gives two collection efficiencies: one for an align time of 2:00 PM and the other for an align time equal to run time (12:00 noon). Three facet shapes are considered: flat, a facet shape calculated from stress analysis (SA), and supersmart (SS). The supersmart facet is one that would focus an incident collimated beam to a point at the facet-receiver slant range for any sun direction. This is, of course, an idealization because it would require a continuously changing surface shape. The SS facet alignments are determined by the align-time geometry. Results are included for each of these facet shapes with and without the use of an error cone. The error cone is taken to be radially symmetric and normally distributed with a standard deviation of \( \sigma = 2.83 \) milliradians. This is our present estimate of the distribution of errors for the initial operation of this facility. When improved error cone information becomes available, the calculations can, of course, be refined. The flat facets are not focused at all, whereas the supersmart facets are focused continuously. The SA facets are focused for optimum performance under the align-time geometry.

Note that the tabulated collection efficiencies range from 35 percent for flat facets with errors that have an align time 2 hours after the run time to 97 percent for the ideal case of supersmart facets with no errors. For the latter, the run time equals the align time. Of course, the collection efficiency of 97 percent is not attainable in practice for three reasons: It is not possible to focus the facets continuously, to correct the facet alignments continuously, or to eliminate all the errors. The table does provide guidance, however, as to where the greatest improvement payoff is. For example, in starting with flat-facet concentrators, it is more effective to change to a facet shape that provides approximate focusing (such as the SA facet) than it is to work directly on eliminating errors. Once an approximate focusing effect is obtained, the control of errors becomes much more important; however, there is little gain in improving upon the SA facets. Furthermore, the align time versus run time causes sufficient differences to require
careful study of calibration strategy. It is clear that the use of smaller facets in any attempt to simplify focusing will still suffer from rather large facet alignment aberrations.

Table 1. Percent of Reflected Power in Aperture for Run Time = 12:00 Noon

<table>
<thead>
<tr>
<th>Facet Shape</th>
<th>Errors Used?</th>
<th>Align Time = 2:00 PM</th>
<th>Align Time = 12:00 Noon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>Yes</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>Flat</td>
<td>No</td>
<td>41</td>
<td>46</td>
</tr>
<tr>
<td>SA</td>
<td>Yes</td>
<td>57</td>
<td>66</td>
</tr>
<tr>
<td>SA</td>
<td>No</td>
<td>75</td>
<td>92</td>
</tr>
<tr>
<td>SS</td>
<td>Yes</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>SS</td>
<td>No</td>
<td>79</td>
<td>97</td>
</tr>
</tbody>
</table>

SA = Stress Analysis
SS = Supersmart

Although these results apply to a specific solar concentrator and receiver aperture and are based on preliminary sunshape and error-cone information, it is clear that interactions between heliostat design, errors, and the focusing and alignment strategy for any central-receiver solar collector will be important. Also, we have illustrated a small sample of the questions a solar collector design engineer must address. The decrease in efficiency that occurs when the align time differs from the run time is caused by astigmatic aberrations. This effect, shown averaged over the zone A field of 78 heliostats, is an interesting one and is important enough that we devote the next section to a more detailed examination of it.

**Heliostat Astigmatic Aberrations**

The individual facets of each heliostat are aligned with respect to the heliostat axis to optimize their performance under the align-time geometry. As the sun direction changes, the tracking mechanism keeps the central
reflected ray from the center of the reference facet correctly aligned on
the aim point. The central reflected rays from the other facets do not
continue to intercept the aim point but, rather, spread out about it to smear out
the image of the sun on the receiver aperture. In this section, we examine
the extent of this effect.

When we apply Eq. (22) of Shealy and Burkhard\textsuperscript{2} to a paraboloidal reflector
of focal length, \( f \), the intensity of reflected light at a distance \( r \) from
the reflector on a surface normal to the reflected central ray is

\[
F = \frac{\rho \sigma}{\left| \left( \frac{r}{f} - \cos \mu \right) \left( \frac{r}{f} - \sec \mu \right) \right|}
\]  

(1)

Here, \( \rho \) is the intensity of the incident collimated beam, \( \sigma \) is the reflectivity
of surface, and \( \mu \) is the angle of incidence. The zeros in the denominator of
Eq. (1) correspond to the primary focus at

\[
r = f \cos \mu
\]  

(2a)

and the secondary focus at

\[
r = f / \cos \mu
\]  

(2b)

Figure 1 shows the bundle of reflected rays when the reflector is
illuminated with a collimated beam of light at a nonzero angle of incidence.
The plane of incidence is defined by a ray incident on the center of the
mirror and the surface normal at the same point. The rays in the plane
of incidence intersect at the primary focus, whereas the rays in a plane
perpendicular to the plane of incidence but containing the central surface
normal to the mirror intersect at the secondary focus. The reflected bundle
of rays intersect in two line focuses as shown in the figure. The primary
focal line is perpendicular to the plane of incidence, whereas the secondary
focal line is in the plane of incidence. As the angle of incidence, \( \mu \),
decreases, the focal lines approach each other and become shorter until at
\( \mu = 0 \) a single focal point at 0 (see Fig. 1) is obtained a distance \( f \) from
the mirror.
Fig. 1. A reflected bundle of rays from a paraboloidal mirror illuminated by a collimated beam of light at a nonzero angle of incidence.

Whenever the align-time geometry of a heliostat corresponds to a zero angle of incidence, the facets are aligned so that the total heliostat approximates a paraboloidal surface. (The facet centers are tangent to such a surface.) When rotated to a nonzero angle of incidence, the focus behavior is similar to that shown in Fig. 1 except that the focal lines now have widths equal to the sun's image size at the corresponding distances.

Figure 2 shows two views of a bundle of rays reflected from a facet of dimension, W. The top portion of the figure shows the primary focus of rays in the plane of incidence. The bottom view shows the secondary focus of rays in a plane orthogonal to the plane of incidence; here the incident and reflected rays are in different planes.
Fig. 2. Primary- and secondary-foci-for a paraboloidal mirror. The top view shows the primary form of rays in the plane of incidence. The bottom view shows the secondary focus of rays in a plane orthogonal to the plane of incidence; here the incident and reflected rays are in different planes.

When a facet is focused for an align-time geometry corresponding to a nonzero angle of incidence ($\mu \neq 0$), the slant range $D$ should be such that $h_1 = h_2$. (Figure 2 defines $h_1$ and $h_2$.) From the geometry of the top diagram

$$\frac{h_1}{D - f \cos \mu} = \frac{W \cos \mu}{f \cos \mu} = \frac{W}{f} \quad ,$$

(3a)
or
\[ h_1 = \frac{W}{f} (D - f \cos \mu) \quad (3b) \]

From the geometry of the bottom diagram
\[ \frac{h_2}{f \sec \mu - D} = \frac{W}{f \sec \mu} \quad (4a) \]

from which
\[ h_2 = \frac{W}{f} (f - \cos \mu) \quad (4b) \]

Requiring that \( h_1 = h_2 = h \) gives
\[ f = D \quad (5) \]

and in this case
\[ h = W (1 - \cos \mu) = 2 W \sin^2 \left( \frac{\mu}{2} \right) \quad (6) \]

It is interesting to note that the ratio \( h/W \) does not depend on the slant range \( D \) from the reflector to the aperture of the receiver. This has important consequences.

Suppose that the heliostat facets are aligned with an align-time geometry corresponding to \( \mu = 0 \), but used at \( \mu \neq 0 \). We apply Eq. 6 to the whole heliostat with \( W \) equal to the heliostat dimension. If the angle subtended by the solar disk is \( \beta \), then the diameter of the "ideal" solar image at the slant range \( D \) is \( \beta D \). The envelope of the solar image with astigmatic aberrations has a diameter of approximately
\[ S = 2 W \sin^2 \left( \frac{\mu}{2} \right) + \beta D \quad (7) \]

Note that if the receiver aperture is sized by applying Eq. (7) to the heliostat of greatest slant range, then heliostats at a smaller slant range could have a larger size \( W \) and still concentrate their reflected power on the receiver. This suggests the following criterion for use in evaluating a heliostat field: Apply Eq. (7) to the heliostat at the greatest slant range and use the resulting \( S \) to define the diameter of an imaginary spherical
receiver. The fraction of the solar energy reflected from the concentrator field that intercepts this sphere is a parameter that quantifies the efficiency of the concentrator field.

The envelope of solid angles $S/D$ is

$$S/D = \frac{2W \sin^2 \left( \frac{\mu}{2} \right)}{D} + \beta$$  \hspace{1cm} (8)

If an acceptance criterion used is one which requires that each heliostat concentrates a given fraction of the sun's energy into a specified cone, then Eq. (8) requires the use of smaller heliostats at shorter slant ranges. Although this kind of criterion may be useful for specifying the reflected beam quality of an individual heliostat, it is of questionable value when applied to a field of heliostats. A higher quality heliostat is needed in the back of the field than is needed at short slant ranges.

In zone A of the heliostat field, heliostat 38, with a slant range of 119.8 m, was found to have the same angle of incidence (0.5699 radian) at 2 PM as does heliostat 141 (slant range of 221.5 m) at 0.4375 hour after noon on December 21. HELIOS was used on these two heliostats to verify Eq. (6). This result has also been experimentally verified by Igel and Hughes using a laboratory optical model of a heliostat.

The example discussed above assumed an align-time geometry with an incident angle of $\mu = 0$ for convenience. However, for some operating conditions it is better to use an align-time geometry corresponding to a nonzero $\mu$. A detailed development for prealignment in such a geometry is given in Reference 3.
Facet Shape Measurements

Before the installation of facets on the heliostats of zone A, a simple measurement technique was used to determine facet quality. Several questions required attention. What is the effect of fabricating facets and mounting them on the heliostat in one location and then transporting them several miles to the concentrator field? Do the daily variations in temperature degrade the facet optical performance? How do facet focal properties change as the heliostat angle of elevation changes? Is a simple test adequate to answer such questions as these? In this section, we describe one such test and show an example of its use.

A bar gage was used to measure the displacement of the front of the facet surface with respect to the plane defined by the facet ring support. The bar was supported at two points directly over the ring support, and feeler gages at several points along the bar measured the distance to the surface. The bar was placed successively along the diagonal directions of the square facet as well as in directions that bisect the centers of the facet edges. One gage, located on the center of the bar, would measure the same displacement in all four of the bar orientations if the ring support were truly planar and if there were no variations in glass thickness. Since neither of these conditions is satisfied exactly, the center gage does not read the same when the bar gage is moved from one position to another. Therefore, the measurements are translated to a common value for the center reading for all four bar orientations.

Figure 3 shows a graph of the data from the four bar positions. The abscissa, X, is the radial distance from the center of the facet in inches, and the ordinate, Y, is the surface displacement in mils ($10^{-3}$ inches). The dotted lines connect readings when the bar is placed perpendicular to the facet edges, and the dashed lines connect the data points for the diagonal positions. When the bar is in a diagonal position, measurements are made at $X = 32$ inches; however, this falls beyond the edge of the facet for the other two bar positions. The solid curve of Fig. 3 is a parabola of focal length 117 m, obtained by curve-fitting the data.
Fig. 3. Bar-gage measurements, $Y$ (mils), versus radial distance, $X$ (inches). The dashed lines connect data taken along the facet diagonals. The dotted lines connect data taken in directions perpendicular to the centers of the facet edges. The solid curve is a parabola of focal length 117 m.

An approximation was used to describe the extent to which the facet varies from the fitted paraboloidal shape. The slopes of the line segments connecting adjacent pairs of measurements were compared with the radial slope of the paraboloidal surface at radii corresponding to the midpoints of the line segments. These comparisons were used to generate statistics for surface slope errors about the fitted paraboloidal surface. Assuming normally distributed slope errors, this example gave a standard deviation of $\sigma = 0.33$ milliradian.
The simulation code HELIOS was used to determine the fraction of the sun's energy that this facet, when used at a slant range equal to its calculated focal length, would concentrate into a 12-milliradian cone. When the sunshape mentioned in the first section of this paper was used at an angle of incidence of \( \mu = 12^\circ \), an efficiency of 97 percent was obtained. There is no particular significance to this value of \( \mu \). The heliostat in zone A that had a slant range closest to 117.5 m was selected. The central facet for this heliostat had an angle of incidence of \( \mu = 12^\circ \) for a run time of noon on March 21. This was convenient because it corresponded to input data already in the code from previous calculations.

It is interesting to examine the above efficiency (fraction of the sun's power concentrated in a 12-mrad core) as a function of the standard deviation of error. Figure 4 shows this function by the solid curve, which was obtained by running HELIOS at several values of the standard deviation \( \sigma \) for a circular normal distribution of slope errors. The rest of the input information is the same as that described above.

![Figure 4](image-url)
In some cases, the facet focal lengths resulting from the curve fitting differs from the focal length intended for the facet. This difference can arise because of errors in calibrating the facet for optimum focal length or because of changes that occur in the facet between focal length calibration and the bar-gage measurements. A typical error in focal length for facets analyzed so far is 20 percent. Figure 4 shows (by the dashed curve) the percent of the sun's energy concentrated into a 12-milliradian cone from a facet at a slant range of 117.5 m but with a focal length of 94 m, which is equal to 80 percent of the slant range.

Most of the facets analyzed to date had slope errors with $\sigma$ in the interval $0.25 \leq \sigma \leq 0.5$ mrad. Slope errors in this interval correspond to reflected beam efficiencies greater than 90 percent, as shown in Fig. 4, for facets with focal lengths within 20 percent of the slant range of 117.5 m. Although for facets focused for use at shorter slant ranges (slant range = 66.2 m) the average slope errors were approximately the same, many of them would not concentrate 90 percent of the energy from the nominal sun's disk into a 12-milliradian cone when used at a slant range equal to their focal length. The reason for this is the increasing importance of the first term on the right of Eq. (8), as discussed in the previous section.

**Summary**

We defined a strategy for prealigning the facets of a heliostat and examined the interaction between the alignment strategy, the focusing of the facets, and the alignment and surface errors. Alignment strategy was shown to have an important effect on the performance of a central receiver power station. The alignment leads to heliostat astigmatic aberration, an important source of beam spreading. This aberration was identified and analyzed. This led to a suggested criterion for evaluating a heliostat field. Finally, the results of some facet quality measurements were described. The data were analyzed and used in conjunction with HELIOS calculations to determine a beam quality parameter. This parameter consisted of the fraction of the reflected sun's energy that is concentrated into a 12-milliradian cone at the slant range appropriate for the facet.
References

