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Redirector Design Methodology for Horizontal Target Plane Applications at the Central Receiver Test Facility

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REDIRECTOR DESIGN METHODOLOGY FOR HORIZONTAL TARGET PLANE APPLICATIONS AT THE CENTRAL RECEIVER TEST FACILITY

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ABSTRACT

The equations necessary for designing a multifaceted redirector that directs energy from a heliostat onto a secondary, sometimes horizontal, target have been derived. Although the equations are quite general, the approach has been formulated with specific applications of the Central Receiver Test Facility (CRTF) and the Sandia Solar Furnace in mind. A computer code, ORC, has been developed that applies the derived set of equations to the CRTF heliostat field. The output of ORC is a preliminary design for the redirector. This output is subsequently used as an input to the CRTF facility code, HELIOS, to obtain a complete flux density distribution on both the redirector and receiver surfaces. Upon examination of these results, the redirector design can be modified and the above procedures repeated until a satisfactory design is obtained. The proposed design methodology is illustrated with a preliminary design example. The new capabilities that a redirector can provide to the CRTF or the Solar Furnace represent a powerful new resource for activities and experiments where radiation direction is an important variable.

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Nomenclature

i, j, k - unit vectors along X, Y, and Z axes

$\hat{I}, \hat{N}, \hat{R}$ - incident, normal and reflected rays, unit vectors

L_1, L_2 - heliostat dimensions, Figure 2

$\hat{N}_1$ - normal vector for a redirector facet

$\hat{R}_1, \hat{R}_2$ - incident and reflected rays from the redirector, unit vectors

$\vec{S}$ - vector describing the redirector plane

X, Y, Z - spatial coordinates in the tower coordinate system

X_0, Y_0, Z_0 - heliostat foundation position

X_A, Y_A, Z_A - aim point coordinates for heliostat

X_F, Y_F, Z_F - position coordinates of target center

X_H, Y_H, Z_H - pierce point of reflected ray from the heliostat with redirector plane, Figure 5

X_J, Y_J, Z_J - a generic point in a facet plane of the redirector

X_P, Y_P, Z_P - midpoint position of center facet on heliostat

X_S, Y_S, Z_S - theoretical focal point of solar furnace

ΔZ - distance from target center to redirector center, Figure 5

ρ_S - elevation angle of sun

ϕ_S - azimuth angle of sun

ρ_t - elevation angle of reflected ray from heliostat

ϕ_t - azimuth angle of reflected ray from heliostat

ψ - angle between redirector plane and horizontal, $0 \leqslant \psi \leqslant 90°$

X', Y', Z' - spatial coordinates in the redirector coordinate system

REDIRECTOR DESIGN METHODOLOGY FOR HORIZONTAL TARGET PLANE APPLICATIONS AT THE CENTRAL RECEIVER TEST FACILITY

Introduction and Purpose

The Central Receiver Test Facility (CRTF), operated for the Department of Energy by Sandia National Laboratories in Albuquerque, New Mexico, was constructed for the purpose of evaluating solar central receiver design concepts. The facility consists of an array of 222 heliostats in a north field configuration that reflects and focuses the sun's energy toward a tower 60 m high (Figure 1). A complete description of the facility is available in the CRTF Experiment Manual.[1]

The central receiver concept for power generation has been demonstrated with the completion of Solar One[2,3] in Barstow, California. The CRTF, however, will continue to support technology development such as the testing of advanced thermal storage concepts. In addition, the CRTF is available as a testing facility for other programs requiring a high heat flux source.

The CRTF provides three features that are important in high-temperature, high flux-density experiments. The energy source is clean, easily controlled, and inexpensive. For these reasons it is desirable to enhance the capabilities of the facility to accept experiments that are not restricted to the use of an upward-directed beam.

In its present configuration, the CRTF is designed specifically for receivers that can accept a cone of energy traveling in an upward direction. A central ray of this cone makes an angle of approximately 30° with the horizontal if the field is aimed at the top of the tower; however, a number of experiments are best performed with a beam whose central ray is directed vertically downward. Examples of operations requiring a horizontal surface plane include metals reduction, refining, and fluid bed reactors. Actually, any process for which it is desirable to vent gaseous

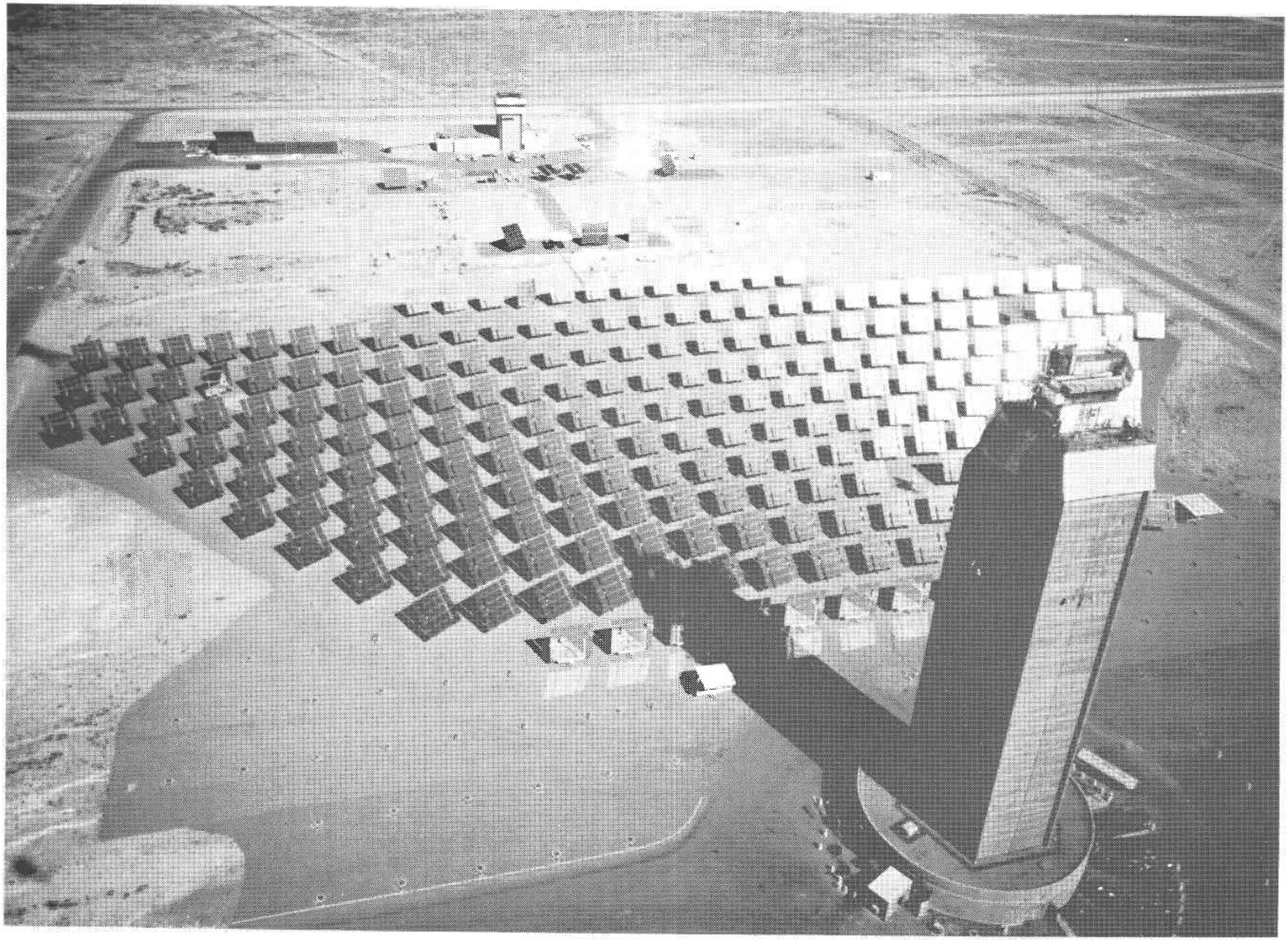

Figure 1. Aerial View of CRTF

products upward while gravity retains other material at the bottom of a vessel should be exposed to a vertically downward-directed beam.

Our objective is to design an apparatus, referred to as the redirector, that will redirect the energy from the heliostat field toward a horizontal test plane. Although we will treat a horizontal target in the analysis and discussion, there is no reason that a target of any other orientation cannot be used. (In the instance of a target of different orientation, minor modification to the code would be required.) A two-phase design procedure will be used. In the first phase, only the central ray from each heliostat will be used to obtain a preliminary redirector design. Initially, this design will take the form of an array of flat facets, each of whose central-most coordinates lie in a single plane. Each facet is oriented so that the array of facets approximates the ideal redirecting surface for the prescribed geometric condition. This information will then be used in the heliostat computer model HELIOS[4,5,6] to determine accurately the flux-density profiles at the reconcentrator and the test plane. If the results are acceptable, the design is complete. If the results are not acceptable, the procedure is repeated, which would constitute the beginning of the second design phase. Refining would continue until an acceptable design is obtained.

This report describes the methodology for the iteration procedure. The resulting equations are programmed into a computer routine, which for the CRTF heliostat field and a given set of input information, calculates the design information necessary for specifying a redirector design. A numerical example is presented representing a preliminary design for a CRTF "zone A," 10-facet redirector. The resulting flux profile on a horizontal target is calculated and graphically presented. The computer code, labeled ORC, is listed in Appendix A.

Mathematical Analysis

This section describes the orientation and geometric shape of a redirector placed at a predetermined position on the CRTF tower. A preliminary design of the redirector will be made by considering only the central ray from the sun and tracing the path of the ray as it intersects the central facet of each heliostat, the redirector, and the target plane. Clearly, the number of variables in this problem must be reduced to make the necessary calculations. The choice of a redirector plane containing the midpoints of an array of facets, each oriented to approximate a pure hypersurface, has been derived from practical engineering concepts. The number, size, and shape of these facets remain design variables. The basic relations of geometric optics will be used to determine for each central heliostat ray the intersection point with the plane of the redirector and the necessary corresponding normal for a facet located at that point on the redirector. The surface so defined will be used in HELIOS to determine the flux-density distribution on the redirector and the target plane. If the distribution is acceptable, this redirector design can be used; if not, the procedure can be repeated until an acceptable design is achieved.

This straightforward approach is attractive because it minimizes the computer time necessary for generating preliminary designs.

In the analysis, the tower coordinate system will be used, and the following parameters will be assumed to be known (Figure 2):

(X_0, Y_0, Z_0)	heliostat foundation position
ρ_S, ϕ_S	elevation, azimuth of the sun
ρ_t, ϕ_t	elevation, azimuth of reflected ray from heliostat
(X_F, Y_F, Z_F)	position of target center
(X_A, Y_A, Z_A)	aim point for heliostat
(X_P, Y_P, Z_P)	position of midpoint of center facet of heliostat
L_1, L_2	heliostat dimensions

The incident central ray from the sun with unit vector

$$\hat{I} = \cos\rho_s \cos\phi_s \,\hat{i} + \cos\rho_s \sin\phi_s \,\hat{j} + \sin\rho_s \,\hat{k} \quad (1)$$

will intersect the center of the central facet at (X_p, Y_p, Z_p) and will be reflected toward the aim point (X_A, Y_A, Z_A). The unit vectors describing the reflected ray and the normal to the heliostat are

$$\hat{R}_1 = \cos\rho_t \cos\phi_t \,\hat{i} + \cos\rho_t \sin\phi_t \,\hat{j} + \sin\rho_t \,\hat{k} \quad (2)$$

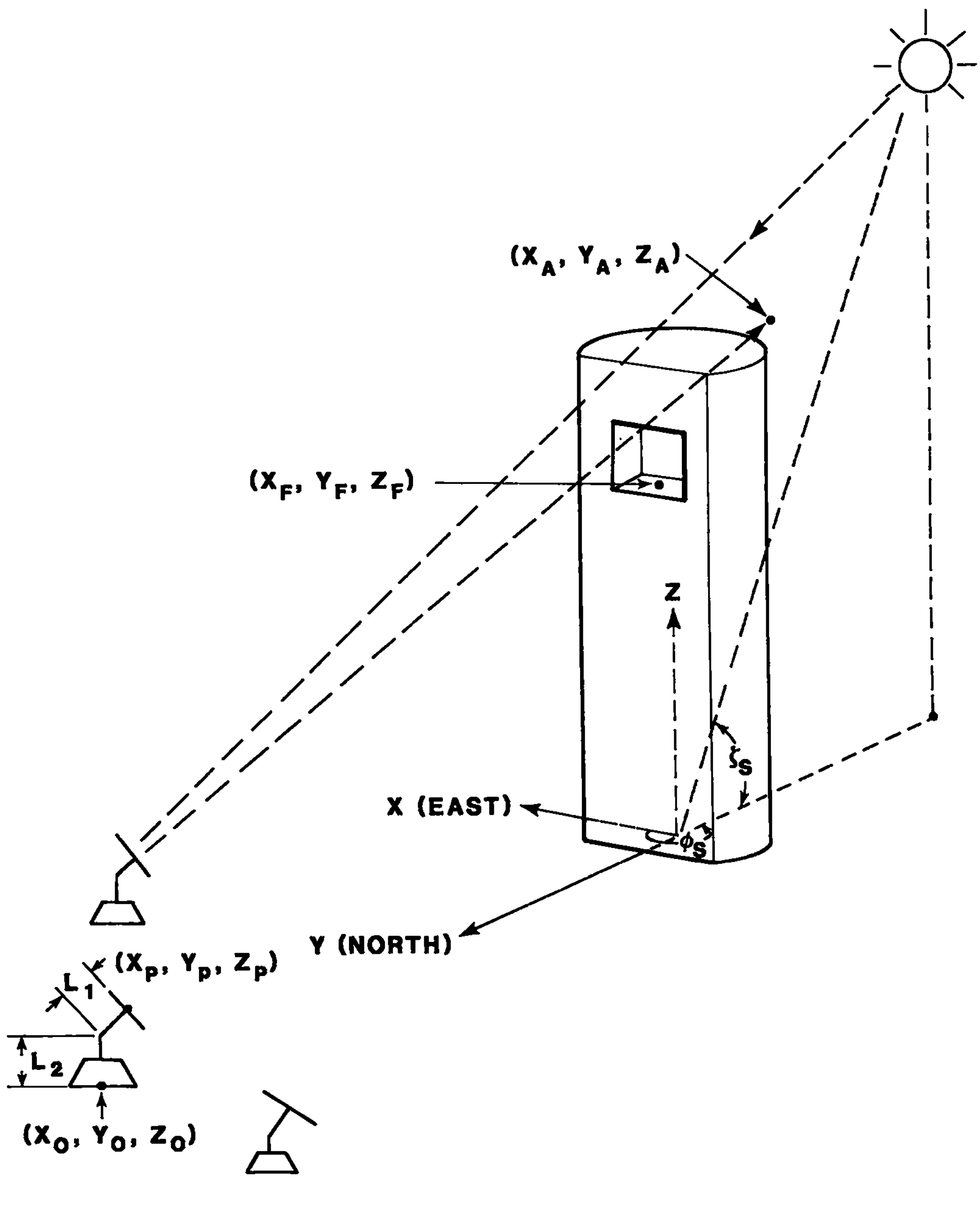

Figure 2. Coordinate System

and

$$\hat{N} = N_X \hat{i} + N_Y \hat{j} + N_Z \hat{k} \tag{3}$$

where

$$\cos \rho_t \cos \phi_t = \frac{X_A - X_P}{\ell}$$

$$\cos \rho_t \sin \phi_t = \frac{Y_A - Y_P}{\ell}$$

$$\sin \rho_t = \frac{Z_A - Z_P}{\ell}$$

$$0 \leqslant \rho_t \leqslant \frac{\pi}{2} \; ; \; \pi \leqslant \phi_t \leqslant 2\pi$$

$$\ell = [(X_A - X_P)^2 + (Y_A - Y_P)^2 + (Z_A - Z_P)^2]^{1/2}$$

$$N_X = \alpha \; (\cos \rho_S \cos \phi_S + \cos \rho_t \cos \phi_t)$$

$$N_Y = \alpha \; (\cos \rho_S \sin \phi_S + \cos \rho_t \sin \phi_t)$$

$$N_Z = \alpha \; (\sin \rho_S + \sin \rho_t)$$

and

$$\alpha^{-2} = 2 + 2 \; (\cos \rho_S \cos \phi_S \cos \rho_t \cos \phi_t + \cos \rho_S \sin \phi_S \cos \rho_t \sin \phi_t + \sin \rho_S \sin \rho_t)$$

To determine the point (X_P, Y_P, Z_P), the normal vector to the heliostat can also be written as

$$\hat{N} = \frac{(X_P - X_0)}{L_1} \hat{i} + \frac{(Y_P - Y_0)}{L_1} \hat{j} + \frac{(Z_P - Z_0 - L_2)}{L_1} \hat{k} \tag{4}$$

where L_1 and L_2 are defined in Figure 2. From Equations 3 and 4, we have

$$X_P = X_0 + \alpha L_1 (\cos \rho_S \cos \phi_S + \cos \rho_t \cos \phi_t) \tag{5}$$

$$Y_P = Y_0 + \alpha L_1 (\cos \rho_S \sin \phi_S + \cos \rho_t \sin \phi_t) \tag{6}$$

$$Z_P = Z_0 + L_2 + \alpha L_1 (\sin \rho_S + \sin \rho_t) \tag{7}$$

These seven equations can be used to solve for the three unknowns, X_P, Y_P, and Z_P. A trial and error procedure is used where X_P, Y_P, and Z_P are initially assumed to equal X_0, Y_0, and $Z_0 + L_2$. The solution converges after only a few iterations. With X_P, Y_P, and Z_P known, the sun ray can be traced to the redirector and to the target plane.

In the geometry presented in Figure 3, we consider the redirector plane to consist of the centers of each of the individual facets of the redirector (Figure 4). By determining the normal vector so that the ray is reflected to the point (X_F, Y_F, Z_F), the proper orientation of each facet is also determined. To determine the proper orientation of each facet, we use the basic relations of geometric optics: the incident ray, the reflected ray, and the normal to the surface are coplanar, while the angle of incidence must equal the angle of reflection. A procedure for determining the unit normal and the equations that describe the location in space of each redirector facet is given by Equations 2 through 19.

The unit vector $\hat{R}_1$ is given by Equation 2 while $\hat{R}_2$ can be written as

$$\hat{R}_2 = \frac{(X_F - X_H)\hat{i} + (Y_F - Y_H)\hat{j} + (Z_F - Z_H)\hat{k}}{[(X_F - X_H)^2 + (Y_F - Y_H)^2 + (Z_F - Z_H)^2]^{1/2}} \tag{8}$$

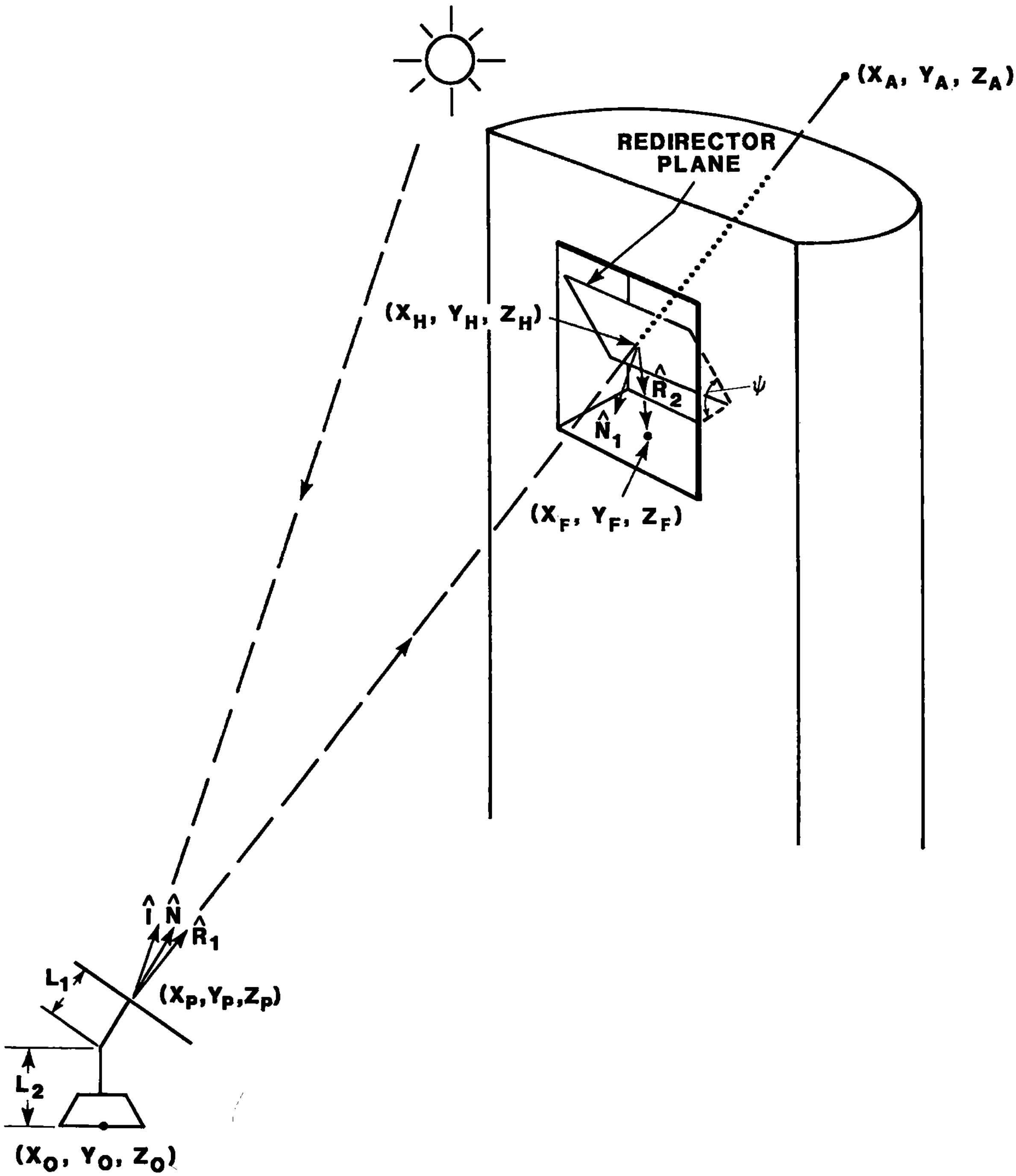

Figure 3. Geometric Description of Redirector Plane

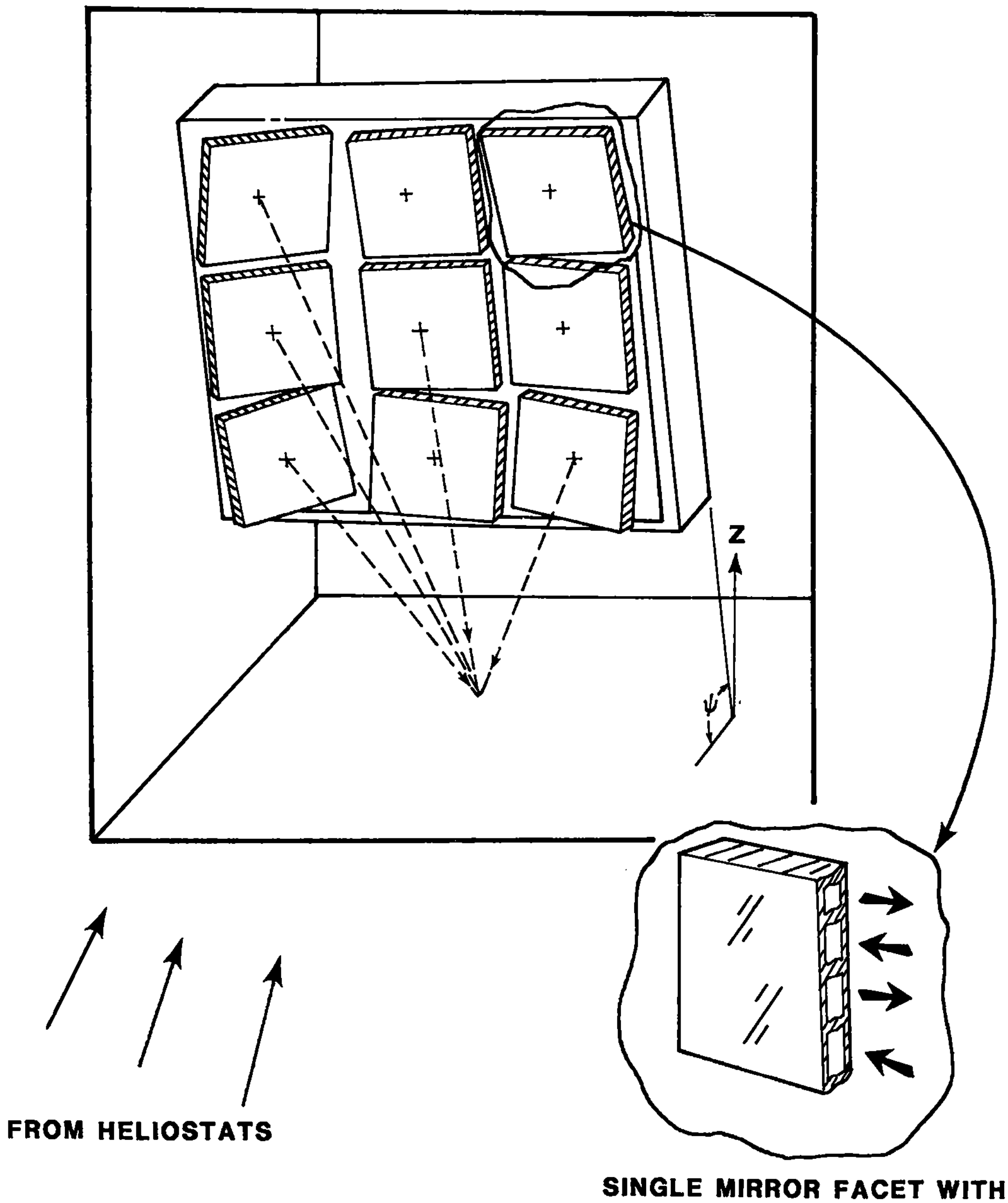

Figure 4. Faceted Redirector Configuration

A vector equation describing any point in the redirector plane is

$$\vec{S} = X\,\hat{i} + Y\,\hat{j} + [(Y - Y_F)\tan\psi + Z_F + \Delta Z]\,\hat{k} \tag{9}$$

where ψ is defined in Figures 3 and 4 and ΔZ is defined in Figure 5. Equation 9 will be used to determine the point where the reflected ray from the heliostat pierces the redirector plane. The parameter ΔZ is used to locate the plane of the redirector in space by locating the point in the redirector plane that is ΔZ units above the center of the target plane (X_F, Y_F, Z_F).

The problem is now reduced to finding the intersection of the incident ray $\hat{R}_1$ with the plane. The unit vector $\hat{R}_1$ has been given by Equation 2 and can also be written as

$$\hat{R}_1 = \frac{(X_H - X_P)}{P}\,\hat{i} + \frac{(Y_H - Y_P)}{P}\,\hat{j} + \frac{(Z_H - Z_P)}{P}\,\hat{k} \tag{10}$$

where

$$P^2 = (X_H - X_P)^2 + (Y_H - Y_P)^2 + (Z_H - Z_P)^2 \tag{11}$$

Comparing Equations 2, 9, and 10, we obtain the following set of equations for determining X_H, Y_H, and Z_H:

$$\frac{X_H - X_P}{P} = \cos\rho_t \cos\phi_t \tag{12}$$

$$\frac{Y_H - Y_P}{P} = \cos\rho_t \sin\phi_t \tag{13}$$

$$\frac{Z_H - Z_P}{P} = \sin\rho_t \tag{14}$$

and

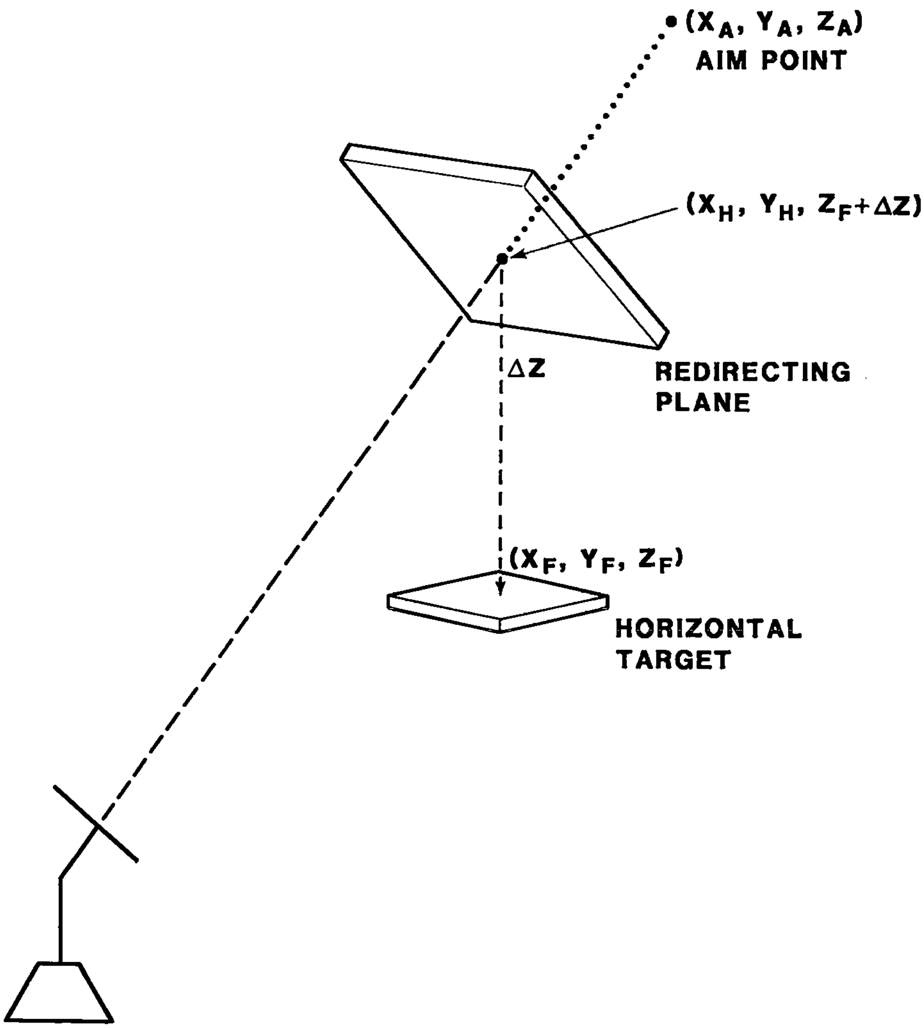

Figure 5. Redirector Plane Location by Means of Parameter ΔZ

$$Z_H = (Y_H - Y_F) \tan \psi + Z_F + \Delta Z \qquad (15)$$

Equations 12 through 14 can be refined to yield

$$Y_H = \frac{(Z_F + \Delta Z - Z_P) \sin \phi_t + Y_P \tan \rho_t - Y_F \tan \psi \sin \phi_t}{\tan \rho_t - \tan \psi \sin \phi_t} \qquad (16)$$

$$Z_H = (Y_H - Y_F) \tan \psi + Z_F + \Delta Z \qquad (17)$$

$$X_H = X_P + \frac{(Y_H - Y_P)}{\tan \phi_t} \qquad (18)$$

Equations 16, 17, and 18 describe the point on the redirector plane where the reflected ray from the central facet on the heliostat strikes the plane. Keeping in mind that this redirector plane consists of the center points X_H, Y_H, and Z_H for each redirector facet, we next determine the normal to the facet and finally an equation describing the facet surface in space. In this manner, the redirector geometry is defined, and this information is used in HELIOS to determine the flux-density distribution on the target plane.

The normal vector $\hat{N}_1$ describing the orientation of a particular redirector facet is obtained from Equations 8 and 10. In particular, it is given by

$$\hat{N}_1 = \frac{-\hat{R}_1 + \hat{R}_2}{[2 - 2\hat{R}_1 \cdot \hat{R}_2]^{1/2}} = N_{1X}\hat{i} + N_{1Y}\hat{j} + N_{1Z}\hat{k} \qquad (19a)$$

Also, the equation describing the facet surface is obtained by setting the inner (dot) product of the normal vector and any vector in the redirector facet plane to zero. The result is

$$N_{1X}(X_J - X_H) + N_{1Y}(Y_J - Y_H) + N_{1Z}(Z_J - Z_H) = 0 \qquad (19b)$$

Note that (X_J, Y_J, Z_J) is a generic point in the redirector facet surface. Equation 19b is a necessary input to HELIOS for calculating the reuslting flux profiles. At this point all the equations for determining the pierce point and facet surface have been determined for a single heliostat and a set of given input parameters. The procedure is repeated for each of the 222 heliostats in the field. For each heliostat, a pierce point in the redirector plane that locates a corresponding redirector facet location, the normal to this facet, and an equation describing this facet surface will be determined.

Once a preliminary redirector design is selected, a HELIOS run will be made to determine flux-density profiles on the redirector plane and the target plane. This information can be used to define cooling requirements for the redirector and to decide if the flux-density profile on the target plane is adequate. If necessary, the procedure can be repeated until the appropriate design is obtained.

A numerical example will be presented in a later section of this report to illustrate the procedure. The numerical example evaluates a 10-facet redirector located in the 140-ft (42.67-m) test bay of the CRTF tower when only zone A (78 closest heliostats) of the CRTF heliostat field is used.

Modification for Solar Furnace

The computer program written for the central tower and heliostat field can be modified to design a redirector for a solar furnace. Consider the geometry shown in Figure 6. The known quantities are the theoretical focal point (X_S, Y_S, Z_S), the center of the target plane (X_F, Y_F, Z_F), and the location of the center for each facet of the concentrator (X_C, Y_C, Z_C). By choosing the origin at the focal point, the unit vectors $\hat{R}_1$ and $\hat{R}_2$ become

$$\hat{R}_1 = \frac{-X_C \hat{i} - Y_C \hat{j} - Z_C \hat{k}}{[X_C^2 + Y_C^2 + Z_C^2]^{1/2}} \tag{20}$$

or

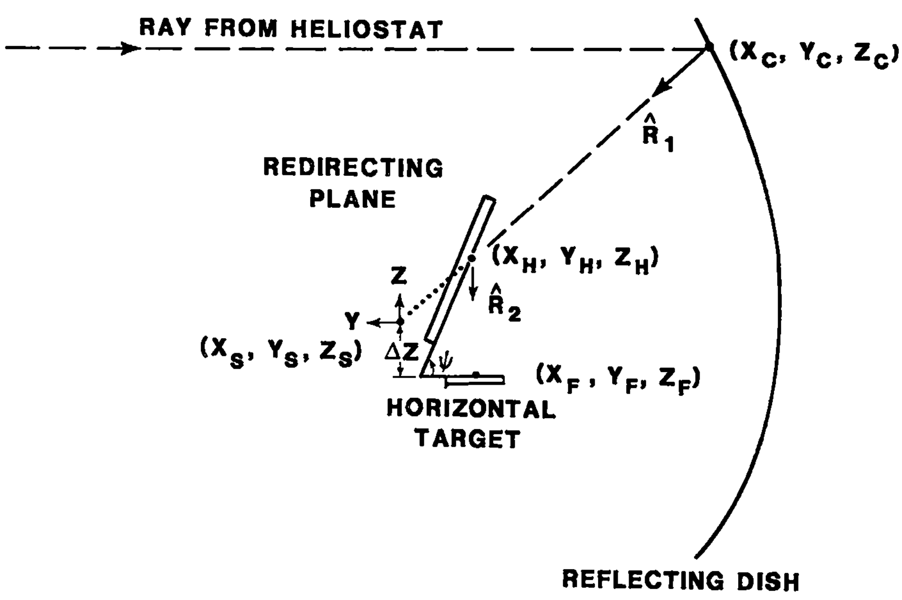

Figure 6. Solar Furnace Geometry

$$\hat{R}_1 = \frac{(X_H - X_C)}{L}\hat{i} + \frac{(Y_H - Y_C)}{L}\hat{j} + \frac{(Z_H - Z_C)}{L}\hat{k} \tag{21}$$

and

$$\hat{R}_2 = \frac{(X_F - X_H)}{\ell}\hat{i} + \frac{(Y_F - Y_H)}{\ell}\hat{j} + \frac{(Z_F - Z_H)}{\ell}\hat{k} \, . \tag{22}$$

In Equations 21 and 22, the parameters L and ℓ are

$$L = [(X_H - X_C)^2 + (Y_H - Y_C)^2 + (Z_H - Z_C)^2]^{1/2} \tag{23}$$

and

$$\ell = [(X_F - X_H)^2 + (Y_F - Y_H)^2 + (Z_F - Z_H)^2]^{1/2} \, . \tag{24}$$

In a manner similar to Equation 9, a convenient vector equation for the redirector plane is given by

$$\vec{S} = X\,\hat{i} + Y\,\hat{j} + [-Y \tan\psi - \Delta Z]\,\hat{k} \tag{25}$$

where the relation $Z = -Y \tan\psi - \Delta Z$ describes the location of this plane. The redirector plane, as before, consists of the center points of the individual facets. Comparing Equations 20, 21, and 25, we obtain the following set of equations for determining the intersection on the redirector plane (X_H, Y_H, Z_H):

$$Y_H = \frac{-Y_C\,(\Delta Z)}{Z_C + Y_C \tan\psi} \tag{26}$$

$$Z_H = -Y_H \tan\psi - \Delta Z \tag{27}$$

$$X_H = X_C + \frac{X_C}{Y_C}(Y_H - Y_C) \tag{28}$$

Once the intersection point has been determined, the reflected ray is known from Equations 22 and 24 and the unit normal from the facet surface is

$$\hat{N}_1 = \frac{-\hat{R}_1 + \hat{R}_2}{[2 - 2\,\hat{R}_1 \bullet \hat{R}_2]^{1/2}} = N_{1X}\,\hat{i} + N_{1Y}\,\hat{j} + N_{1Z}\,\hat{k} \tag{29}$$

Thus, with the unit normal known, an equation describing the surface of each facet can be obtained in a manner similar to that used for Equation 19b,

$$N_{1X}\,(X_J - X_H) + N_{1Y}\,(Y_J - Y_H) + N_{1Z}\,(Z_J - Z_H) = 0\ . \tag{30}$$

Numerical Examples

To illustrate the procedure discussed in the previous sections, specific examples will be discussed. We will first consider a ray reflected from one heliostat and determine its intersection point on the redirector to demonstrate the procedure and then present results using the 78 heliostats in zone A of the CRTF field.

Example 1

Consider the situation where the following parameters are given (all dimensions in meters):

a. aim point $(X_A, Y_A, Z_A) = (0, 0, 54.86)$
b. center of target plane $(X_F, Y_F, Z_F) = (0, 6.10, 48.77)$
c. $\Delta Z = +2.66$
d. $\phi = 45°$
e. time of day = solar noon
f. day of year = day 80
g. heliostat foundation, $(X_0, Y_0, Z_0) = (4.89, 107.30, 0.41)$
h. $L_1 = 0.32$, $L_2 = 3.99$

For this day and time, the solar azimuth and elevation angles are known to be $\phi_S = 270°$ and $\rho_S = 54.95°$ at the CRTF in Albuquerque, New Mexico. The unit vector describing the sun position is

$$\hat{I} = -0.5743\,\hat{j} + 0.8186\,\hat{k} \tag{31}$$

An iteration scheme is used to determine the center of the central facet for each heliostat, (X_P, Y_P, Z_P). We start by assuming $X_P = X_0$, $Y_P = Y_0$, and $Z_P = Z_0 + L_2$. The elevation and azimuth angles are then calculated (Equation 3),

$$\rho_t = \tan^{-1} \frac{Z_A - Z_P}{[(X_A - X_P)^2 + (Y_A - Y_P)^2]^{1/2}} \tag{32}$$

$$\phi_t = \tan^{-1} \frac{Y_A - Y_P}{X_A - X_P} \tag{33}$$

A new approximation for (X_P, Y_P, Z_P) is then obtained from Equations 5 through 7. For this case, the following values are obtained after a few iterations:

$$(X_P, Y_P, Z_P) = (4.88, 107.05, 4.61) \tag{34}$$

After the above point is calculated, Equations 2, 8, 9, 16, 17, 18, and 19 are used to determine the remaining parameters:

$$\hat{R}_1 = -0.0413\,\hat{i} - 0.9044\,\hat{j} + 0.4246\,\hat{k} \tag{35}$$

$$Y_H = 6.49 \text{ m} \tag{36}$$

$$Z_H = 51.82 \text{ m} \tag{37}$$

$$X_H = 0.3 \text{ m} \tag{38}$$

$$\hat{R}_2 = -0.0958\,\hat{i} - 0.1265\,\hat{j} - 0.9873\,\hat{k} \tag{39}$$

$$\hat{N}_1 = -0.0338\,\hat{i} + 0.4823\,\hat{j} - 0.8753\,\hat{k} \tag{40}$$

Also, from Equations 36 through 38 and Equation 40, the equation for any point in the redirector facet surface given by Equation 19b is

$$S_F = -0.0338\ (X - 0.3) + 0.4823\ (Y - 6.49) - 0.8753\ (Z - 51.82) = 0 \quad (41)$$

The above procedure is then repeated for each of the heliostats in the field.

Example 2

The next example considers the 78 heliostats in zone A with the following parameters used as input (all dimensions in meters):

a. aim point, $(X_A, Y_A, Z_A) = (0., 5.92, 46.08)$
b. center of target plane, $(X_F, Y_F, Z_F) = (0., 8., 42.67)$
c. $\Delta Z = 2.18$
d. $\psi = 55°$
e. time of day = solar noon
f. day of year = day 80
g. $L_1 = 0.32$, $L_2 = 3.99$

The first step is to determine the transformation from the tower (X,Y,Z) coordinate system to the redirector plane (X',Y',Z') coordinate system. The relationship between the two systems is given by (see Figure 7)

$$X' = -X \quad (42a)$$

$$Y' = Y \sin \psi - Z \cos \psi - (Y_{ref} \sin \psi - Z_{ref} \cos \psi) \quad (42b)$$

$$Z_R' = Y \cos \psi + Z \sin \psi - (Z_{ref} \sin \psi + Y_{ref} \cos \psi) \quad (42c)$$

(Note the (X',Y',Z') system is not a right-handed system; it is used for display of graphical results only.) The parameters Y_{ref} and Z_{ref} are then determined in the following manner: we choose heliostat 241 as our reference (see Figure 11). Input parameter ΔZ is used to define the geometric equation for the redirector plane (from the Z component of Equation 9),

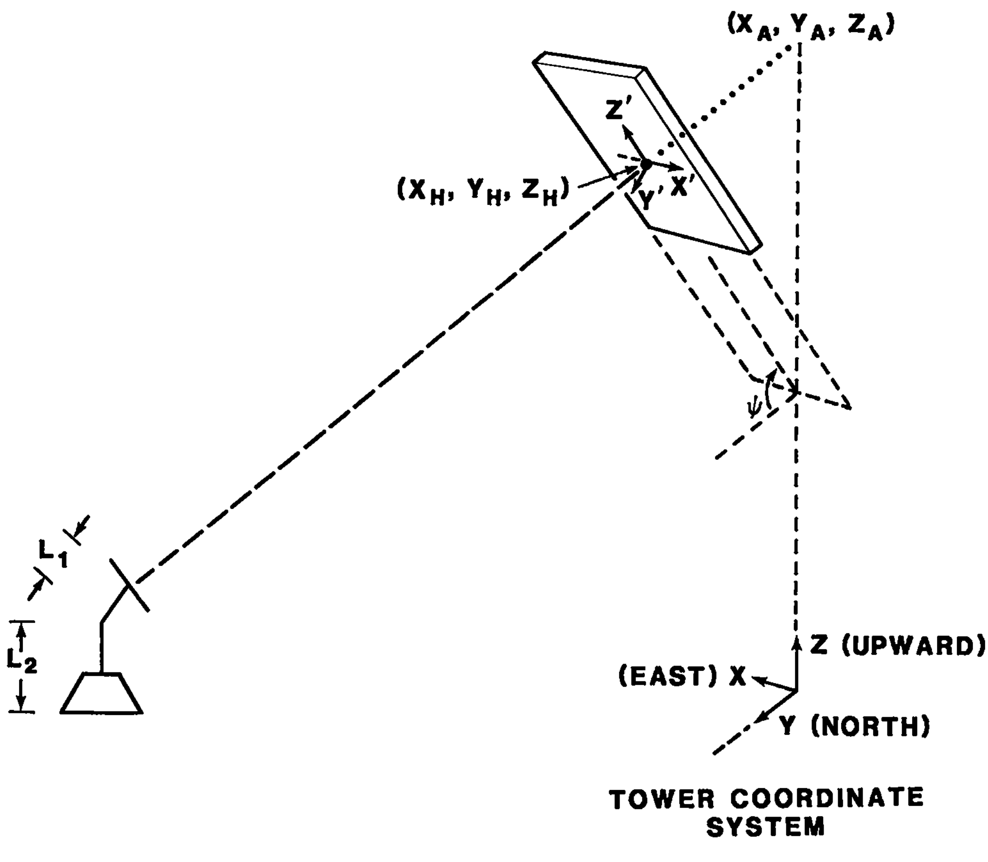

Figure 7. Redirector Plane Orientation and Location of (X',Y',Z') Coordinate System

$$Z = (Y - Y_F) \tan \phi + Z_F + \Delta Z$$

This equation is used to obtain the pierce point in the tower (X,Y,Z) coordinate system. In this example, $(X_H, Y_H, Z_H) = (0.15, 8.19, 44.84)$. We require that this point correspond to

$$(X'_H, Y'_H, Z'_H) = (-0.15, 0, 0)$$

in the redirector coordinate system. In this manner we determine Y_{ref} and Z_{ref}, from Equation 42 to be

$$Y_{ref} = 8.19$$

$$Z_{ref} = 44.84$$

The parameters of the problem were then used as input to ORC (see Appendix A for code listing, input and output of numerical example 2). The output was subsequently used as input to HELIOS (see Appendix B for updates required for HELIOS).

Figure 8 illustrates the flux-density profile as calculated by HELIOS at the redirector plane. This information could be used to calculate cooling requirements for the redirector facets. Figure 9 shows the pierce points on the redirector plane of the zone A heliostats with the 90% power contour as determined by the HELIOS code. Based on the results shown in Figures 8 and 9, we decided to use 10 facets, each 0.84 by 1.22 m, to redirect the "zone A" beam onto the horizontal target. The facet numbering sequence is shown in Figure 10.

Recall the central ray of the center facet of each heliostat will intersect the redirector plane to locate the center of the optimum redirector facet for that heliostat. Each intersection point has a corresponding normal vector. To determine the equation for each of the redirector-facet surfaces of Figure 10, we first computed an average normal vector for each facet, the results of which are shown in Table 1. Figure 11 shows the zone A heliostat configuration and the numbering system of Table 1.

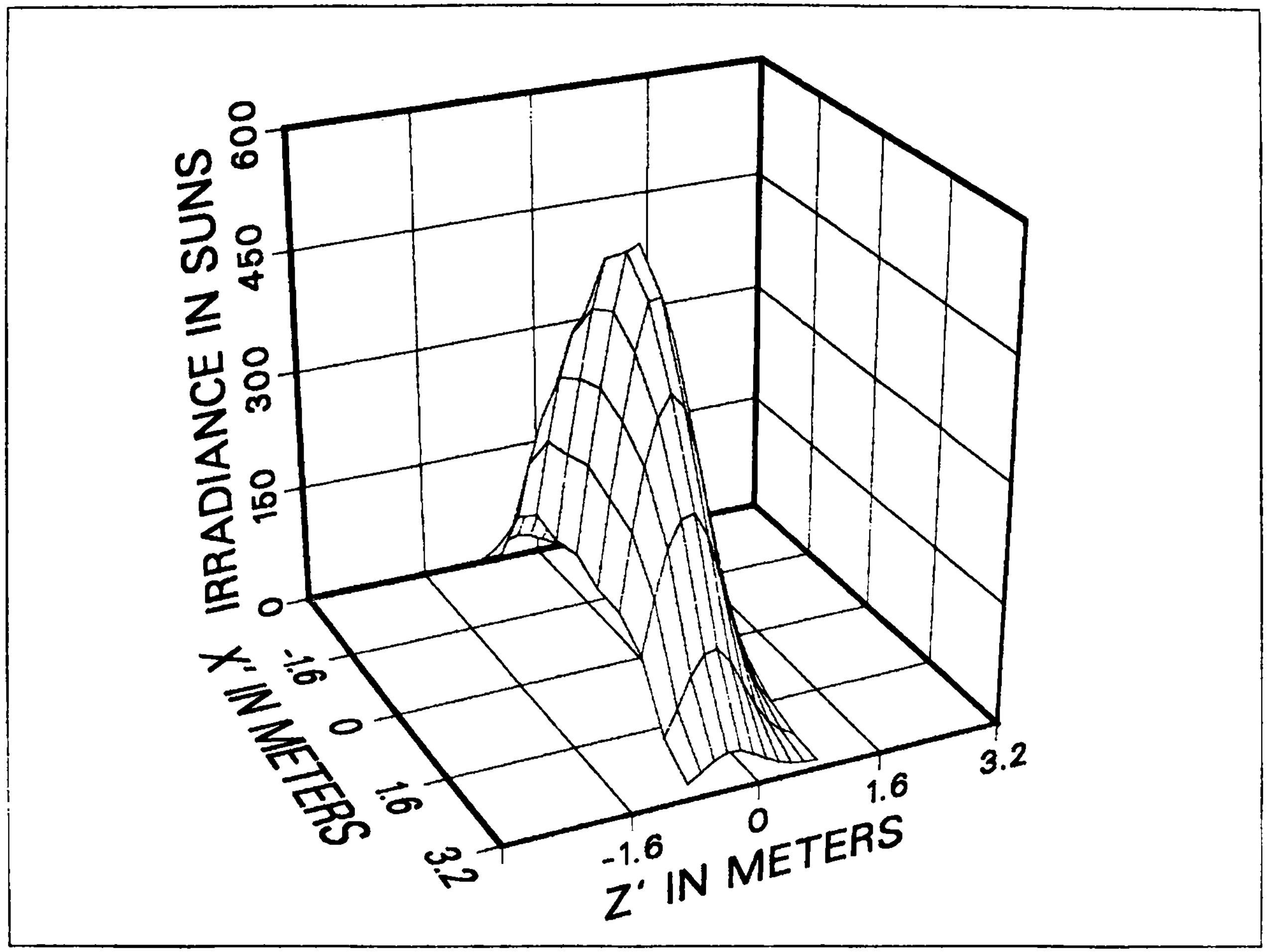

Figure 8. Flux-Density Profile on Redirector Plane of Numerical Example 2

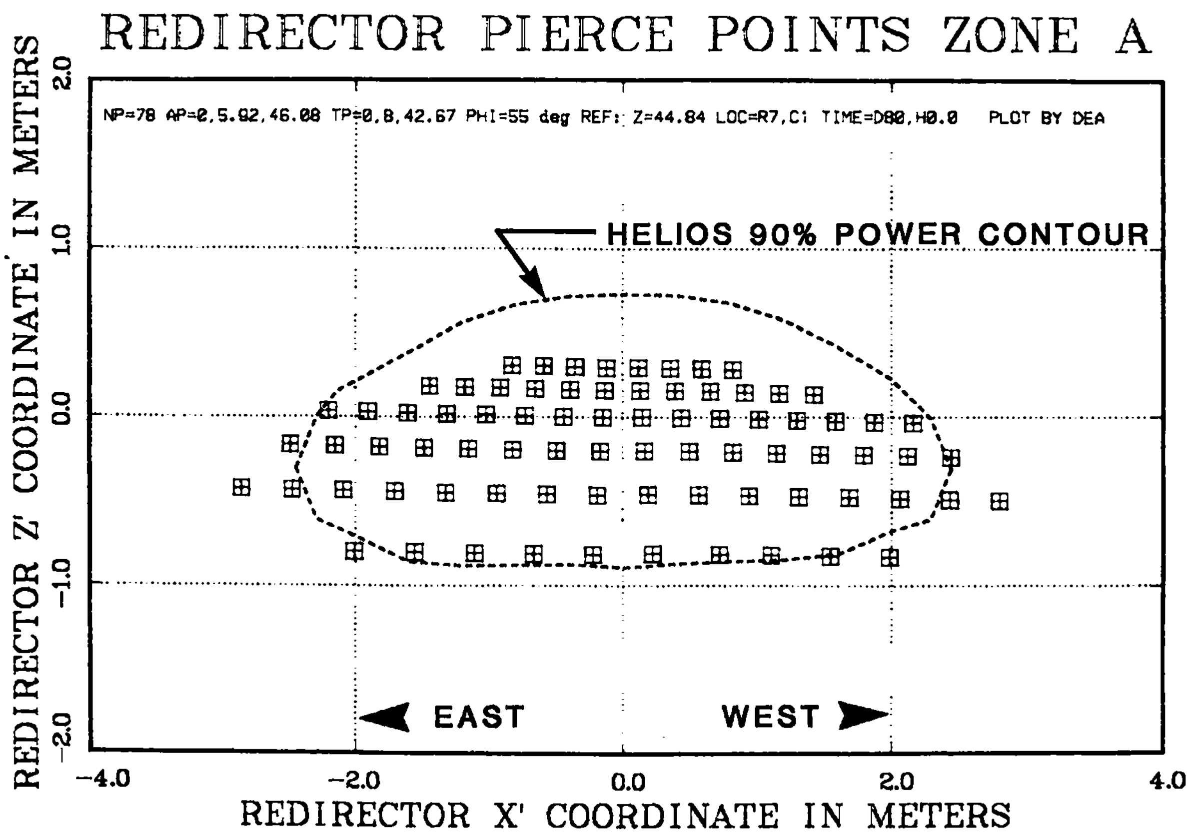

Figure 9. Pierce Points of Central Ray of Each of the 78 CRTF Zone A Heliostats on a Redirector Plane Tilted 35° from Vertical (in Redirector Coordinate System) for Numerical Example 2. The 90% contour of the flux density from zone A is superimposed with dashed line.

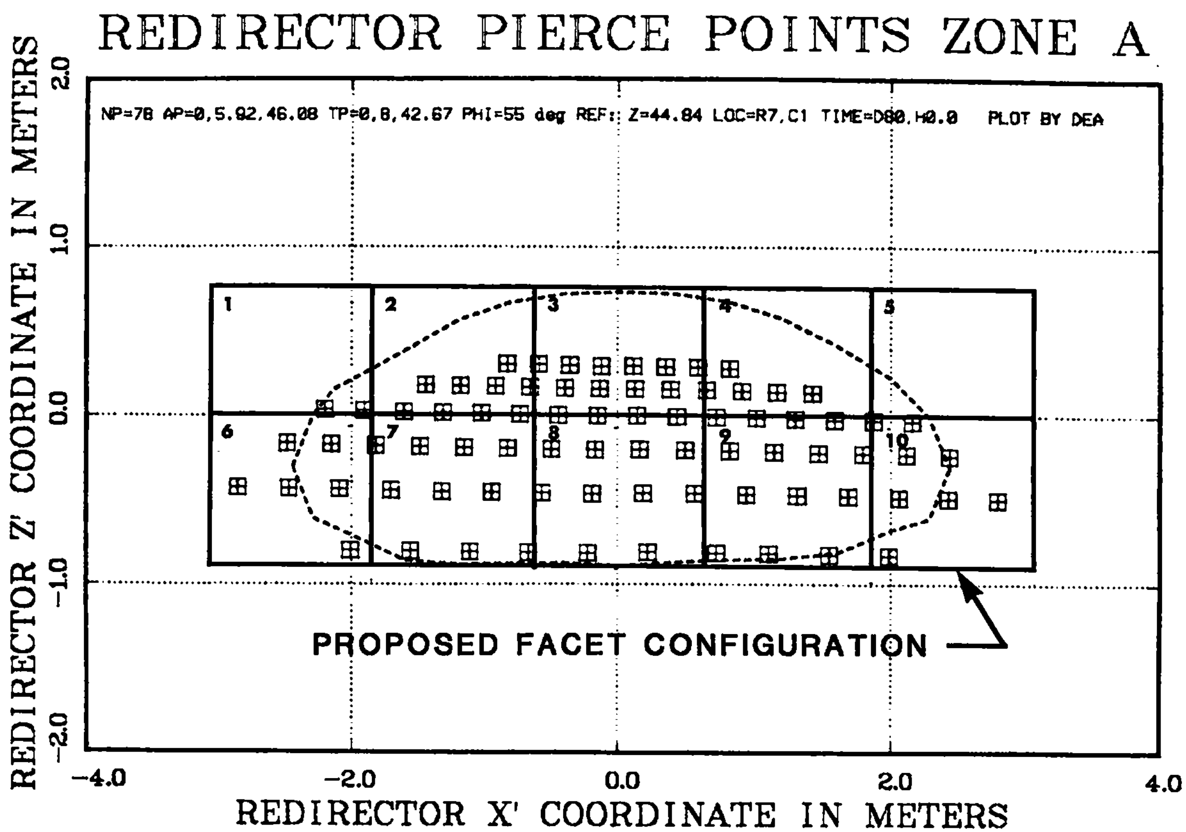

Figure 10. Redirector Facets for Numerical Example 2

Table 1

Redirector Facet Map (Tower Coordinate System)

Facet	Heliostat ID Numbers (Figure 11) Whose Central Ray Intersects Domain of Redirector Facets (Figure 10)	Average Redirector-Facet Normal
1	247, 248	$-0.0489\ \hat{i} + 0.4928\ \hat{j} - 0.8687\ \hat{k}$
2	243, 244, 245, 246, 252, 253, 254 255, 263	$-0.0302\ \hat{i} + 0.4866\ \hat{j} - 0.8731\ \hat{k}$
3	58, 59, 67, 68, 77, 78, 79, 241, 242, 250, 251, 260, 261, 262	$-0.0001\ \hat{i} + 0.4845\ \hat{j} - 0.8748\ \hat{k}$
4	60, 61, 62, 63, 69, 70, 71, 72, 80	$0.0324\ \hat{i} + 0.4847\ \hat{j} - 0.8741\ \hat{k}$
5	64, 65	$0.0549\ \hat{i} + 0.4902\ \hat{j} - 0.8699\ \hat{k}$
6	215, 227, 228, 229, 238, 239	$-0.0939\ \hat{i} + 0.4879\ \hat{j} - 0.8679\ \hat{k}$
7	40, 212, 213, 214, 224, 225, 226, 234, 235, 236, 237	$-0.0714\ \hat{i} + 0.4687\ \hat{j} - 0.8805\ \hat{k}$
8	28, 39, 49, 50, 211, 222, 223, 232, 233	$-0.0056\ \hat{i} + 0.4554\ \hat{j} - 0.8903\ \hat{k}$
9	29, 30, 31, 41, 42, 43, 51, 52, 53, 54	$0.0862\ \hat{i} + 0.4694\ \hat{j} - 0.8788\ \hat{k}$
10	32, 44, 45, 46, 55, 56	$0.0999\ \hat{i} + 0.4868\ \hat{j} - 0.8678\ \hat{k}$

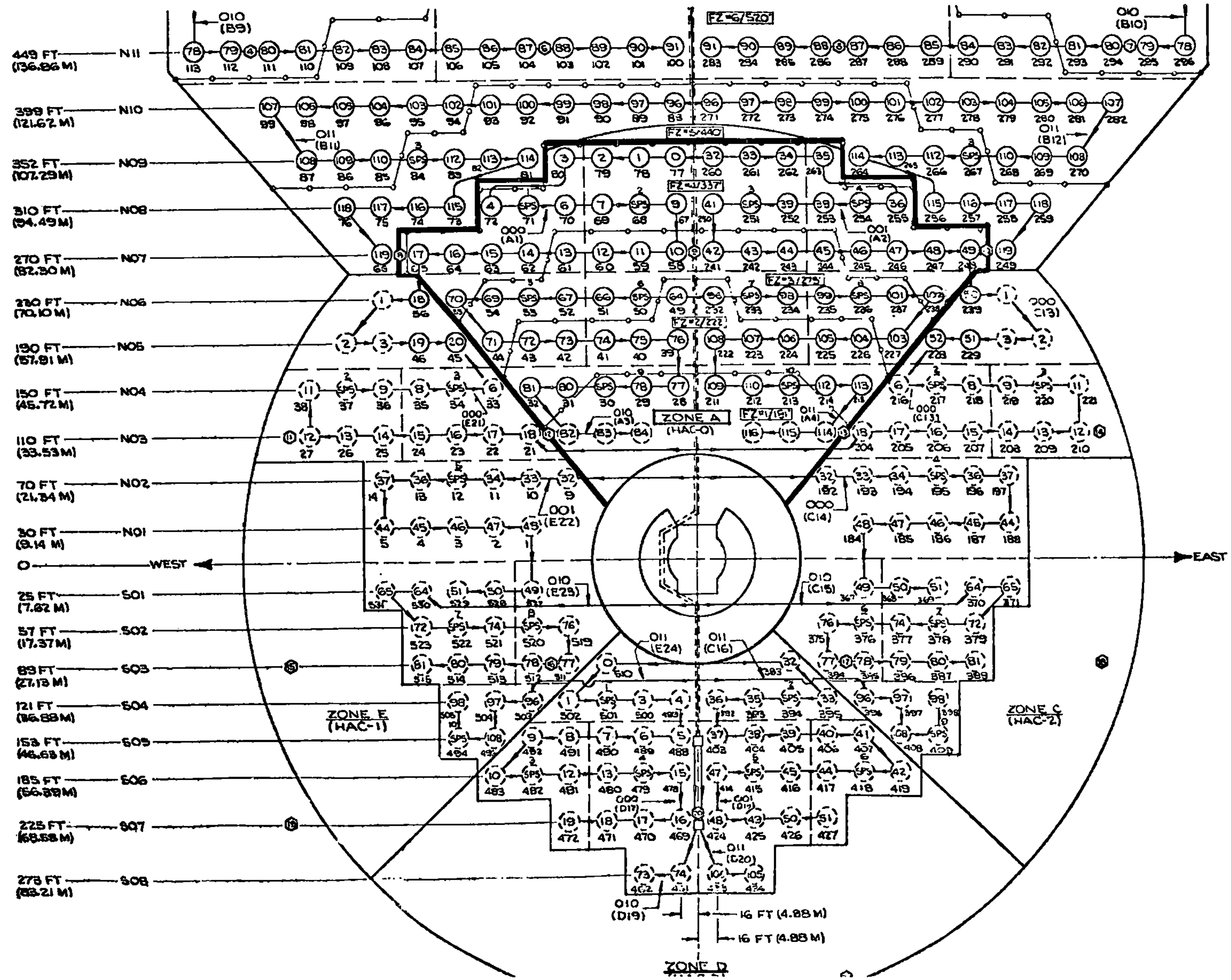

Figure 11. The CRTF Heliostat Field with Zone A Identified by Outline

It is noted that assigning a simple arithmetic average of the calculated optimum redirector normals contained in each of the Figure 10 facet maps will not produce the optimum flux pattern on the given target plane. However, we have selected the redirector facet normals in this manner for simplicity. Perhaps an area or energy weighting scheme would be a better way to determine the facet normals of the redirector. The next step is to obtain a set of unit vectors $\hat{e}_{u1}$ and $\hat{e}_{u2}$ that lie in the facet plant. These vectors are needed to determine the location in space of any point in the facet plane. One method for doing this[3] is to project the normal vector into the horizontal plane and rotate it 90° clockwise to obtain $\hat{e}_{u1}$. If $\hat{e}_{u3}$ is taken as

$$\hat{e}_{u3} = -N_1 \ ,$$

then $\hat{e}_{u2}$ is just

$$\hat{e}_{u2} = \hat{e}_{u3} \times \hat{e}_{u1}$$

The vectors $\hat{e}_{u1}$ and $\hat{e}_{u2}$ lie in the facet plane and can be used to locate any point in the plane. This information is used in the HELIOS code to determine the flux-density distributions on the redirector plane and on the target plane. To illustrate the procedure, a sample calculation for facet 1 follows:

The center of facet 1 is located at

$$(X'_H, Y'_H, Z'_H) = (-2.44, 0, 0.34)$$

for the redirector coordinate system

or

$$(X, Y, Z) = (2.44, 8.39, 45.11)$$

for the tower coordinate system

with a unit normal

$$\hat{N}_1 = -0.0489\ \hat{i} + 0.4928\ \hat{j} - 0.8687\ \hat{k}$$

Projecting this vector into the horizontal plane and normalizing it, we obtain

$$\hat{N}_H = \frac{-0.0489\ \hat{i} + 0.4928\ \hat{j}}{[(-0.0489)^2 + (0.4928)^2]^{1/2}} = -0.0987\ \hat{i} + 0.9951\ \hat{j}$$

Rotation of $\hat{N}_H$ through 90° yields

$$\hat{e}_{u1} = 0.9951\ \hat{i} + 0.0987\ \hat{j}$$

Since

$$\hat{e}_{u3} = -\hat{N}_1 = 0.0489\ \hat{i} - 0.4928\ \hat{j} + 0.8687\ \hat{k}$$

then

$$\hat{e}_{u2} = \hat{e}_{u3} \times \hat{e}_{u1} = -0.086\ \hat{i} + 0.864\ \hat{j} + 0.495\ \hat{k}$$

Any point in the facet plane can easily be determined in tower coordinates from the relationship (see Figure 12),

$$\vec{P} = X\ \hat{i} + Y\ \hat{j} + Z\ \hat{k} + X_1\ \hat{e}_{u1} + X_2\ \hat{e}_{u2}$$

The specific relation for facet 1 is

$$\vec{P} = [2.44 + 0.9951\ X_1 - 0.086\ X_2]\ \hat{i}$$

$$+ [8.39 + 0.0987\ X_1 + 0.864\ X_2]\ \hat{j}$$

$$+ [45.11 + 0.495\ X_2]\ \hat{k}$$

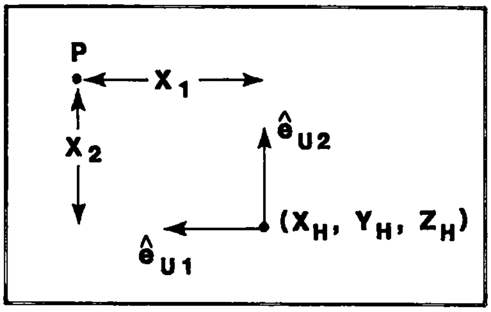

Figure 12. Unit Vectors in Facet Plane on Redirector

This information is used as input to the HELIOS code to obtain the results shown in Figure 13.

The profile of Figure 13 must now be evaluated with the intended application in mind. If a different flux profile is required it may be necessary to increase the number of redirector facets or refine the algorithm used to orient the redirector facets. As we have shown, there are a great number of variables that can be changed. It is the responsibility of the analyst to determine the constraints of his or her particular problem.

Summary

In this report we have described the methodology and approach for designing and evaluating a multifaceted redirector. This redirector is intended to redirect the energy from the CRTF heliostat field or a solar furnace similar to the Sandia Solar Furnace onto a secondary (in this case horizontal) target. A computer code (ORC) has been developed whose output can be used as input to the CRTF optical code (HELIOS) for evaluating redirector design performance. In a final configuration, it is envisioned that a multifaceted redirector could be designed with "tuneable" facets that could be computer controlled using the methodology derived here to provide any desired flux-density profile on a horizontal target.

The new capabilities that a redirector can provide to the CRTF or the Sandia Solar Furnace represent a powerful new resource for activities and experiments in which radiation direction is an important variable.

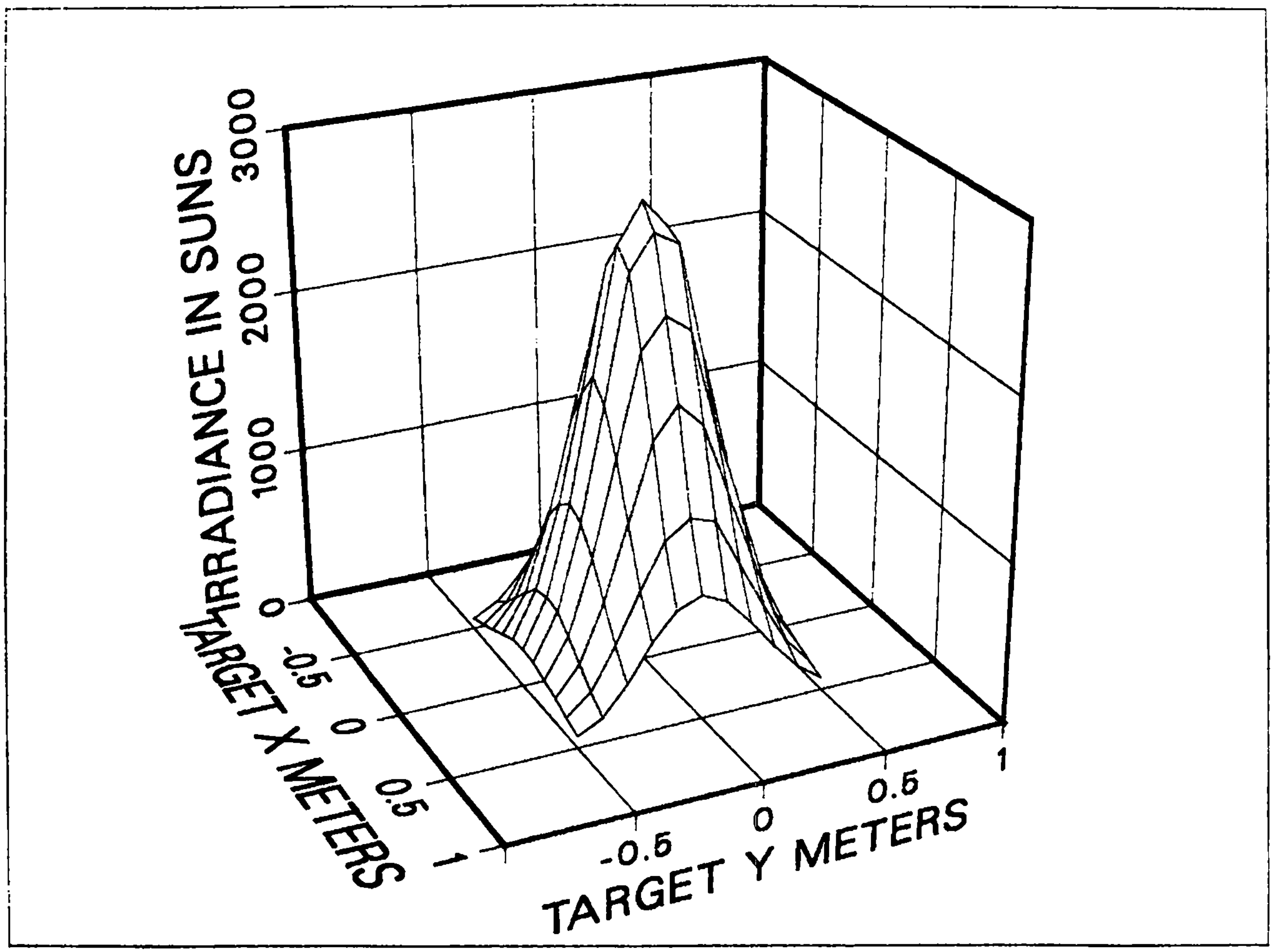

Figure 13. Flux Profile on the Horizontal Target after Redirection by a 10-Facet Redirector

References

1. J. T. Holmes et al, Central Receiver Test Facility (CRTF) Experiment Manual, SAND77-1173 (rev) (Albuquerque: Sandia Laboratories, March 1979).

2. J. J. Bartel and P. E. Skvarna, Overview of the Construction and Start-Up of the $10\ MW_e$ Solar Thermal Central Receiver Pilot Plant April 1983, SAND83-8021 (Albuquerque: Sandia National Laboratories, June 1983).

3. J. J. Bartel and P. E. Skvarna, $10MW_e$ Solar Thermal Central Receiver Pilot Plant: 1982 Operational Test Report, SAND83-8027 (Albuquerque: Sandia National Laboratories, to be published).

4. F. Biggs and C. N. Vittitoe, The Helios Model for the Optical Behavior of Reflecting Solar Concentrators, SAND76-0347 (Albuquerque: Sandia Laboratories, March 1979).

5. C. N. Vittitoe and F. Biggs, A User's Guide to HELIOS: A Computer Program for Modeling the Optical Behavior of Reflecting Solar Concentrators. Part I. Introduction and Code Input, SAND81-1180 (Albuquerque: Sandia National Laboratories, August 1981).

6. C. N. Vittitoe and F., Biggs, A User's Guide to HELIOS: A Computer Program for Modeling the Optical Behavior of Reflecting Solar Concentrators. Part III. Appendices Concerning HELIOS -- Code Details, SAND81-1562 (Albuquerque: Sandia National Laboratories, September 1981).

APPENDIX A

Program ORC

The ORC code calculates the pierce points of the central ray from each heliostat in the redirector plane. In addition, the surface orientation required for each reconcentrator facet is evaluated. This information is then used in the HELIOS code to determine flux-density distributions on the test plane. A listing of the program, as well as the input and output for numerical example 2, is included.

```
LNH,F=OPTICS
C     PROGRAM   OPTICS
C
C     PROGRAM DEVELOPED BY
C
C     WARREN E. PHIPPS JR.
C     CADET, USMA
C
C     DAN E. ARVIZU
C     SANDIA NATIONAL LABORATORIES
C
C     GEORGE P. MULHOLLAND
C     NEW MEXICO STATE UNIVERSITY
C
C
C     THE PURPOSE OF THIS CODE IS TO AID IN THE DESIGN OF A REDIRECTOR
C     FOR THE CENTRAL RECEIVER TEST FACILITY.
C
C     THIS CODE CALCULATES THE LOCATION AND ORIENTATION OF EACH
C     FACET OF A REDIRECTING SURFACE. EACH FACET CENTER IS
C     CONTAINED IN A PLANE WHICH IS DEFINED BY AN ANGLE OF ROTATION
C     ABOUT X-TOWER COORD. AND A Z TARGET VALUE FOR A REF. HELIOSTAT
C
C
C     INPUT:
C
C     TITLE OF THE SPECIFIC INPUT
C     NUMBER OF HELIOSTATS TO BE ANALYZED,NP
C     HELIOSTAT NUMBER AS REFERENCED IN THE HELIOS PROGRAM
C     AIM POINT FOR EACH HELIOSTAT
C     DESIRED TARGET POINT OF THE REDIRECTED BEAM
C     DAY OF YEAR
C     TIME OF DAY WITH SOLAR NOON BEING 0. HRS
C     ANGLE THAT REDIRECTING SURFACE MAKES WITH THE HORIZONTAL,PHE
C     INITIAL Z-COORDINATE FOR THE REFERENCE PIERCE POINT IN ORDER
C     TO DETERMINE THE REDIRECTING SURFACE
C     REFERENCE ROW FOR THE INITIAL Z-COORDINATE OF THE REFERENCE
C     PIERCE POINT
C     REFERENCE COLUMN FOR THE INTIAL Z-COORDINATE OF THE REFERENCE
C     PIERCE POINT
C
C
C
C     OUTPUT:
C
C     HELIOSTAT NUMBER AS REFERENCED IN THE HELIOS PROGRAM
C     POSITION OF THE CENTER OF THE CENTER FACET OF EACH HELIOSTAT IN
C     TOWER COORDINATES
C     PIERCE POINT ON REDIRECTOR OF RAY FROM CENTER FACET OF EACH
C     HELIOSTAT IN TOWER COORDINATES
C     DISTANCE BETWEEN THE REFERENCE PIERCE POINT AND THE OTHER
C     PIERCE POINTS
C     ANGLE BETWEEN THE CENTER FACET AND THE INCOMING RAY
C
C
C
C     INPUT FORMAT FOR VARIABLE AIM POINTS AND TARGET POINTS:
C     CARD 1: TITLE OF PROGRAM RUN--FORMAT (18A4)
```

```
C      CARD 2: NUMBER OF HELIOSTATS,0,0--FORMAT (3I5)
C      CARD 3: HELIOSTAT NO#,AIM POINT,TARGET POINT
C      --FORMAT (I5,6F7.2)
C      CARD 4: Z-COORDINATE PIERCE POINT,REF. ROW,REF. COLUMN
C      --FORMAT (F7.2,I2,I2)
C      CARD 5: ANGLE PHE--FORMAT (F7.2)
C      CARD 6: DAY,HOUR--FORMAT (F4.0,F5.2)
C
C
C      INPUT FORMAT FOR CONSTANT AIM POINT AND VARIABLE TARGET POINTS:
C      CARD 1: TITLE OF PROGRAM RUN--FORMAT (18A4)
C      CARD 2: NUMBER OF HELIOSTATS,1,0--FORMAT (3I5)
C      CARD 3: CONSTANT AIM POINT--FORMAT (3F7.2)
C      CARD 4: HELIOSTAT NO#,TARGET POINT--FORMAT (I5,3F7.2)
C      CARD 5: Z-COORDINATE PIERCE POINT,REF. ROW,REF. COLUMN
C      --FORMAT (F7.2,I2,I2)
C      CARD 6: ANGLE PHE--FORMAT (F7.2)
C      CARD 7: DAY,HOUR--FORMAT (F4.0,F5.2)
C
C
C      INPUT FORMAT FOR VARIABLE AIM POINT AND CONSTANT TARGET POINT:
C      CARD 1: TITLE OF PROGRAM RUN--FORMAT (18A4)
C      CARD 2: NUMBER OF HELIOSTATS,0,1--FORMAT (3I5)
C      CARD 3: CONSTANT TARGET POINT--FORMAT (3F7.2)
C      CARD 4: HELIOSTAT NO#,AIM POINT--FORMAT (I5,3F7.2)
C      CARD 5: Z-COORDINATE PIERCE POINT,REF.ROW,REF. COLUMN
C      --FORMAT (F7.2,I2,I2)
C      CARD 6: ANGLE PHE--FORMAT (F7.2)
C      CARD 7: DAY,HOUR--FORMAT (F4.0,F5.2)
C
C
C      INPUT FORMAT FOR CONSTANT AIM POINT AND TARGET POINT:
C      CARD 1: TITLE OF PROGRAM RUN--FORMAT (18A4)
C      CARD 2: NUMBER OF HELIOSTATS,1,1--FORMAT (3I5)
C      CARD 3: CONSTANT AIM POINT, CONSTANT TARGET POINT
C      --FORMAT (6F7.2)
C      CARD 4: HELIOSTAT NO#--FORMAT (I5)
C      CARD 5: Z-COORDINATE PIERCE POINT,REF. ROW,REF. COLUMN
C      --FORMAT (F7.2,I2,I2)
C      CARD 6: ANGLE PHE--FORMAT (F7.2)
C      CARD 7: DAY,HOUR--FORMAT (F4.0,F5.2)
C
C
C
C      THE MAIN VARIABLES USED IN THIS PROGRAM:
C
C
C      ANGLE--ARRAY OF THE ARCCOSINE OF THE VARIABLE (IDOTN)
C      AP--ARRAY OF THE DISTANCE FROM THE AIM POINT TO THE POSITION
C      OF THE CENTER FACET OF EACH HELIOSTAT
C      AZ--AZIMITH OF THE SUN'S POSITION WITH THE TOWER AS REFERENCE
C      C--ARRAY OF THE COLUMN POSITION OF EACH HELIOSTAT
C      C1--REFERENCE COLUMN BY WHICH THE PROPER ZH CAN BE CALCULATED
C      EL-ELEVATION OF THE SUN'S POSITION WITH THE TOWER AS REFERENCE
C      FX--ARRAY OF THE X-COORDINATES OF THE FOUNDATION OF HELIOSTAT
C      FY--ARRAY OF THE Y-COORDINATES OF THE FOUNDATION OF HELIOSTAT
C      FZ--ARRAY OF THE Z-COORDINATES OF THE FOUNDATION OF HELIOSTAT
C      H1H2--ARRAY OF DISTANCE BETWEEN PIERCE POINTS AND THE REFERENCE
```

```
C      PIERCE POINT
C      HN--ARRAY OF THE HELIOSTAT NUMBER AS NUMBERED BY THE HELIOS
C      PROGRAM
C      HP--ARRAY OF THE HELIOSTAT NUMBER AS NUMBERED BY THE HELIOS
C      PROGRAM--INPUT BY USER
C      IDOTN--ARRAY OF THE NEGATIVE DOT PRODUCT OF THE I AND NORMAL
C      VECTORS
C      L--ARRAY OF THE I COMPONENT OF THE I-VECTOR
C      M--ARRAY OF THE J COMPONENT OF THE I-VECTOR
C      N--ARRAY OF THE K COMPONENT OF THE I-VECTOR
C      NP--NUMBER OF HELIOSTATS TO BE ANALYZED
C      PHE--ANGLE WHICH PIERCE PLANE MAKES WITH HORIZONTAL
C      PI--CONSTANT OF PI
C      R--ARRAY OF THE ROW POSITION OF EACH HELIOSTAT
C      R1--REFERENCE ROW BY WHICH THE PROPER ZH CAN BE CALCULATED
C      XA--ARRAY OF X-COORDINATES OF AIM POINT
C      XF--ARRAY OF X-COORDINATES OF THE TARGET POINT
C      XH--ARRAY OF X-COORDINATES OF THE PIERCE POINT
C      XN--ARRAY OF THE I COMPONENT OF THE NORMAL VECTOR
C      XP--ARRAY OF X-COORDINATES OF THE CENTER FACET OF HELIOSTAT
C      XT--ARRAY OF X-COORD. OF THE PIERCE POINT IN TARGET COORD.
C      YA--ARRAY OF Y-COORDINATES OF AIM POINT
C      YF--ARRAY OF Y-COORDINATES OF THE TARGET POINT
C      YH--ARRAY OF Y-COORDINATES OF THE PIERCE POINT
C      YN--ARRAY OF J COMPONENT OF THE NORMAL VECTOR
C      YP--ARRAY OF Y-COORDINATES OF THE CENTER FACET OF HELIOSTAT
C      YT--ARRAY OF Y-COORD. OF THE PIERCE POINT IN TARGET COORD.
C      ZA--ARRAY OF Z-COORDINATES OF AIM POINT
C      ZF--ARRAY OF Z-COORDINATES OF THE TARGET POINT
C      ZH--ARRAY OF Z-COORDINATES OF THE PIERCE POINT
C      ZN--ARRAY OF THE K COMPONENT OF THE NORMAL VECTOR
C      ZP--ARRAY OF THE Z-COORDINATES OF THE CENTER FACET OF HELIOSTAT
C      ZT--ARRAY OF THE Z-COORD. OF THE PIERCE POINT IN TARGET COORD.
C
C
C      *************************************************************
       PROGRAM OPTICS(TAPE1,TAPE2,TAPE3)
C
C
C      THE PURPOSE OF THE MAIN PROGRAM IS TO READ THE INPUT,CALL ADJOIN-
C      ING SUBROUTINES TO PERFORM THE APPROPRIATE CALCULATIONS, AND
C      PRINT THE RESULTANT OUTPUT.
C
C
C      COMMON THE MAIN VARIABLES BY BLOCKS
C
       COMMON/BLOCK1/XA(222),YA(222),ZA(222)
       COMMON/BLOCK2/XP(222),YP(222),ZP(222)
       COMMON/BLOCK3/XH(222),YH(222),ZH(222)
       COMMON/BLOCK5/PHE,PI,H1H2(222)
       COMMON/BLOCK6/XF(222),YF(222),ZF(222)
       COMMON/BLOCK7/XN(222),YN(222),ZN(222),ANGLE(222)
       COMMON/BLOCK8/AZ,EL
       COMMON/BLOCK9/FX(222),FY(222),FZ(222)
       COMMON/BLOCK11/R,C,HN,HP,R1,C1
       COMMON/BLOCK4/L,M,N,AP(222)
       COMMON/BLOCK12/XT(222),YT(222),ZT(222)
       REAL L(222),N(222),M(222),IDOTN(222)
```

```
      INTEGER R(222),C(222),HN(222),HP(222),R1,C1
      DIMENSION TITLE(18),XTT(222),ZTT(222)
C
C     INTIALIZE THE VARIABLES R,C,HN
C
      DATA (R(I),I=1,222)/
     14,  4,  4,  4,  4,  4,  4,  4,  4,  4,  5,  5,
     15,  5,  5,  5,  5,  5,  5,  5,  6,  5,  6,  6,
     16,  6,  6,  6,  6,  6,  6,  6,  6,  6,  6,  6,
     17,  7,  7,  7,  7,  7,  7,  7,  7,  7,  7,  7,
     17,  7,  7,  7,  8,  8,  8,  8,  8,  8,  8,  8,
     18,  8,  8,  8,  9,  9,  9,  9,  9,  9,  9,  9,
     17,  7,  8,  8,  8,  8,  8,  8,  8,  8,  9,  9,
     19,  9,  9,  9,  9,  9,  9,  9,  9,  9,  9,  9,
     110, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10,
     110, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10,
     111, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11,
     111, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11,
     111, 11, 11, 11, 12, 12, 12, 12, 12, 12, 12, 12,
     112, 12, 12, 12, 12, 12, 12, 12, 12, 12, 12, 12,
     112, 12, 12, 12, 12, 12, 12, 12, 13, 13, 13, 13,
     113, 13, 13, 13, 13, 13, 13, 13, 13, 13, 13, 13,
     113, 13, 13, 13, 13, 13, 13, 13, 13, 13, 13, 13,
     114, 14, 14, 14, 14, 14, 14, 14, 14, 14, 14, 14,
     16,  5,  5,  6,  5,  5/
      DATA (C(I),I=1,222)/
     11,  2,  3,  4,  5, -1, -2, -3, -4, -5,  1,  2,
     13,  4,  5,  6, -1, -2, -3, -4, -5, -6,  1,  2,
     13,  4,  5,  6,  7, -1, -2, -3, -4, -5, -6, -7,
     11,  2,  3,  4,  5,  6,  7,  8, -1, -2, -3, -4,
     1-5, -6, -7, -8,  1,  2,  3,  4,  5,  6, -1, -2,
     1-3, -4, -5, -6,  1,  2,  3,  4, -1, -2, -3, -4,
     19, -9,  7,  8,  9, 10, -7, -8, -9,-10,  5,  6,
     17,  8,  9, 10, 11, -5, -6, -7, -8, -9,-10,-11,
     11,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12,
     1-1, -2, -3, -4, -5, -6, -7, -8, -9,-10,-11,-12,
     11,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12,
     113, 14, -1, -2, -3, -4, -5, -6, -7, -8, -9,-10,
     1-11,-12,-13,-14,  1,  2,  3,  4,  5,  6,  7,  8,
     19, 10, 11, 12, 13, 14, -1, -2, -3, -4, -5, -6,
     1-7, -8, -9,-10,-11,-12,-13,-14,  1,  2,  3,  4,
     15,  6,  7,  8,  9, 10, 11, 12, 13, 14, -1, -2,
     1-3, -4, -5, -6, -7, -8, -9,-10,-11,-12,-13,-14,
     11,  2,  3,  4,  5,  6, -1, -2, -3, -4, -5, -6,
     1-8, -8, -7,  8,  8,  7/
      DATA (HN(I),I=1,222)/
     1211,212,213,214,215, 28, 29, 30, 31, 32,222,223,
     1224,225,226,227, 39, 40, 41, 42, 43, 44,232,233,
     1234,235,236,237,238, 49, 50, 51, 52, 53, 54, 55,
     1241,242,243,244,245,246,247,248, 58, 59, 60, 61,
     162, 63, 64, 65,250,251,252,253,254,255, 67, 68,
     169, 70, 71, 72,260,261,262,263, 77, 78, 79, 80,
     1249, 66,256,257,258,259, 73, 74, 75, 76,264,265,
     1266,267,268,269,270, 81, 82, 83, 84, 85, 86, 87,
     1271,272,273,274,275,276,277,278,279,280,281,282,
     188, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99,
     1283,284,285,286,287,288,289,290,291,292,293,294,
     1295,296,100,101,102,103,104,105,106,107,108,109,
```

```
     1110,111,112,113,297,298,299,300,301,302,303,304,
     1305,306,307,308,309,310,114,115,116,117,118,119,
     1120,121,122,123,124,125,126,127,311,312,313,314,
     1315,316,317,318,319,320,321,322,323,324,128,129,
     1130,131,132,133,134,135,136,137,138,139,140,141,
     1325,326,327,328,329,330,142,143,144,145,146,147,
     156, 46, 45,239,229,228/
C
C     INTIALIZE THE VARIABLES FX,FY,FZ
C
      DATA (FX(I),I=1,50)/
     116.043,   48.039,   79.910,  111.952,  143.938,
     1-15.986,  -52.045,  -79.907, -111.928, -143.945,
     116.042,   48.068,   79.940,  111.947,  143.873,
     1175.908,  -15.892,  -47.901,  -79.913, -111.916,
     1-143.905, -175.898,   16.003,   48.009,   79.922,
     1111.908,  143.865,  175.901,  207.951,  -15.926,
     1-47.970,  -79.879, -111.883, -144.007, -175.952,
     1-207.943,   16.143,   48.122,   79.926,  111.982,
     1143.989,  175.949,  207.970,  239.987,  -15.932,
     1-47.960,  -79.800, -111.963, -143.912, -175.719/
      DATA (FX(I),I=51,100)/
     1-207.892, -239.788,   16.051,   48.015,   80.005,
     1111.905,  143.954,  175.916,  -16.001,  -47.994,
     1-79.993, -111.954, -143.758, -175.865,   16.040,
     147.979,   80.019,  111.985,  -16.010,  -48.025,
     1-79.965, -111.975,  271.592, -271.843,  207.938,
     1239.918,  271.888,  303.853, -207.711, -239.819,
     1-271.815, -303.800,  143.957,  175.955,  207.966,
     1239.916,  271.903,  303.811,  335.868, -143.908,
     1-175.874, -207.914, -239.876, -271.893, -303.841,
     1-335.903,   15.958,   47.982,   80.015,  111.943/
      DATA (FX(I),I=101,150)/
     1143.903,  175.969,  207.980,  239.940,  271.967,
     1303.810,  335.846,  368.028,  -15.960,  -47.996,
     1-79.900, -111.914, -143.931, -175.860, -207.806,
     1-239.972, -271.803, -303.875, -335.793, -367.854,
     115.996,   48.011,   80.003,  111.974,  143.929,
     1175.965,  207.933,  239.916,  271.923,  303.857,
     1335.795,  367.936,  399.853,  431.905,  -15.973,
     1-47.987,  -79.981, -111.961, -143.978, -175.925,
     1-207.953, -239.908, -271.831, -303.907, -335.838,
     1-367.881, -399.862, -431.818,   15.976,   47.981/
      DATA (FX(I),I=151,200)/
     180.008,  111.971,  143.920,  175.875,  207.977,
     1239.918,  271.882,  303.850,  335.888,  367.904,
     1399.901,  431.862,  -16.054,  -48.011,  -79.988,
     1-111.947, -143.976, -175.903, -207.939, -239.900,
     1-271.945, -303.887, -335.846, -367.870, -399.939,
     1-431.883,   15.867,   47.982,   80.013,  111.907,
     1143.909,  175.947,  207.949,  239.932,  271.934,
     1303.867,  335.902,  367.850,  399.934,  431.903,
     1-16.059,  -47.946,  -79.936, -111.934, -143.864,
     1-175.964, -207.944, -239.830, -271.925, -304.029/
      DATA (FX(I),I=201,222)/
     1-335.894, -367.838, -399.874, -431.816,   16.093,
     147.977,   80.036,  111.874,  143.929,  175.962,
     1-16.010,  -48.054,  -80.074, -111.960, -143.977,
```

```
1-175.940, -230.928, -230.830, -207.865,  230.844,
1230.890,  207.874/
 DATA (FY(I),I=1,50)/
1150.075,  150.095,  150.092,  150.085,  150.061,
1150.052,  150.034,  150.086,  150.054,  150.042,
1190.061,  190.101,  190.043,  190.085,  190.070,
1190.089,  190.073,  190.072,  189.996,  190.018,
1190.051,  189.981,  229.955,  229.971,  230.020,
1229.985,  229.960,  229.978,  230.043,  229.997,
1229.992,  229.995,  230.007,  229.953,  230.006,
1230.011,  269.938,  269.946,  270.006,  270.011,
1269.981,  270.049,  269.956,  269.995,  270.046,
1270.003,  270.002,  269.959,  270.031,  269.991/
 DATA (FY(I),I=51,100)/
1270.019,  269.983,  309.997,  310.000,  310.050,
1310.034,  309.986,  309.990,  310.038,  310.013,
1309.965,  310.011,  309.988,  309.972,  352.018,
1351.960,  351.988,  352.019,  352.048,  352.087,
1351.989,  351.998,  269.995,  270.033,  309.979,
1309.970,  309.986,  309.979,  309.966,  310.026,
1310.003,  310.010,  352.017,  352.001,  351.989,
1352.023,  351.980,  352.003,  351.999,  351.988,
1352.023,  352.019,  352.032,  352.011,  351.990,
1351.963,  398.985,  398.953,  399.033,  398.911/
 DATA (FY(I),I=101,150)/
1398.942,  399.003,  398.962,  398.919,  398.973,
1399.055,  399.027,  398.816,  399.000,  398.950,
1398.969,  398.970,  398.919,  398.914,  398.935,
1399.021,  399.037,  399.040,  399.035,  398.971,
1448.944,  448.981,  448.948,  448.960,  448.988,
1448.936,  448.982,  448.937,  448.954,  448.952,
1448.858,  448.868,  448.970,  448.897,  448.978,
1448.969,  448.956,  448.897,  448.994,  448.976,
1449.001,  449.081,  449.056,  449.019,  449.041,
1448.985,  449.027,  449.033,  506.958,  506.910/
 DATA (FY(I),I=151,200)/
1506.946,  506.922,  506.981,  506.947,  506.971,
1506.917,  506.940,  507.014,  506.966,  506.917,
1507.012,  506.946,  506.962,  506.957,  506.984,
1506.912,  506.962,  506.929,  506.919,  506.920,
1506.944,  506.961,  506.988,  507.014,  507.018,
1507.009,  569.936,  569.938,  569.976,  569.929,
1569.924,  569.941,  569.924,  569.919,  569.949,
1569.873,  569.893,  569.935,  569.951,  569.903,
1569.954,  569.890,  569.995,  570.047,  570.001,
1569.919,  570.047,  570.081,  569.969,  569.951/
 DATA (FY(I),I=201,222)/
1569.987,  569.950,  569.994,  569.939,  638.975,
1638.973,  638.891,  638.921,  638.872,  638.865,
1638.826,  638.919,  638.797,  638.996,  638.947,
1638.952,  230.024,  190.109,  190.084,  230.058,
1190.091,  190.101/
 DATA (FZ(I),I=1,90)/
1-.401,     .059,     .399,     .859,    1.329,    -.761,
1-1.191,  -1.651,   -2.081,   -2.581,    -.131,     .260,
1.700,    1.229,    1.909,    2.559,    -.581,    -.091,
1-1.491,  -2.041,   -2.531,   -3.231,     .189,     .509,
11.159,   1.699,    2.409,    3.049,    3.679,    -.311,
```

```
     1-.781,  -1.311,  -1.801,  -2.531,  -3.161,  -3.801,
     1.570,   1.050,   1.630,   2.330,   2.050,   3.570,
     14.250,  4.870,   .010,    -.561,   -1.111,  -1.661,
     1-2.451, -3.161,  -3.761,  -4.511,  .010,    1.530,
     12.260,  2.030,   3.510,   4.130,   .420,    -.151,
     1-.701,  -1.451,  -2.181,  -2.021,  1.350,   2.160,
     12.700,  3.430,   .700,    .110,    -.531,   -1.301,
     15.650,  -5.351,  4.770,   5.430,   6.000,   6.830,
     1-3.661, -4.401,  -5.221,  -6.041,  4.030,   4.710,
     15.300,  6.010,   6.500,   7.330,   8.050,   -2.161/
      DATA (FZ(I),I=91,180)/
     1-2.011, -3.581,  -4.371,  -5.071,  -5.061,  -6.711,
     11.600,  2.520,   3.250,   4.000,   4.570,   5.280,
     15.010,  6.580,   7.180,   7.830,   8.580,   0.500,
     1.060,   .330,    -.471,   -1.161,  -1.071,  -2.631,
     1-3.441, -4.101,  -4.051,  -5.601,  -6.431,  -7.141,
     11.710,  2.550,   3.230,   3.060,   4.720,   5.480,
     16.140,  6.800,   7.620,   8.420,   0.060,   0.810,
     110.540, 11.040,  1.080,   .300,    -.471,   -1.231,
     1-1.831, -2.751,  -3.461,  -4.121,  -4.001,  -5.851,
     1-6.561, -7.241,  -7.721,  -8.371,  1.000,   2.580,
     13.350,  4.000,   4.840,   5.570,   6.270,   7.030,
     17.870,  8.650,   0.370,   10.140,  10.820,  11.680,
     11.230,  .420,    -.361,   -1.081,  -1.021,  -2.701,
     1-3.421, -4.121,  -4.061,  -5.611,  -6.421,  -7.251,
     1-7.721, -8.281,  2.070,   2.700,   3.450,   4.210/ .
      DATA (FZ(I),I=181,222)/
     14.050,  5.670,   6.350,   7.170,   7.010,   8.710,
     10.410,  10.200,  11.020,  11.800,  1.270,   .560,
     1-.141,  -.801,   -1.681,  -2.401,  -3.261,  -3.061,
     1-4.741, -5.581,  -6.311,  -7.041,  -7.631,  -8.101,
     12.200,  2.870,   3.620,   4.420,   5.130,   5.800,
     11.550,  .810,    .210,    -.771,   -1.541,  -2.381,
     1-4.671, -4.731,  -4.031,  4.300,   3.760,   3.120/
C
C     CALCULATE THE CONSTANT PI
C
      PI=ATAN(1.)*4.
C
C     READ IN THE TITLE,NO# OF POINTS,AND CHECK IF EITHER
C     THE AIM POINT OR TARGET POINT OR BOTH ARE CONSTANT
C
      READ (1,100)(TITLE(I),I=1,18)
      READ (1,101)NP,IAIM,ITARGET
C
C     CHECK IF AIM POINT OR TARGET POINT IS CONSTANT
C
      IF(IAIM.EQ.1.AND.ITARGET.EQ.1) GO TO 106
      IF(IAIM.EQ.1) GO TO 107
      IF(ITARGET.EQ.1) GO TO 108
C
C     READ IN VALUES FOR VARIABLE AIM POINT AND TARGET POINT
C
      DO 85 I=1,NP
      READ (1,102)HP(I),XA(I),YA(I),ZA(I),XF(I),YF(I),ZF(I)
   85 CONTINUE
      GO TO 90
C
```

```
C     READ IN VALUES FOR CONSTANT AIM POINT AND TARGET POINT
C
  106 READ (1,109)CXA,CYA,CZA,CXF,CYF,CZF
      DO 110 I=1,NP
      READ (1,114)HP(I)
      XA(I)=CXA
      YA(I)=CYA
      ZA(I)=CZA
      XF(I)=CXF
      YF(I)=CYF
      ZF(I)=CZF
  110 CONTINUE
      GO TO 99
C
C     READ IN VALUES FOR CONSTANT AIM POINT AND VARIABLE TARGET
C     POINT
C
  107 READ (1,111)CXA,CYA,CZA
      DO 112 I=1,NP
      READ (1,113)HP(I),XF(I),YF(I),ZF(I)
      XA(I)=CXA
      YA(I)=CYA
      ZA(I)=CZA
  112 CONTINUE
      GO TO 99
C
C     READ IN VALUES FOR VARIABLE AIM POINT AND CONSTANT TARGET
C     POINT
C
  108 READ (1,111)CXF,CYF,CZF
      DO 115 I=1,NP
      READ (1,113)HP(I),XA(I),YA(I),ZA(I)
      XF(I)=CXF
      YF(I)=CYF
      ZF(I)=CZF
  115 CONTINUE
C
C     READ IN REMAINING INPUT
C
   99 READ (1,103)ZH(1),R1,C1
      READ (1,104)PHE
      READ (1,105)DAY,HOUR
  100 FORMAT("1",18A4)
  101 FORMAT(3I5)
  102 FORMAT(I5,6F7.2)
  103 FORMAT(F7.2,I2,I2)
  104 FORMAT(F7.2)
  105 FORMAT(F4.0,F5.2)
  109 FORMAT(6F7.2)
  111 FORMAT(3F7.2)
  113 FORMAT(I5,3F7.2)
  114 FORMAT(I5)
C
C     CALL SUBROUTINE TO ASSOCIATE THE HELIOSTAT NO# WITH
C     THE FOUNDATION POINTS AND SORT BY ROW AND COLUMN
C
      CALL SORTPT(NP)
C
```

```
C     CALL SUBROUTINE TO CALCULATE THE AZIMITH AND ELEVATION
C     OF THE SUN
C
      CALL SUN(DAY,HOUR,AZ,EL)
C
C     CALL SUBROUTINE TO CALCULATE THE THE POSITION OF THE
C     CENTER FACET OF EACH HELIOSTAT IN TOWER COORDINATES
C
      CALL POINTS(NP)
C
C     CONVERT PHE FROM DEGREES TO RADIANS
C
      PHE=PI*PHE/180.
C
C     CALL SUBROUINE TO CALCULATE THE COMPONENTS OF THE I-
C     VECTOR
C
      CALL IVECTOR(NP)
C
C     CALL SUBROUTINE TO CALCULATE THE PIERCE POINTS
C
      CALL PIERCE(NP)
C
C     CALL SUBROUTINE TO REFINE PIERCE POINTS TO LIE IN A PLANE
C
      CALL CORPIER(NP)
C
C     CALL SUBROUTINE TO CALCULATE THE NORMAL VECTOR TO THE
C     REDIRECTING SURFACE AND THE ANGLE BETWEEN THIS NORMAL
C     AND THE INCIDENT HELIOSTAT RAY
C
      CALL NVECTOR(NP)
C
C
C     PRINT THE OUTPUT
C
      WRITE (2,100) (TITLE(I),I=1,18)
      WRITE (2,80)
   80 FORMAT(1X,72("*"),//)
      WRITE (2,50)
   50 FORMAT(7X,"HELIOSTAT",16X,"PIERCE",16X,"TARGET",7X,"ANGLE")
      WRITE (2,51)
   51 FORMAT(7X,"POSITION",17X,"POINT",16X,"POSITION",//)
      WRITE (2,52)
   52 FORMAT(1X,72("*"))
      IF(NP.EQ.1) GO TO 60
      DO 61 I=1,NP
      WRITE (2,200) HN(I)
  200 FORMAT(10X,I4)
      WRITE (2,53) XP(I),YP(I),ZP(I),XH(I),YH(I),ZH(I),XT(I),YT(I),
     1ZT(I),ANGLE(I)
   53 FORMAT(1X,F7.2,F7.2,F7.2,1X,3(F7.2),1X,3(F7.2),1X,F6.1)
   61 CONTINUE
      GO TO 62
   60 WRITE (2,53) XP(1),YP(1),ZP(1),XH(1),YH(1),ZH(1),XT(1),YT(1),
     1ZT(1),ANGLE(1)
   62 CONTINUE
      DO 63 I=1,NP
```

```
      ZTT(I)=ZT(I)-ZT(1)
      XTT(I)=-XT(I)
      WRITE(3,53)XTT(I),ZTT(I)
   63 CONTINUE
      WRITE(2,100) (TITLE(I),I=1,18)
      WRITE(2,55)
      WRITE(2,56)
      WRITE(2,57)
      WRITE(2,58)
      WRITE(2,59)
   55 FORMAT(1X,72("*"),//)
   56 FORMAT(18X," DIRECTION COSINES FOR FACET NORMALS ")
   57 FORMAT(18X,"        IN TOWER REFERENCE FRAME          ",//)
   58 FORMAT(7X,"HELIOSTAT",14X,"FACET NORMAL",9X,"PIERCE POINT",//)
   59 FORMAT(1X,72("*"))
      DO 64 I=1,NP
      WRITE(2,54)HN(I),XN(I),YN(I),ZN(I),XH(I),YH(I),ZH(I)
   64 CONTINUE
   54 FORMAT(10X,I4,9X,3(F7.4),1X,3(F7.2))
      STOP
      END
      SUBROUTINE IVECTOR(NP)
C
C     THIS SUBROUTINE CALCULATES THE I,J,AND K COMPONENTS OF THE
C     VECTOR FROM THE CENTER FACET OF EACH HELIOSTAT TO ITS SPECIFIC
C     AIM POINT.
C
C     VARIABLES SPECIFIC TO THIS SUBROUTINE:
C     AP1--DUMMY VARIABLE USED TO CONTINUE THE CALCULATION OF
C     AP(1)
C     APN--DUMMY VARIABLE USED TO CONTINUE THE CALCULATION OF
C     AP(I)
C
C
C     COMMON THE MAIN VARIABLES IN BLOCKS
C
      COMMON/BLOCK1/XA(222),YA(222),ZA(222)
      COMMON/BLOCK2/XP(222),YP(222),ZP(222)
      COMMON/BLOCK4/L,M,N,AP(222)
      REAL L(222),M(222),N(222)
C
C     INITIALIZE THE DUMMY VARIABLES TO EQUAL 0.
C
      AP1=0.
      APN=0.
C
C     CHECK IF ONLY ONE HELIOSTAT HAS BEEN ENTERED
C
      IF(NP.EQ.1)GO TO 22
      GO TO 23
C
C     CALCULATE THE DISTANCE FROM CENTER FACET TO AIM POINT FOR
C     ONLY ONE HELIOSTAT
C
   22 AP1=(XA(1)-XP(1))**2.+(YA(1)-YP(1))**2.
      AP(1)=(AP1+(ZA(1)-ZP(1))**2.)**.5
C
C     CALCULATE THE I,J,K COMPONENTS OF THE I-VECTOR
```

```
C
      L(1)=(XA(1)-XP(1))/AP(1)
      M(1)=(YA(1)-YP(1))/AP(1)
      N(1)=(ZA(1)-ZP(1))/AP(1)
      GO TO 30
C
C     USE DO LOOP TO CALCULATE THE DISTANCE FROM THE CENTER FACET
C     TO AIM POINT AND THE I,J,K COMPONENTS OF THE I-VECTOR FOR
C     MORE THAN ONE HELIOSTAT
C
   23 DO 14 I=1,NP
      APN=((XA(I)-XP(I))**2.+(YA(I)-YP(I))**2.+(ZA(I)-ZP(I))**2.)
      AP(I)=APN**.5
      L(I)=(XA(I)-XP(I))/AP(I)
      M(I)=(YA(I)-YP(I))/AP(I)
      N(I)=(ZA(I)-ZP(I))/AP(I)
   14 CONTINUE
C
C     RETURN TO THE MAIN PROGRAM
C
   30 RETURN
      END
      SUBROUTINE PIERCE(NP)
C
C     THIS SUBROUTINE CALCULATES THE COORDINATES FOR THE PIERCE POINT
C     GIVEN THE INTIAL Z-COORDINATE.  THIS SUBROUTINE ALSO CALCULATES
C     THE APPROXIMATE Z-COORDINATE OF EACH PIERCE POINT BY THE LAW OF
C     SINES.
C
C     VARIABLES SPECIFIC TO THIS SUBROUTINE:
C
C     AH--DISTANCE FROM AIM POINT TO THE PIERCE POINT
C     DOTI--DOT PRODUCT OF THE I-VECTOR OF THE REFERENCE HELIOSTAT
C     AND THE I-VECTOR OF THE OTHER HELIOSTATS
C     PH--DISTANCE FROM THE CENTER FACET TO THE PIERCE POINT
C     PSI--ANGLE BETWEEN THE I-VECTOR AND THE HORIZONTAL
C     THETA--ANGLE BETWEEN THE I-VECTOR OF THE REFERENCE HELIOSTAT
C     AND THE I-VECTOR OF THE OTHER HELIOSTATS WITH THE
C     AIM POINT AS THE VERTEX
C
C     COMMON AND DIMENSION THE VARIABLES
C
      COMMON/BLOCK2/XP(222),YP(222),ZP(222)
      COMMON/BLOCK5/PHE,PI,H1H2(222)
      COMMON/BLOCK3/XH(222),YH(222),ZH(222)
      COMMON/BLOCK11/R,C,HN,HP,R1,C1
      COMMON/BLOCK4/L,M,N,AP(222)
      REAL L(222),M(222),N(222)
      INTEGER R(222),C(222),HN(222),HP(222),R1,C1
      DIMENSION PH(222),PSI(222),AH(222)
C
C     GIVEN THE INITIAL Z-COORDINATE CALCULATE THE X- AND
C     Y-COORDINATE OF THE PIERCE POINT FOR THE REFERENCE
C     HELIOSTAT
C
      PH(1)=(ZH(1)-ZP(1))/N(1)
      XH(1)=XP(1)+L(1)*PH(1)
      YH(1)=YP(1)+M(1)*PH(1)
```

```
C
C     INITIALIZE THE VARIABLE H1H2
C
      H1H2(1)=0.
C
C     CHECK IF ONLY ONE HELIOSTAT TO BE ANALYZED
C
      IF(NP.EQ.1) GO TO 35
C
C     CALCULATE PSI AND AH FOR THE REFERENCE HELIOSTAT
C
      PSI(1)=ACOS(-1*M(1))
      AH(1)=AP(1)-PH(1)
C
C     USE DO LOOP TO CALCULATE THE PIERCE POINTS FOR THE REST
C     OF THE HELIOSTATS
C
      DO 16 I=2,NP
C
C     CHECK TO SEE IF THE NEW HELIOSTAT IS IN THE SAME ROW AS
C     AS THE PREVIOUS HELIOSTAT.  IF SO, THEN APPROXIMATE THE
C     NEW Z-COORDINATE WITH THE Z-COORDINATE OF THE PREVIOUS
C     CALCULATED PIERCE POINT
C
      IF(R(I).EQ.R(I-1)) GO TO 17
C
C     USE LAW OF SINES TO APPROXIMATE THE Z-COORDINATE IF
C     HELIOSTAT IS IN A DIFFERENT ROW FROM THE REFERENCE ROW
C
      DOTI=L(I)*L(1)+M(I)*M(1)+N(I)*N(1)
      THETA=ACOS(DOTI)
C
C     CHECK TO SEE IF CURRENT ROW IS IN BEHIND REFERENCE ROW
C
      IF(R(I).GT.R1)GO TO 14
      PSI(I)=ACOS(-M(I))
      H1H2(I)=AH(1)*SIN(THETA)/(SIN(PI-PHE-PSI(I)))
      ZH(I)=ZH(1)-ABS(H1H2(I))*SIN(PHE)
      GO TO 18
   14 CONTINUE
      H1H2(I)=AH(1)*SIN(THETA)/(SIN(0.-THETA+PHE+PSI(1)))
      ZH(I)=ABS(H1H2(I))*SIN(PHE)+ZH(1)
      GO TO 18
   17 ZH(I)=ZH(I-1)
      H1H2(I)=0.
   18 PH(I)=(ZH(I)-ZP(I))/N(I)
      XH(I)=XP(I)+L(I)*PH(I)
      YH(I)=YP(I)+M(I)*PH(I)
   16 CONTINUE
C
C     RETURN TO THE MAIN PROGRAM
C
   35 RETURN
      END
      SUBROUTINE NVECTOR(NP)
C
C     THIS SUBROUTINE CALCULATES THE NORMAL TO THE REDIRECTING SURFACE
C     AT THE PIERCE POINT OF THE HELIOSTAT CENTRAL RAY WITH THE
```

```
C     REDIRECTOR PLANE AND THE ANGLE BETWEEN THE REDIRECTOR NORMAL AND
C     THE INCOMING RAY FROM THE CENTER OF THE HELIOSTAT CENTER FACET.
C     THIS ANGLE SHOULD BE MINIMIZED IN ORDER TO MAXIMIZE THE
C     EFFICIENCY OF THE REDIRECTOR-CONCENTRATOR.
C
C     VARIABLES SPECIFIC TO THE SUBROUTINE:
C
C     IDOTR--DOT PRODUCT OF THE I AND R VECTORS
C     R--DISTANCE BETWEEN THE TARGET POINT AND THE PIERCE POINT
C     XIR--I COMPONENT OF THE VECTOR SUM OF THE I AND R VECTORS
C     XR--ARRAY OF THE I COMPONENT OF THE VECTOR FROM THE PIERCE
C     POINT TO THE TARGET POINT
C     YIR--J COMPONENT OF THE VECTOR SUM OF THE I AND R VECTORS
C     YR--ARRAY OF THE J COMPONENT OF THE VECTOR FROM THE PIERCE
C     POINT TO THE TARGET POINT
C     ZIR--K COMPONENT OF THE VECTOR SUM OF THE I AND R VECTORS
C     ZR--ARRAY OF THE K COMPONENT OF THE VECTOR FROM THE PIERCE
C     POINT OT THE TARGET POINT
C     ANGLE--ANGLE BETWEEN REDIRECTOR NORMAL AND THE INCOMING
C     HELIOSTAT CENTRAL RAY
C
C
C     COMMON AND DIMENSION THE VARIABLES
C
      COMMON/BLOCK3/XH(222),YH(222),ZH(222)
      COMMON/BLOCK7/XN(222),YN(222),ZN(222),ANGLE(222)
      COMMON/BLOCK6/XF(222),YF(222),ZF(222)
      COMMON/BLOCK4/L,M,N,AP(222)
      COMMON/BLOCK5/PHE,PI,H1H2(222)
      REAL L(222),N(222),M(222),IDOTN(222),IDOTR
      DIMENSION XR(222),YR(222),ZR(222)
C
C     CHECK IF ONLY ONE HELIOSTAT IS TO BE ANALYZED
C
      IF(NP.EQ.1) GO TO 36
C
C     USE DO LOOP TO CALCULATE THE COMPONENETS OF THE R VECTOR
C     AND TO CALCULATE THE NORMAL VECTOR
      DO 19 I=1,NP
      R=((XF(I)-XH(I))**2.+(YF(I)-YH(I))**2.+(ZF(I)-ZH(I))**2.)**.5
      XR(I)=(XF(I)-XH(I))/R
      YR(I)=(YF(I)-YH(I))/R
      ZR(I)=(ZF(I)-ZH(I))/R
      XIR=-1.*L(I)+XR(I)
      YIR=-1.*M(I)+YR(I)
      ZIR=-1.*N(I)+ZR(I)
      IDOTR=L(I)*XR(I)+M(I)*YR(I)+N(I)*ZR(I)
      XN(I)=XIR/(2.-2.*IDOTR)**.5
      YN(I)=YIR/(2.-2.*IDOTR)**.5
      ZN(I)=ZIR/(2.-2.*IDOTR)**.5
      IDOTN(I)=-1.*L(I)*XN(I)-M(I)*YN(I)-N(I)*ZN(I)
      ANGLE(I)=ACOS(IDOTN(I))
C
C     CONVERT ANGLE TO DEGREES FROM RADIANS
      ANGLE(I)=180.*ANGLE(I)/PI
   19 CONTINUE
C
C     RETURN TO MAIN PROGRAM
```

```
C
      GO TO 37
C
C     CALCULATE THE NORMAL VECTOR FOR ONLY ONE HELIOSTAT
C
   36 R1=(XF(1)-XH(1))**2.+(YF(1)-YH(1))**2.+(ZF(1)-ZH(1))**2.
      R=R1**.5
      XR(1)=(XF(1)-XH(1))/R
      YR(1)=(YF(1)-YH(1))/R
      ZR(1)=(ZF(1)-ZH(1))/R
      XIR=-1.*L(1)+XR(1)
      YIR=-1.*M(1)+YR(1)
      ZIR=-1.*N(1)+ZR(1)
      IDOTR=L(1)*XR(1)+M(1)*YR(1)+N(1)*ZR(1)
      XN(1)=XIR/(2.-2.*IDOTR)**.5
      YN(1)=YIR/(2.-2.*IDOTR)**.5
      ZN(1)=ZIR/(2.-2.*IDOTR)**.5
      IDOTN(1)=-1.*L(1)*XN(1)-M(1)*YN(1)-N(1)*ZN(1)
      ANGLE(1)=ACOS(IDOTN(1))
C
C     CONVERT ANGLE TO DEGREES FROM RADIANS
      ANGLE(1)=180.*ANGLE(1)/PI
C
C     RETURN TO MAIN PROGRAM
C
   37 RETURN
      END
      SUBROUTINE SUN(DAY,HOUR,AZ,EL)
C
C     THIS SUBROUTINE WAS TAKEN FROM THE HELIOS CODE.  IT CONTAINS
C     THE CRTF LATITUDE AND LONGITUDE IN THE CALCULATION. ANY QUESTIONS
C     SHOULD BE REFERRED TO THE DOCUMENTATION OF THE HELIOS PROGRAM.
C     THIS SUBROUTINE RETURNS THE AZIMUTH AZ AND ELEVTION EL OF THE
C     SUN IN RADIANS.  THE AZIMUTH IS MEASURED COUNTER-CLOCKWIZE FROM
C     THE EAST.  INPUT IS THE DAY OF YEAR (DAY=80 FOR MARCH 21) AND
C     TIME OF DAY.  HOUR=0. FOR SOLAR NOON WITH NEGATIVE BEING
C     MORNING AND POSITIVE BEING EVENING.  HOUR IS IN HOURS.
C
      PI=ATAN(1.)*4.
      CON=PI/180.
      PHIL=35.0517*CON
      DELS=23.45229*SIN(2.*PI*(DAY-80.)/365.)*CON
      HS=15.*HOUR*CON
      EL=SIN(PHIL)*SIN(DELS)+COS(DELS)*COS(PHIL)*COS(HS)
      EL=PI/2.-ACOS(EL)
      AZ=SIN(DELS)*COS(PHIL)-COS(DELS)*SIN(PHIL)*COS(HS)
      AZ=ATAN2(AZ,-COS(DELS)*SIN(HS))
      RETURN
      END
      SUBROUTINE POINTS(NP)
C
C     THIS SUBROUTINE CALCULATES THE X,Y,Z COORDINATES OF THE CENTER
C     OF THE CENTER FACET OF EACH HELIOSTAT GIVEN THE AZIMUTH AND ELE-
C     VATION OF THE SUN; THE AIM POINT; AND THE FOUNDATION POINT OF
C     EACH HELIOSTAT.
C
C     VARIABLES SPECIFIC TO THE SUBROUTINE:
C
```

```
C     A--DIRECTION COSINE IN THE I DIRECTION OF THE CENTRAL RAY
C     FROM HELIOSTAT TO THE SUN
C     1/ALPHA--MAGNITUDE OF NORMAL VECTOR FROM HELIOSTAT
C     B--DIRECTION COSINE IN THE J DIRECTION OF THE CENTRAL RAY
C     FROM HELIOSTAT TO THE SUN
C     C--DIRECTION COSINE IN THE K DIRECTION OF THE CENTRAL RAY
C     FROM HELIOSTAT TO THE SUN
C     DELTA--ERROR CRITERIA
C     ERRTOL--ERROR TOLERANCE
C     PHET--AZIMUTH ANGLE OF THE HELIOSTAT
C     THE--ELEVATION ANGLE OF THE HELIOSTAT
C
C     COMMON AND DIMENSION THE VARIABLES
C
      COMMON/BLOCK1/XA(222),YA(222),ZA(222)
      COMMON/BLOCK2/XP(222),YP(222),ZP(222)
      COMMON/BLOCK9/FX(222),FY(222),FZ(222)
      COMMON/BLOCK8/AZ,EL
      COMMON/BLOCK5/PHE,PI,H1H2(222)
      DIMENSION X(222,20),Y(222,20),Z(222,20)
C
C     INITIALIZE THE ERROR TOLERANCE
C
      DATA ERRTOL/1.0E-4/
C
C     CALCULATE THE DIRECTION COSINES OF THE CENTRAL RAY
C
      A=COS(EL)*COS(AZ)
      B=COS(EL)*SIN(AZ)
      C=SIN(EL)
C
C     USE DO LOOP TO ASSIGN THE FIRST APPROXIMATION OF THE
C     COORDINATES TO THE CENTER FACET
C
      DO 90 I=1,NP
      X(I,1)=FX(I)
      Y(I,1)=FY(I)
      Z(I,1)=FZ(I)+13.001
C
C     USE DO LOOP TO CALCULATE THE ITH APPROXIMATION OF THE
C     COORDINATES TO THE CENTER FACET AND CHECK IF NEW
C     APPROXIMATIONS MEET THE ERROR TOLERANCE
C
      DO 95 J=2,20
      THE=(ZA(I)-Z(I,J-1))
      THE=THE/(((X(I,J-1)-XA(I))**2.+(Y(I,J-1)-YA(I))**2.)**.5)
      THE=ATAN(THE)
      PHET=ATAN((YA(I)-Y(I,J-1))/(XA(I)-X(I,J-1)))
C
C     MAKE SURE THAT THE ANGLE PHET IS IN THE 2ND AND
C     3RD QUADRANTS
C
      PHET=PHET+PI
      ALPHA=A*COS(THE)*COS(PHET)+B*COS(THE)*SIN(PHET)+C*SIN(THE)
      ALPHA=2.+2.*ALPHA
      ALPHA=(1/ALPHA)**0.5
      X(I,J)=(A+COS(THE)*COS(PHET))*ALPHA*1.043+FX(I)
      Y(I,J)=(B+COS(THE)*SIN(PHET))*ALPHA*1.043+FY(I)
```

```
      Z(I,J)=(C+SIN(THE))*ALPHA*1.043+FZ(I)+13.081
      DELTA=(X(I,J)-X(I,J-1))**2.+(Y(I,J)-Y(I,J-1))**2.
      DELTA=(DELTA+(Z(I,J)-Z(I,J-1))**2.)**.5
      NO=J
      IF(DELTA.LE.ERRTOL)GO TO 96
   95 CONTINUE
C
C     ASSIGN THE COORDINATES OF THE CENTER FACET THE FINAL
C     APPROXIMATION
C
   96 XP(I)=X(I,NO)
      YP(I)=Y(I,NO)
      ZP(I)=Z(I,NO)
   90 CONTINUE
C
C     RETURN TO MAIN PROGRAM
C
      RETURN
      END
      SUBROUTINE SORTPT(NP)
C
C     THIS SUBROUTINE SORTS THE INPUT IN ORDER THAT THE INDEPENDENT
C     VARIABLES ARE IN THE PROPER SEQUENTIAL ORDER SO THAT THE
C     POSITION-DEPENDENT VARIABLES CAN BE PROPERLY CALCULATED.
C
C     VARIABLES SPECIFIC TO THIS SUBROUTINE:
C
C     CTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE C ARRAY
C     FXTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE FX ARRAY
C     FYTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE FY ARRAY
C     FZTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE FZ ARRAY
C     ITEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE HN ARRAY
C     NR--ARRAY OF THE NUMBER OF HELIOSTATS INPUTTED IN EACH ROW
C     NRI--COUNTER OF THE NUMBER OF HELIOSTATS INPUTTED
C     RIC--DUMMY VARIABLE TO REPRESENT THE ROW NUMBER FOR THE SORT-
C     ING BY ROWS
C     RITEMP--DUMMY VARIABLE TO INCREMENT THE VARIABLE RIC TO CHECK
C     EVERY ROW
C     RTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE R ARRAY
C     XATEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE XA ARRAY
C     XFTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE XF ARRAY
C     YATEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE YA ARRAY
C     YFTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE YF ARRAY
C     ZATEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE ZA ARRAY
C     ZFTEMP--TEMPORARY STORAGE IN ORDER TO SWITCH THE ORDER OF THE
C     VALUES IN THE ZF ARRAY
C
```

```
C     COMMON AND DIMENSION THE VARIABLES
C
      COMMON/BLOCK1/XA(222),YA(222),ZA(222)
      COMMON/BLOCK6/XF(222),YF(222),ZF(222)
      COMMON/BLOCK9/FX(222),FY(222),FZ(222)
      COMMON/BLOCK11/R,C,HN,HP,R1,C1
      INTEGER R(222),C(222),HN(222),HP(222),R1,C1
      INTEGER RTEMP,CTEMP,RIC,TEMP,R1TEMP
      DIMENSION NR(222)
C
C     USE DO LOOP TO SEARCH THE HN ARRAY FOR THE HELIOSTAT
C     NUMBERS INPUTTED IN THE HP ARRAY. THEN ALSO TRANSFER THE
C     R,C,FX,FY,FZ ARRAYS SO THAT THE ARRAYS ARE IN THE ORDER
C     OF THE USER INPUT VALUES IN THE DATA FILE
C
      DO 60 I=1,NP
      TEMP=HP(I)
      DO 61 N=1,222
      IF(TEMP.EQ.HN(N))GO TO 62
      GO TO 61
   62 ITEMP=HN(I)
      HN(I)=HN(N)
      HN(N)=ITEMP
      RTEMP=R(I)
      R(I)=R(N)
      R(N)=RTEMP
      CTEMP=C(I)
      C(I)=C(N)
      C(N)=CTEMP
      FXTEMP=FX(I)
      FX(I)=FX(N)
      FX(N)=FXTEMP
      FYTEMP=FY(I)
      FY(I)=FY(N)
      FY(N)=FYTEMP
      FZTEMP=FZ(I)
      FZ(I)=FZ(N)
      FZ(N)=FZTEMP
      GO TO 60
   61 CONTINUE
   60 CONTINUE
C
C     INTIALIZE THE COUNTER NR1 AND ASSIGN RIC THE REFERENCE ROW
C     VALUE
C
      NR1=0
      RIC=R1
C
C     USE NESTED DO LOOPS TO SORT THE ARRAYS WHICH MATCH
C     SPECIFIC HELIOSTATS BY THE ROW THAT THE HELIOSTATS ARE IN
C
      DO 67 N=1,11
      NR(N)=0
      DO 65 I=1,NP
C     THE ROWS ARE ORGANIZED BY THE REF. ROW NO# AND THEN ROW 4-
C     14 SKIPPING THE REF. ROW
      IF(R(I).EQ.RIC) GO TO 66
      GO TO 65
```

```
   66 NR1=NR1+1
      RTEMP=R(NR1)
      R(NR1)=R(I)
      R(I)=RTEMP
      CTEMP=C(NR1)
      C(NR1)=C(I)
      C(I)=CTEMP
      ITEMP=HN(NR1)
      HN(NR1)=HN(I)
      HN(I)=ITEMP
      FXTEMP=FX(NR1)
      FX(NR1)=FX(I)
      FX(I)=FXTEMP
      FYTEMP=FY(NR1)
      FY(NR1)=FY(I)
      FY(I)=FYTEMP
      FZTEMP=FZ(NR1)
      FZ(NR1)=FZ(I)
      FZ(I)=FZTEMP
      XATEMP=XA(NR1)
      XA(NR1)=XA(I)
      XA(I)=XATEMP
      YATEMP=YA(NR1)
      YA(NR1)=YA(I)
      YA(I)=YATEMP
      ZATEMP=ZA(NR1)
      ZA(NR1)=ZA(I)
      ZA(I)=ZATEMP
      XFTEMP=XF(NR1)
      XF(NR1)=XF(I)
      XF(I)=XFTEMP
      YFTEMP=YF(NR1)
      YF(NR1)=YF(I)
      YF(I)=YF(NR1)
      ZFTEMP=ZF(NR1)
      ZF(NR1)=ZF(I)
      ZF(I)=ZFTEMP
      NR(N)=NR(N)+1
   65 CONTINUE
      R1TEMP=N+3
      IF(R1TEMP.GE.R1) GO TO 68
      RIC=R1TEMP
      GO TO 69
   68 RIC=R1TEMP+1
   69 IF(RIC.GT.14) GO TO 70
   67 CONTINUE
   70 NR1=1
C
C     USE NESTED DO LOOPS TO SORT EACH ROW OF HELIOSTATS SO THAT
C     THE FIRST HELIOSTAT INPUTED IN THAT ROW IS IN THE REF.
C     COLUMN
C
      DO 71 I=1,11
      IF(NR(I).EQ.0) GO TO 71
      NUMB=NR(I)+NR1-1
      DO 72 N=NR1,NUMB
      IF(C(N).EQ.C1) GO TO 73
      GO TO 72
```

```
C
C     SWITCH THE VALUES IN ALL OF THE ARRAYS
C
   73 ITEMP=HN(NR1)
      HN(NR1)=HN(N)
      HN(N)=ITEMP
      RTEMP=R(NR1)
      R(NR1)=R(N)
      R(N)=RTEMP
      CTEMP=C(NR1)
      C(NR1)=C(N)
      C(N)=CTEMP
      FXTEMP=FX(NR1)
      FX(NR1)=FX(N)
      FX(N)=FXTEMP
      FYTEMP=FY(NR1)
      FY(NR1)=FY(N)
      FY(N)=FYTEMP
      FZTEMP=FZ(NR1)
      FZ(NR1)=FZ(N)
      FZ(N)=FZTEMP
      XATEMP=XA(NR1)
      XA(NR1)=XA(N)
      XA(N)=XATEMP
      YATEMP=YA(NR1)
      YA(NR1)=YA(N)
      YA(N)=YATEMP
      ZATEMP=ZA(NR1)
      ZA(NR1)=ZA(N)
      ZA(N)=ZATEMP
      XFTEMP=XF(NR1)
      XF(NR1)=XF(N)
      XF(N)=XFTEMP
      YFTEMP=YF(NR1)
      YF(NR1)=YF(N)
      YF(N)=YFTEMP
      ZFTEMP=ZF(NR1)
      ZF(NR1)=ZF(N)
      ZF(N)=ZFTEMP
      GO TO 74
   72 CONTINUE
   74 NR1=NR1+NR(I)
   71 CONTINUE
C
C     RETURN TO MAIN PROGRAM
C
      RETURN
      END
      SUBROUTINE CORPIER(NP)
C
C     THIS SUBROUTINE REFINES THE PIERCE POINT CALCULATION FROM
C     PIERCE SO THAT ALL PIERCE POINTS FALL IN A PLANE
C
      COMMON/BLOCK2/XP(222),YP(222),ZP(222)
      COMMON/BLOCK3/XH(222),YH(222),ZH(222)
      COMMON/BLOCK4/L,M,N,AP(222)
      COMMON/BLOCK5/PHE,PI,H1H2(222)
      COMMON/BLOCK7/XN(222),YN(222),ZN(222),ANGLE(222)
```

```
      COMMON/BLOCK11/R,C,HN,HP,R1,C1
      COMMON/BLOCK12/XT(222),YT(222),ZT(222)
      REAL L(222),M(222),N(222),PH(222)
      INTEGER R(222),C(222)
C
C     REFINE THE ZH REFERENCE ESTIMATES BY REPEATING
C     THE AVERAGING OF THE Y-TOWER VALUES FIVE TIMES
C
      DO 500 J=1,5
C
C     CONVERT TOWER COORDINATES TO TARGET COORDINATES
C
      DO 10 I=1,NP
      XT(I)=XH(I)
      YT(I)=SIN(PHE)*YH(I)-COS(PHE)*ZH(I)
      ZT(I)=COS(PHE)*YH(I)+SIN(PHE)*ZH(I)
   10 CONTINUE
C
C     AVERAGE THE Y-TARGET COORD. FROM THE CALL TO PIERCE
C
      YTSUM=0.0
      DO 100 I=1,NP
      YTSUM=YTSUM+YT(I)
  100 CONTINUE
      YTAVG=YTSUM/NP
C
C     CALCULATE THE ZT VALUE THAT IS IN THE DESIRED PLANE
C     AND ALSO IS ON THE RAY FROM THE HELIOSTAT TO THE AIM POINT
C
      DO 200 I=1,NP
      ZT(I)=-M(I)*(YTAVG*COS(PHE)+ZH(I))+N(I)*(YH(I)-YTAVG*SIN(PHE))
      ZT(I)=ZT(I)/(N(I)*COS(PHE)-M(I)*SIN(PHE))
      ZH(I)=-COS(PHE)*YTAVG+SIN(PHE)*ZT(I)
  200 CONTINUE
C
C     CALCULATE NEW PIERCE POINTS
C
      DO 300 I=1,NP
      PH(I)=(ZH(I)-ZP(I))/N(I)
      XH(I)=XP(I)+L(I)*PH(I)
      YH(I)=YP(I)+M(I)*PH(I)
  300 CONTINUE
  500 CONTINUE
C
C     RETURN TO MAIN PROGRAM
C
      RETURN
      END
```

Following is a sample input/output sequence.

```
LNH,F=TAPE1
 NP=078 AP=0,19.42,151.18 TP=0,26.24,140 REF: Z=147.1 LOC=R7,C1 PHI=56 TIME=D80,H0.0
00 780000100001
0000.000019.420151.180000.000026.240140.00
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0055.00
000.00.00
/
```

LNH,F=TAPE2
NP=078 AP=0,19.42,151.18 TP=0,26.24,140 REF: Z=147.1 LOC=R7,C1 PHI=55 TI

****

	HELIOSTAT POSITION			PIERCE POINT			TARGET POSITION			ANGLE
241	16.11	269.16	14.36	.48	26.88	147.10	.48	-62.35	135.91	33.4
59	-48.09	270.23	13.53	-1.43	26.87	147.09	-1.43	-62.35	135.90	34.6
60	-80.01	270.21	12.97	-2.37	26.86	147.08	-2.37	-62.35	135.89	36.8
61	-112.25	270.15	12.41	-3.33	26.85	147.06	-3.33	-62.35	135.87	39.6
62	-144.26	270.19	11.60	-4.27	26.84	147.05	-4.27	-62.35	135.85	42.7
63	-176.12	270.12	10.87	-5.21	26.83	147.03	-5.21	-62.35	135.83	45.8
64	-208.34	270.12	10.25	-6.15	26.82	147.02	-6.15	-62.35	135.82	48.8
65	-240.28	270.06	9.49	-7.09	26.81	147.00	-7.09	-62.35	135.79	51.6
58	-15.98	270.28	14.11	-.48	26.88	147.10	-.48	-62.35	135.92	33.4
242	48.03	269.17	14.83	1.44	26.88	147.11	1.44	-62.35	135.92	34.7
243	79.78	269.24	15.41	2.39	26.89	147.12	2.39	-62.35	135.94	37.0
244	111.78	269.25	16.11	3.35	26.90	147.13	3.35	-62.35	135.96	39.9
245	143.74	269.23	16.72	4.31	26.91	147.15	4.31	-62.35	135.97	43.1
246	175.66	269.31	17.34	5.27	26.92	147.16	5.27	-62.35	135.99	46.3
247	207.64	269.23	18.01	6.24	26.93	147.18	6.24	-62.35	136.01	49.4
248	239.62	269.28	18.63	7.21	26.94	147.19	7.21	-62.35	136.02	52.3
211	16.00	149.42	13.49	.73	25.34	144.91	.73	-62.35	133.24	17.7
29	-52.22	150.09	12.92	-2.37	25.35	144.91	-2.37	-62.35	133.24	26.0
30	-80.17	150.13	12.44	-3.63	25.34	144.90	-3.63	-62.35	133.23	33.3
31	-112.27	150.06	11.98	-5.08	25.33	144.88	-5.08	-62.35	133.21	40.8
32	-144.36	150.02	11.46	-6.52	25.32	144.87	-6.52	-62.35	133.19	47.0
28	-16.04	150.13	13.36	-.73	25.35	144.92	-.73	-62.35	133.26	17.8
212	47.91	149.44	13.94	2.19	25.35	144.92	2.19	-62.35	133.25	24.9
213	79.70	149.45	14.27	3.64	25.36	144.93	3.64	-62.35	133.26	33.4

214	111.68	149.45	14.72	5.11	25.37	144.94	5.11	-62.35	133.28	41.0
215	143.60	149.44	15.10	6.58	25.37	144.96	6.58	-62.35	133.29	47.3
222	16.00	189.35	13.71	.62	26.01	145.85	.62	-62.35	134.39	24.9
40	-48.05	190.20	13.11	-1.85	26.01	145.85	-1.85	-62.35	134.39	28.3
41	-80.16	190.11	12.60	-3.09	26.00	145.84	-3.09	-62.35	134.38	33.5
39	-15.94	190.22	13.53	-.62	26.01	145.87	-.62	-62.35	134.41	25.0
223	47.95	189.39	14.11	1.86	26.01	145.86	1.86	-62.35	134.40	28.4
224	79.76	189.34	14.54	3.10	26.02	145.87	3.10	-62.35	134.42	33.7
225	111.70	189.40	15.05	4.34	26.03	145.89	4.34	-62.35	134.43	39.3
226	143.57	189.40	15.73	5.59	26.04	145.90	5.59	-62.35	134.45	44.6
227	175.56	189.43	16.37	6.85	26.05	145.92	6.85	-62.35	134.47	49.2
228	207.48	189.45	16.93	8.11	26.06	145.93	8.11	-62.35	134.49	53.2
229	239.46	189.46	17.56	9.37	26.07	145.95	9.37	-62.35	134.51	56.7
42	-112.24	190.10	12.03	-4.32	25.99	145.83	-4.32	-62.35	134.36	39.1
43	-144.30	190.10	11.52	-5.54	25.98	145.81	-5.54	-62.35	134.34	44.2
44	-176.34	190.00	10.79	-6.77	25.96	145.79	-6.77	-62.35	134.32	48.8
45	-208.36	190.07	9.97	-7.97	25.95	145.78	-7.97	-62.35	134.30	52.7
46	-240.36	190.07	9.25	-9.18	25.94	145.76	-9.18	-62.35	134.28	56.1
232	15.97	229.21	14.00	.54	26.50	146.55	.54	-62.35	135.25	29.8
56	-240.44	230.04	9.32	-8.00	26.43	146.46	-8.00	-62.35	135.13	53.5
55	-208.42	230.06	10.12	-6.95	26.44	146.48	-6.95	-62.35	135.15	50.3
233	47.91	229.23	14.40	1.62	26.50	146.56	1.62	-62.35	135.26	31.8
234	79.76	229.28	14.96	2.70	26.51	146.58	2.70	-62.35	135.28	35.2
235	111.69	229.26	15.49	3.78	26.52	146.59	3.78	-62.35	135.29	39.3
236	143.59	229.24	16.20	4.87	26.53	146.60	4.87	-62.35	135.31	43.4
237	175.58	229.28	16.83	5.96	26.54	146.62	5.96	-62.35	135.33	47.3
238	207.59	229.35	17.45	7.05	26.55	146.64	7.05	-62.35	135.35	50.9
239	239.45	229.38	18.08	8.15	26.56	146.65	8.15	-62.35	135.37	54.1
52	-112.19	230.15	12.10	-3.76	26.48	146.53	-3.76	-62.35	135.21	39.0

53	-144.38	230.06	11.52	-4.83	28.47	146.51	-4.83	-62.35	135.10	43.0
54	-176.38	230.09	10.87	-5.80	26.46	146.40	-5.80	-62.35	135.18	46.8
49	-15.07	230.10	13.70	-.54	26.50	146.56	-.54	-62.35	135.26	20.0
50	-48.11	230.18	13.32	-1.62	26.50	146.55	-1.62	-62.35	135.25	31.8
51	-80.11	230.16	12.77	-2.60	26.40	146.54	-2.60	-62.35	135.23	35.0
250	16.02	309.20	14.67	.43	27.18	147.53	.43	-62.35	136.43	36.0
68	-48.11	310.27	13.93	-1.28	27.17	147.52	-1.28	-62.35	136.43	36.9
69	-80.19	310.21	13.38	-2.14	27.17	147.51	-2.14	-62.35	136.41	38.4
70	-112.22	310.23	12.61	-2.98	27.16	147.49	-2.98	-62.35	136.40	40.5
71	-144.08	310.19	11.87	-3.83	27.14	147.48	-3.83	-62.35	136.38	42.8
72	-176.25	310.14	11.12	-4.68	27.13	147.46	-4.68	-62.35	136.36	45.3
67	-16.04	310.31	14.52	-.43	27.18	147.53	-.43	-62.35	136.44	36.1
251	47.93	309.20	15.29	1.28	27.19	147.54	1.28	-62.35	136.45	37.0
252	79.87	309.26	16.02	2.14	27.20	147.55	2.14	-62.35	136.47	38.7
253	111.72	309.25	16.69	3.00	27.21	147.57	3.00	-62.35	136.48	40.8
254	143.73	309.21	17.26	3.87	27.21	147.58	3.87	-62.35	136.50	43.3
255	175.65	309.23	17.88	4.73	27.22	147.59	4.73	-62.35	136.51	45.9
260	16.02	351.20	15.09	.39	27.43	147.89	.39	-62.35	136.88	38.2
78	-48.14	352.37	14.20	-1.16	27.43	147.88	-1.16	-62.35	136.87	38.8
79	-80.15	352.26	13.54	-1.93	27.42	147.87	-1.93	-62.35	136.86	39.9
80	-112.22	352.25	12.67	-2.69	27.41	147.86	-2.69	-62.35	136.84	41.4
77	-16.05	352.34	14.88	-.39	27.44	147.90	-.39	-62.35	136.89	38.3
261	47.91	351.15	15.90	1.16	27.44	147.91	1.16	-62.35	136.90	38.9
262	79.90	351.18	16.53	1.93	27.45	147.92	1.93	-62.35	136.92	40.2
263	111.82	351.22	17.17	2.71	27.46	147.93	2.71	-62.35	136.93	41.8

NP=078 AP=0,19.42,151.18 TP=0,26.24,140 REF: Z=147.1 LOC=R7,C1 PHI=55 TI

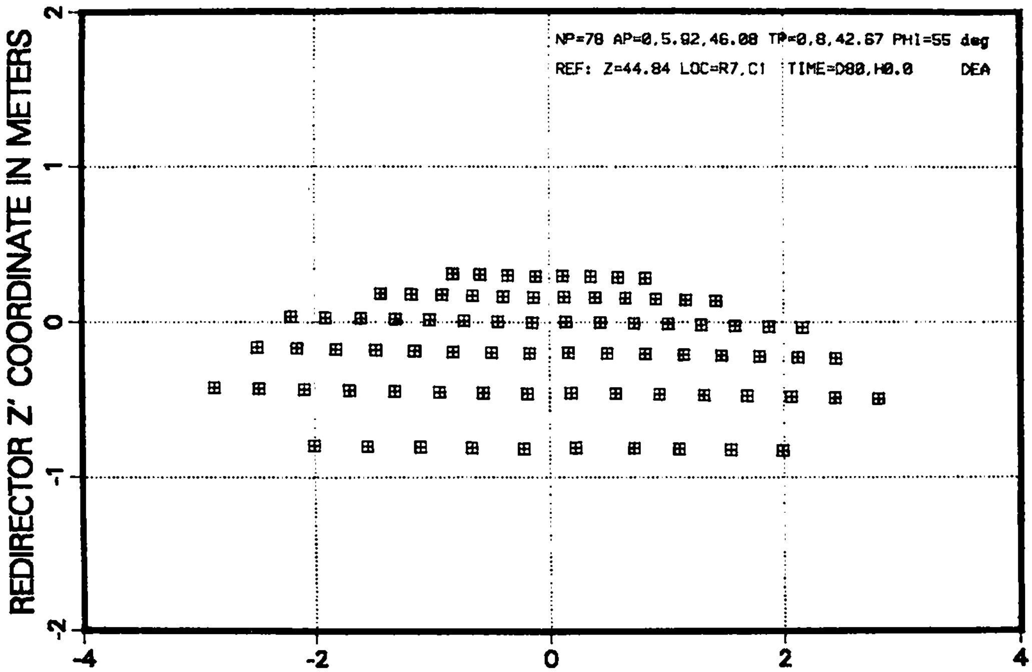
****

DIRECTION COSINES FOR FACET NORMALS
IN TOWER REFERENCE FRAME

HELIOSTAT	FACET NORMAL			PIERCE POINT		
241	-.0065	.4709	-.8822	.48	26.88	147.10
59	.0189	.4722	-.8813	-1.43	26.87	147.09
60	.0290	.4745	-.8798	-2.37	26.86	147.08
61	.0390	.4777	-.8777	-3.33	26.85	147.06
62	.0460	.4812	-.8754	-4.27	26.84	147.05
63	.0509	.4849	-.8731	-5.21	26.83	147.03
64	.0540	.4885	-.8709	-6.15	26.82	147.02
65	.0558	.4919	-.8689	-7.09	26.81	147.00
58	.0064	.4711	-.8821	-.48	26.88	147.10
242	-.0187	.4726	-.8811	1.44	26.88	147.11
243	-.0291	.4754	-.8793	2.39	26.89	147.12
244	-.0373	.4792	-.8769	3.35	26.90	147.13
245	-.0431	.4832	-.8745	4.31	26.91	147.15
246	-.0467	.4872	-.8720	5.27	26.92	147.16
247	-.0486	.4911	-.8698	6.24	26.93	147.18
248	-.0492	.4946	-.8677	7.21	26.94	147.19
211	-.0317	.4525	-.8912	.73	25.34	144.91
29	.0912	.4584	-.8841	-2.37	25.35	144.91
30	.1204	.4657	-.8767	-3.63	25.34	144.90
31	.1372	.4745	-.8695	-5.08	25.33	144.88
32	.1421	.4826	-.8643	-6.52	25.32	144.87
28	.0315	.4522	-.8914	-.73	25.35	144.92
212	-.0855	.4574	-.8852	2.19	25.35	144.92
213	-.1193	.4654	-.8770	3.64	25.36	144.93
214	-.1350	.4742	-.8700	5.11	25.37	144.94
215	-.1385	.4823	-.8650	6.58	25.37	144.95
222	-.0178	.4492	-.8932	.62	26.01	145.85
40	.0490	.4531	-.8901	-1.85	26.01	145.85
41	.0748	.4595	-.8850	-3.09	26.00	145.84
39	.0175	.4493	-.8932	-.62	26.01	145.87
223	-.0499	.4532	-.8900	1.86	26.01	145.86
224	-.0738	.4598	-.8850	3.10	26.02	145.87
225	-.0886	.4675	-.8795	4.34	26.03	145.89
226	-.0957	.4753	-.8746	5.59	26.04	145.90
227	-.0976	.4823	-.8706	6.85	26.05	145.92
228	-.0962	.4883	-.8674	8.11	26.06	145.93
229	-.0928	.4933	-.8649	9.37	26.07	145.95
42	.0908	.4671	-.8795	-4.32	25.99	145.83
43	.0993	.4747	-.8745	-5.54	25.98	145.81
44	.1027	.4815	-.8704	-6.77	25.96	145.79
45	.1027	.4873	-.8672	-7.97	25.95	145.78
46	.1006	.4923	-.8646	-9.18	25.94	145.76
232	-.0105	.4588	-.8885	.54	26.50	146.55
56	.0760	.4904	-.8682	-8.00	26.43	146.46
55	.0754	.4860	-.8707	-6.95	26.44	146.48
233	-.0302	.4614	-.8867	1.62	26.50	146.56
234	-.0461	.4658	-.8837	2.70	26.51	146.58
235	-.0576	.4713	-.8801	3.78	26.52	146.59
236	-.0647	.4772	-.8764	4.87	26.53	146.60
237	-.0684	.4828	-.8731	5.96	26.54	146.62
238	-.0694	.4879	-.8701	7.05	26.55	146.64
239	-.0687	.4923	-.8677	8.15	26.56	146.65
52	.0595	.4703	-.8805	-3.76	26.48	146.53
53	.0681	.4758	-.8769	-4.83	26.47	146.51

54	.0730	.4811	-.8736	-5.89	26.46	146.49
49	.0104	.4590	-.8884	-.54	26.50	146.56
50	.0303	.4612	-.8868	-1.62	26.50	146.55
51	.0470	.4652	-.8840	-2.69	26.49	146.54
250	-.0040	.4824	-.8759	.43	27.18	147.53
68	.0118	.4831	-.8755	-1.28	27.17	147.52
69	.0191	.4844	-.8746	-2.14	27.17	147.51
70	.0254	.4861	-.8735	-2.98	27.16	147.49
71	.0307	.4882	-.8722	-3.83	27.14	147.48
72	.0348	.4906	-.8707	-4.68	27.13	147.46
67	.0040	.4827	-.8758	-.43	27.18	147.53
251	-.0116	.4836	-.8752	1.28	27.19	147.54
252	-.0183	.4856	-.8740	2.14	27.20	147.55
253	-.0238	.4879	-.8725	3.00	27.21	147.57
254	-.0281	.4906	-.8709	3.87	27.21	147.58
255	-.0311	.4934	-.8693	4.73	27.22	147.59
260	-.0024	.4932	-.8699	.39	27.43	147.89
78	.0072	.4934	-.8698	-1.16	27.43	147.88
79	.0117	.4939	-.8694	-1.93	27.42	147.87
80	.0160	.4947	-.8689	-2.69	27.41	147.86
77	.0024	.4933	-.8698	-.39	27.44	147.90
261	-.0070	.4941	-.8694	1.16	27.44	147.91
262	-.0111	.4953	-.8687	1.93	27.45	147.92
263	-.0145	.4968	-.8677	2.71	27.46	147.93

REDIRECTOR PIERCE POINTS ZONE A



REDIRECTOR X' COORDINATE IN METERS

APPENDIX B

HELIOS Updates

The mathematical models used in HELIOS are fully explained in Reference 3. A complete description of the procedures required to run the code are given in SAND81-1180 and SAND81-1562. HELIOS has recently been modified to accept reconcentrators with up to six panels. This revision was specifically written for the McDonnell-Douglas-Rocketdyne external cavity receiver. The updates required for this particular redirector design and a brief explanation of the purpose of each subroutine follow:

1. BASKET tabulates the portion of the target that accepts the reflected ray from the redirector or reconcentrator.

```
*DELETE       BASKET.4,BASKET.42
C
C       ROUTINE DETERMINES WHICH BASKET THE RECONCENTRATOR DIRECTS
C       ENERGY INTO.  THE RECEIVER IS CENTERED AT (0.,8.,42.67)
C       WITH XEXT=1. AND YEXT=1. FACING UP
C
        IF(ABS(XI).GT.0.55) GO TO 10
C
C       BASKETS MADE LARGER THAN RECEIVER SO BASKET MIDPOINTS
C       CORRESPOND TO THE 121 TARGET POINTS IN THE RECEIVER.
        DEY=0.1
        YMAX=8.5+DEY*0.5
        YMIN=7.5-DEY*0.5
        IF(YI.GT.YMAX) GO TO 10
        IF(YI.LT.YMIN) GO TO 10
        IF(ABS(ZI-42.67).LT.1.E-5) GO TO 20
        WRITE (6,99999) XI,YI,ZI
        STOP 222
   10   IBASX=-1
        IBASY=-1
        RETURN
   20   IBASY=0
        Y-YMAS
   30   IBASY=IBASY+1
        Y=Y-DEY
```

```
      IF(YI.GT.Y) GO TO 40
      GO TO 30
   40 DEX=0.1
      XMAX=0.5+DEX*0.5
      X=XMAX
      IBASX=0
   50 X=X-DEX
      IBASX=IBASX+1
      IF(XI.GT.X) GO TO 60
      GO TO 50
   60 IF (IBASX.GT.11.OR.IBASY.GT.11) GO TO 10
      RETURN
C
99999 FORMAT (IX,6HBASKET,3E15.5)
C
      END
```

2. USERTG is a routine to specify tower coordinates XTA, YTA, and ZTA and normal vector VMT(I) I = 1,3 at target point number NTAG. This form describes the 10 panels of the redirector.

```
*DELETE         USTG1.31,USTG1.143
      IF(ISECT.LE.0.OR.ISECT.GT.10) GO TO 150
      NR=(NTAG-1)/IXPTS+1
      NTU=(NR-1)*IXPTS
      NCOL=NTAG-NTU
      GO TO (10,20,30,40,50,60,70,80,90,100),ISECT
   10 XTA=8.0000
      YTA=27.5259
      ZTA=148.0150
      ANX=-.0489
      ANY=.4928
      ANZ=-0.8687
      GO TO 110
   20 XTA=4.0000
      YTA=27.5259
      ZTA=148.0150
      ANX=-.0302
      ANY=.4866
      ANZ=-.8731
      GO TO 110
   30 XTA=0.0000
      YTA=27.5259
      ZTA=148.0150
      ANX=.0001
      ANY=.4845
      ANZ=-0.8748
      GO TO 110
   40 XTA=-4.0000
      YTA=27.5259
      ZTA=148.0150
```

```
      ANX=.0324
      ANY=.4847
      ANZ=-.8741
      GO TO 110
 50   XTA=-8.0
      YTA=27.5259
      ZTA=148.0150
      ANX=.0549
      ANY=.4902
      ANZ=-.8699
      GO TO 110
 60   XTA=8.0
      YTA=25.9486
      ZTA=145.7623
      ANX=-.0939
      ANY=.4879
      ANZ=-.8679
      GO TO 110
 70   XTA=4.0
      YTA=25.9486
      ZTA=145.7623
      ANX=-.0714
      ANY=.4687
      ANZ=-.8805
      GO TO 110
 80   XTA=0.0
      YTA=25.9486
      ZTA=145.7623
      ANX=-.0056
      ANY=.4554
      ANZ=-.8903
      GO TO 110
 90   XTA=-4.0
      YTA=25.9486
      ZTA=145.7623
      ANX=.0862
      ANY=.4694
      ANZ=-.8788
      GO TO 110
100   XTA=-8.0
      YTA=25.9486
      ZTA=145.7623
      ANX=.0999
      ANY=.4868
      ANZ=-.8678
110   ASQ=(ANX*ANX+ANY*ANY)**0.5
      DX=4.0
      DZ=2.75
      E1X=ANY/ASQ
      E1Y=-ANX/ASQ
      E2X=E1Y*ANZ
      E2Y=-E1X*ANZ
      E2Z=-ANX*E1Y+E1X*ANY
      DX=DX/FLOAT(IXPTS-1)
```

```
      DZ=DZ/FLOAT(IYPTS-1)
      AFLX=FLOAT(IXPTS-1)*(DX/2.)
      AFLY=FLOAT(IYPTS-1)*(DZ/2.)
      XA=XTA+AFLX*E1X+AFLY*E2X
      YA=YTA+AFLX*E1Y+AFLY*E2Y
      ZA=ZTA+AFLY*E2Z
      AFCOL=FLOAT(NCOL-1)*DX
      AFRO=FLOAT(NR-1)*DZ
      XTA=(XA+AFCOL*(-E1X)+AFRO*(-E2X))*.3048
      YTA=(YA+AFCOL*(-E1Y)+AFRO*(-E2Y))*.3048
      ZTA=(ZA+AFRO*(-E2Z))*.3048
  135 VMT(1)=ANX
      VMT(2)=ANY
      VMT(3)=ANZ
      RETURN
  150 WRITE(NOUT,99999)
      STOP 111
C
99999 FORMAT(2X,50HSTOP IN USERTS, USER DEFINED TARGET SURFACE ERROR.)
      END
```

3. RARE generates the ratio of an element of area on a redirector facet to an element of area on the target.

```
*DELETE       RAREC.20,RAREC.59
      RAREA=5.5*A*20.*(.3048**2)/10.
      RA=(1.+.1)*(1.+.1)
      RAREA=RAREA/RA
      RETURN
      END
```

4. POWREC integrates the flux-density incident upon each of the 10 redirector surfaces. It is necessary to redimension RECOP to accept the 10 redirectors.

```
*DELETE      POWREC.9,POWREC.35
      DIMENSION RECOP(121,10),HITE(11,11)
      DO 120 ISECT=1,IRECP
      AXEXT=1.2192
      DX=AXEXT/FLOAT(IXPTS-1)
      DZ=0.08382
```

5. The variables BASK, NWRC, NWRE, and RECOP must be redimensioned in the following subroutines to accept the 10 redirector panels:

```
*DELETE,FACETC.16
      *YTA,ZTA,NTAG1,XT0,YT0,ZT0,BASK(11,12,10),RECN(3),BASKM
```

```
*DELETE,TCIRPC.7
        DIMENSION VFE(3),TV(3),UTV(3),NWRC(10,121),VMT(3),B(3),
*DELETE,FACETC.13
        COMMON/NWRAYS/NWRC(10,121),NWRE(10,11,11),IBASX,IBASY,RAREA,
*DELETE,PHIC.27
       *YTA,ZTA,NTAG1,XT0,YT0,ZT0,BASK(11,11,10),RECN(3),BASKM
*DELETE,C.45
       *YTA,ZTA,NTAG1,XT0,YT0,ZT0,BASK(11,11,10),RECN(3),BASKM
*DELETE,C.56
       *RECD(3),RECOP(121,10),PDT(121),TPDT(3,121),HITE(11,11),
*DELETE,C.38
        COMMON/NWRAYS/NWRC(10,121),NWRE(10,11,11),IBASX,IBASY,RAREA,
```

6. Three DO loops in Overlay C must be revised to allow for the 10 redirector panels.

```
*DELETE,C.74
        DO 30 K=1,10
*DELETE,C.79
        DO 70 I1=1,10
*DELETE,C.85
        DO 100 I1=1,10
```

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