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Mirror Alignment Techniques for Point-Focus Solar Concentrators

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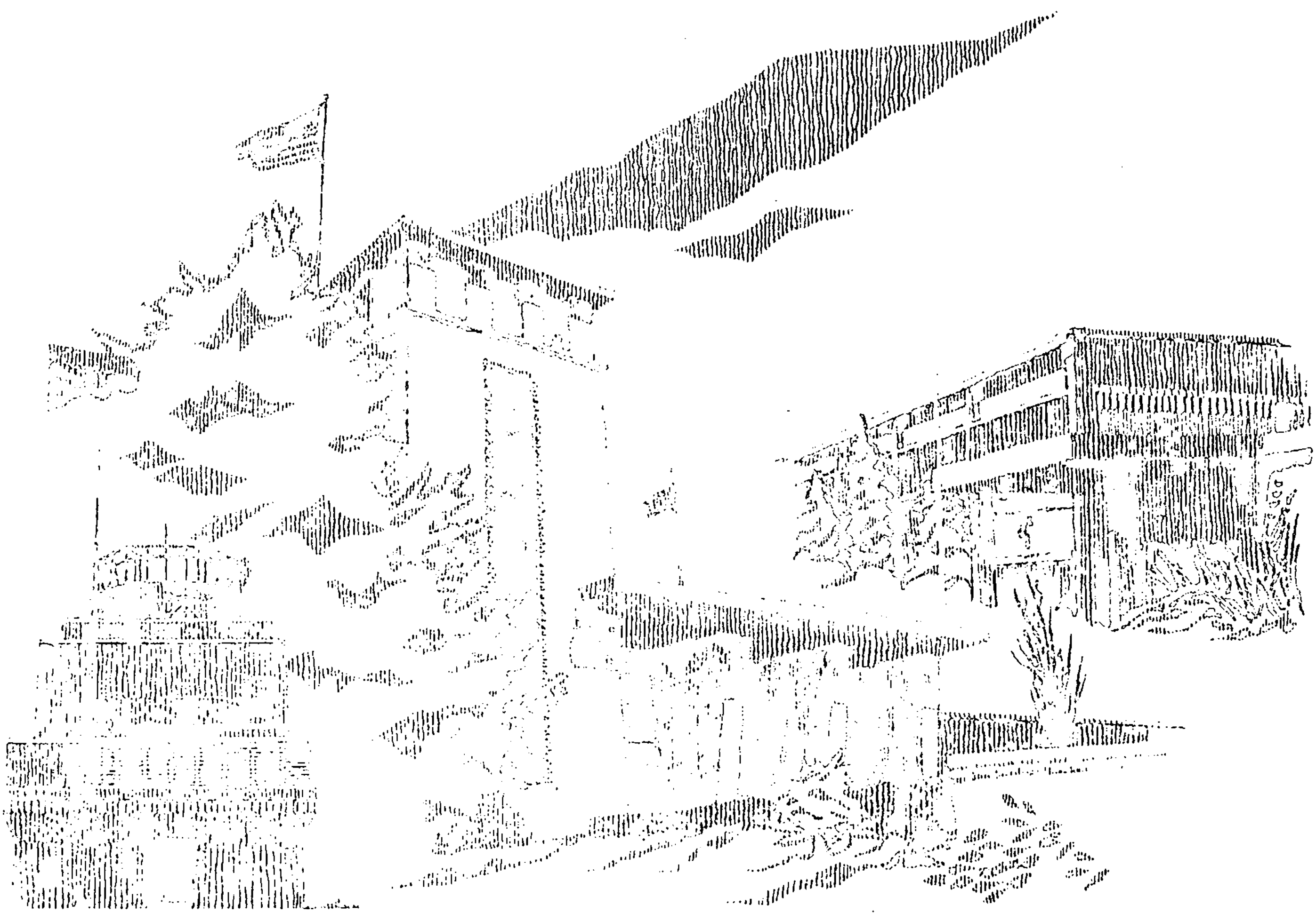

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ABSTRACT

Accurate alignment and focus of mirror facets are critical for the integration of concentrators and receivers in many of the low-cost stretched-membrane concentrators currently under development. In this report, the theoretical development of computer software that traces light rays from a source to a facet of a point-focusing solar concentrator and then to a target is given. Examples of approaches for the alignment of faceted point-focusing solar concentrators, which make use of targets generated by this computer program, are also presented.

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INTRODUCTION

Distributed point-focusing solar concentrators are being developed for dish-Stirling systems (Bean and Kubo 1990; Mancini 1991). Many of these concentrators make use of faceted mirrors that have to be aligned to a particular aim point. Stretched-membrane facets also require focusing. Precise mirror alignment and focusing of faceted solar concentrators have two benefits. First is the improvement in the concentration ratio of the collector. The receiver aperture diameter can therefore be smaller, thereby reducing thermal losses from the receiver and improving the overall efficiency of the concentrator/receiver (collector) system. More important, flux intensities on the receiver are sensitive to facet alignment and focus. Depending on the number of facets, the flux intensity of individual facets can be high. If the reflected images of individual facets are allowed to overlap on the receiver (due to poor alignment), the resulting peak flux intensity can have serious consequences of receiver survivability and/or life. Improper focusing can also contribute to flux "hot spots."

The mirror alignment techniques presented here use artificial light sources. Figure 1 is a schematic of a multifaceted point-focus (dish) concentrator and illustrates the basic approach. Light from a source is reflected from the concentrator facets to a target. From basic geometric principles, the shape and location of the reflected light on the target can be predicted. Alignment is accomplished by adjusting the facet's aim so that the reflected image falls on the predetermined location.

The development of alignment targets involves tracing rays from a light source, to a facet, and then to a target. The equations presented below are based on vector methods used in analytic geometry and generally follow the same approach used by Terry Hagen in the "Dish Optical Analysis Program" (MIRROR7), which is provided as Appendix A to this report. The principal difference between this and the Hagen approach is the use of a coordinate system with the origin at the concentrator's vertex and with the z-axis along the concentrator's optical axis. (In the Hagen analysis, the focal point is the origin and the x-axis is along the concentrator's optical axis.) The FACALGN program presented in Appendix B is, therefore, more readily adaptable to facet input files used in the Sandia-developed CIRCE and CIRCE2 concentrator analysis codes (Ratzel and Boughton 1987; Romero 1992). The MIRROR7 code has been extensively used and has been verified to result in excellent mirror alignment. The MIRROR7 and FACALGN codes produce results that are in agreement when the input parameters are adjusted to account for the different coordinate systems. The FACALGN code has also been enhanced to (1) allow for off-axis light sources, (2) allow off-axis aim points, (3) calculate eight (vs. four) target points for circular facets, and (4) consider hexagonal facets.

In this report, techniques for mirror alignment are described. The governing equations used to draw the alignment targets are developed, and the listings for the MIRROR7 and FACALGN Basic computer programs are provided. Examples illustrating the implementation of these techniques for alignment and focus are also presented.

THEORETICAL DEVELOPMENT

Consider the coordinate system illustrated in Fig. 2. In it the concentrator vertex is the origin. The z-axis is the optical axis of the dish; the facet center location in space is given by its

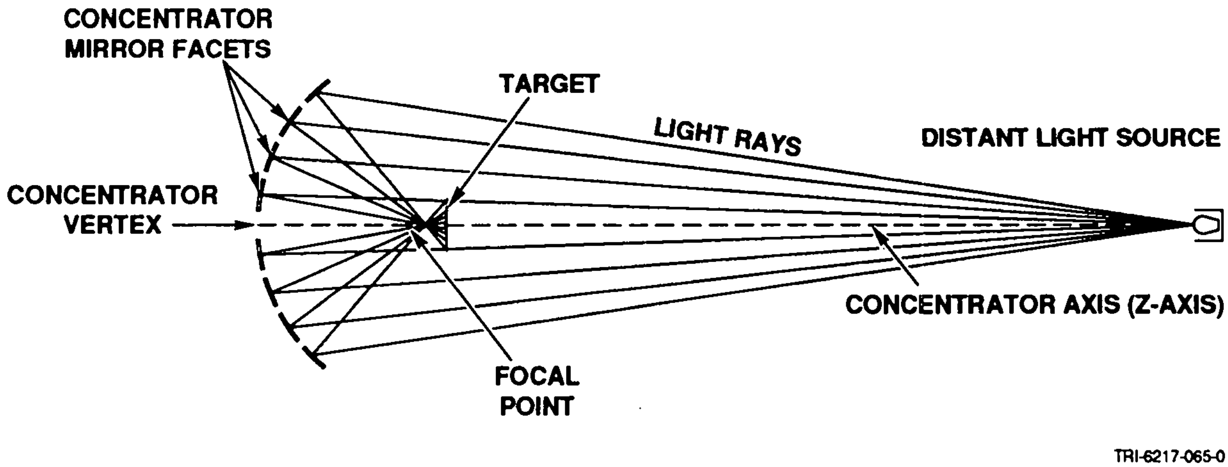

Figure 1. Schematic showing the light source alignment technique. Light from a source at a specified location is reflected from the concentrator facets to an alignment target. The facets' aim and, if necessary, focal length are adjusted to make the reflected images correspond to the theoretically derived locations and shapes drawn on the target.

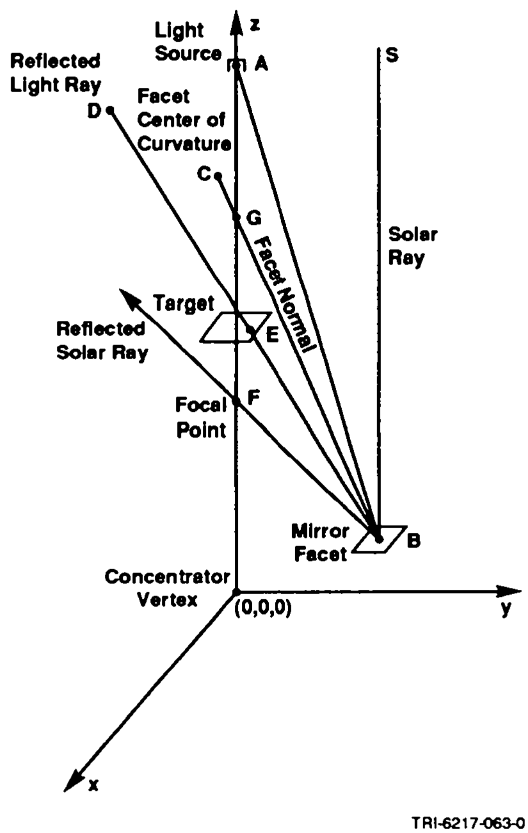

Figure 2. Schematic showing the coordinate system, and locations of the mirror, target, focal point (aim point), light source, and the solar and light rays.

coordinates (B_x, B_y, B_z); and the target is located along and perpendicular to the z-axis. For light to be reflected from the sun to the focal plane, the mirror normal must bisect the angle SBF. In the plane created by SBF (Fig. 3), the distance between points F and G is equal to the distance between points B and F. Point G, in Fig. 3, is at the intersection of the facet normal and a line parallel to the z-axis through the focal point. The location of the facet center of curvature, C, can be determined from the facet radius of curvature, R, and the unit vector of **BG**.

In Fig. 2, the reflected vector **BD** can be calculated from the incoming light source vector **BA**, and the mirror normal vector **BC** by the use of the following vector mathematics equation:

$$BD = 2 \left[\frac{BA \times BC}{BC \times BC} \right] BC - BA , \qquad \text{(Eq. 1)}$$

where the x, y, and z components of vectors **BA** and **BC** are

$$BA_x = A_x - B_x, BA_y = A_y - B_y, BA_z = A_z - B_z \text{ , and} \qquad \text{(Eq. 2)}$$

$$BC_x = C_x - B_x, BC_y = C_y - B_y, BC_z = C_z - B_z , \qquad \text{(Eq. 3)}$$

respectively.

The dot products in Eq. 1 are

$$\mathbf{BA} \times \mathbf{BC} = BA_x \times BC_x + BA_y \times BC_y + BA_z \times BC_z , \qquad \text{(Eq. 4)}$$

and

$$\mathbf{BC} \times \mathbf{BC} = BC_x \times BC_x + BC_y \times BC_y + BC_z \times BC_z . \qquad \text{(Eq. 5)}$$

Equation 1 is based on the law of reflection and has been derived for unit vectors by Biggs and Vittitoe (1976). Note that vector **BD** (from Eq. 1) has the same magnitude as vector **BA**.

The location of where vector **BD** intersects the target plane (point E) can be calculated by scaling the x and y components of vector **BC** in accordance with the z component, which is known.

The scale factor between vector **BE** and vector **BD**, M, is therefore,

$$M = \frac{E_z - B_z}{D_z - B_z} . \qquad \text{(Eq. 6)}$$

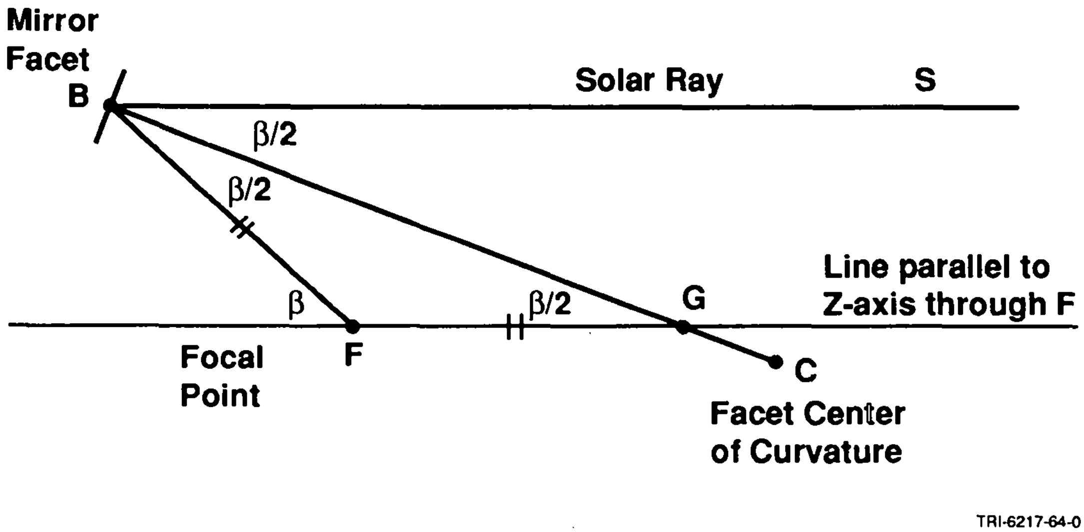

Figure 3. Two-dimensional representation of the coordinate system that shows that the distance from the mirror to the focal point is equal to the distance between the focal point and where the mirror normal crosses the mirror optical axis.

The x and y coordinates at the target, point E, are therefore,

$$E_y = B_y + M\,(D_y - B_y)\ , \text{ and} \qquad \text{(Eq. 7)}$$

$$E_z = B_z + M\,(D_z - B_z)\ . \qquad \text{(Eq. 8)}$$

The above equations determine the target location of light reflected from the mirror's center location. To determine the shape of the reflected image, the same basic equations are used to trace rays from the light source to the facet's corners or edges and then to the target plane.

Determining the location of the facet's corner and edges is simplified by calculating their positions in a coordinate system that has its origin at the facet's center of curvature, C, and has its z-axis along the facet's normal. The facet's center position in this (facet) coordinate system is therefore (0,0,-Rho), where Rho is the facet's radius of curvature. The coordinates (x,y,z) of one of a rectangular facet's corners in the facet coordinate system, for example, are (W/2, H/2, $-(Rho^2 - (W/2)^2 - (H/2)^2)^{1/2}$), where W is the facet's width (along the x-axis), and H is the facet's height (along the y-axis). The corner and edge locations in the original (x,y,z) coordinate system are determined by performing rotational and translational transformations.

The polar coordinate angles, ϕ and θ, that are used in the conversion equations between a rectangular coordinate system and a polar coordinate system, Fig. 4, are useful for determining the rotational angles, Y and Z, between the two coordinate systems. Note that Fig. 4 is a different perspective of the coordinate system shown in Fig. 2. In Fig. 4, $Z = 90 - \theta$, and $Y = 90 - \phi$. As can be seen in Fig. 4, in order to align the primary coordinate system (x,y,z) along

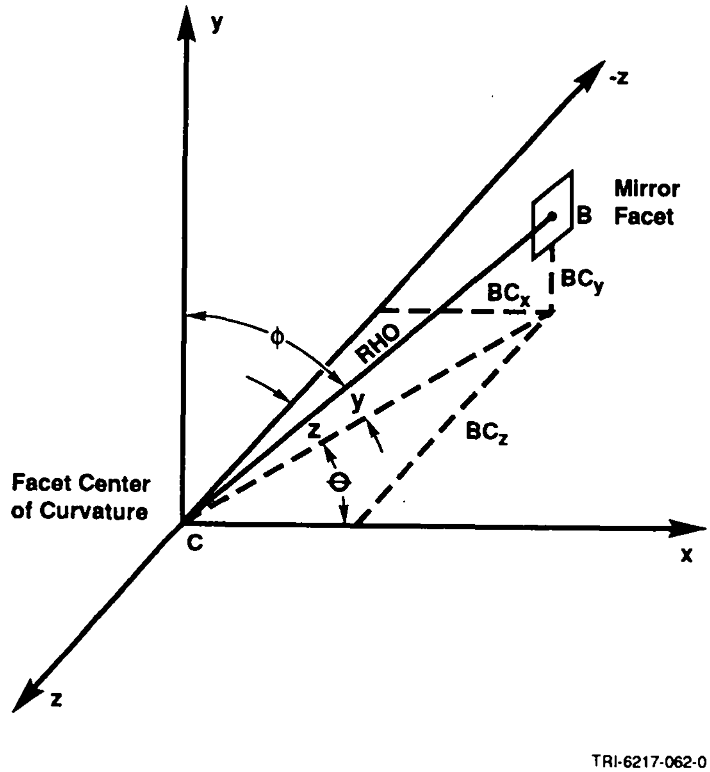

Figure 4. Schematic that shows the relationship between the facet and the primary (x,y,z) coordinate systems. To align the primary coordinate system with the facet coordinate systems, the primary coordinate system must be rotated around the y-axis by -Z and around the x-axis by -Y.

the facet coordinate system (vector **BC**), we must rotate the primary coordinate system around the y-axis by -Z and rotate the primary coordinate system around the x-axis by -Y.

The coordinate conversion equations used to determine ϕ and θ, respectively, are

$$\cos\phi = -BC_y \,/\, Rho \,, \qquad \text{(Eq. 9)}$$

and

$$\cos\theta = -BC_x \,/\, (Rho \times \sin\phi) \,. \qquad \text{(Eq. 10)}$$

The matrix transformation that rotates the primary coordinate system about the y-axis, Ry, by the angle Z is:

$$R_y = \begin{matrix} \cos Z & 0 & -\sin Z \\ 0 & 1 & 0 \\ \sin Z & 0 & \cos Z \end{matrix} \,. \qquad \text{(Eq. 11)}$$

The matrix transformation that rotates the primary coordinate system about the x-axis, Rx, by the angle Y is

$$R_x = \begin{matrix} 1 & 0 & 0 \\ 0 & \cos Y & -\sin Y \\ 0 & \sin Y & \cos Y \end{matrix} \quad . \qquad \text{(Eq. 12)}$$

The basis for Eq. 11 and Eq. 12 can be found in analytic geometry textbooks such as Morrill (1969).

The complete rotational transformation matrix, R_y x R_x, is

$$R_y x R_x = \begin{matrix} \cos Z & -\sin Z \sin Y & -\sin Z \cos Y \\ 0 & \cos Y & -\sin Y \\ \sin Z & \sin Y \cos Z & \cos Z \cos Y \end{matrix} \quad . \qquad \text{(Eq. 13)}$$

(Note that, as discussed above, the original coordinate system is rotated through the angles -Z and -Y to align it with the facet coordinate system.)

The inverse rotational matrix, R_y x R_x^{-1}, that rotates the facet coordinate system into the original (x,y,z) coordinate system, is

$$R_y x R_x^{-1} = \begin{matrix} \cos Z & 0 & -\sin Z \\ \sin Z \sin Y & \cos Y & -\sin Y \cos Z \\ \sin Z \cos Y & \sin Y & \cos Z \cos Y \end{matrix} \quad . \qquad \text{(Eq. 14)}$$

To translate the coordinate system from point C to the origin in the original (x,y,z) coordinate system, the facet's center of curvature location (C_x,C_y,C_z) is added to the rotated results from Eq. 14.

The computer program that implements these calculations for a single square, rectangular, circular, or hexagonal facet is called FACALGN and is listed in Appendix B. It is written in advanced Basic for IBM-compatible personal computers. Inputs to the program are (1) a mirror identification number, (2) the location of the light source relative to the dish vertex (A_x,A_y,A_z), (3) the coordinates of the mirror facet location (B_x,B_y,B_z), (4) the facet's aim point (F_x,F_y,F_z), (5) the facet radius of curvature, and (6) the location of the target along the z-axis (E_z). All dimensions are in meters. The program can be readily adapted to accept this data from input files and to write results to output files or plotters to draw targets.

ALIGNMENT PROCEDURES

Several techniques for mirror alignment based on the use of a light source have been used. Lasers can be used to determine the facet's center reflection location on a target, or the entire concentrator can be illuminated to produce facet patterns on the target. Light source and target positions can be varied to adapt to specific requirements. In all of the techniques, the light source is located along or near the optical axis of the concentrator.

Laser Alignment

The first approach makes use of a laser, which is convenient to locate behind the vertex of the dish, pointing along the dish axis. The laser defines the z-axis of the concentrator. In this "laser alignment" technique, a small, flat mirror, which can be swiveled about its reflective surface, is attached to the center of the target and serves as the light source, Fig. 5. The target is mounted perpendicular to the dish at a distance of 2 to 2.3 dish focal lengths from the vertex (1 to 1.3 focal lengths behind the focal point). Target location is usually a tradeoff of target size and separation of target points. The target board for this approach need only have the center locations designated. Alignment is accomplished by reflecting the laser beam to the centers of each of the facets and adjusting them until the reflected laser light falls on the calculated location. This approach has the advantage that with a powerful enough laser, alignment can be accomplished during the day. Also in a large field of dishes, where a distant light source may not be accessible to all concentrators, alignment by this technique is possible. It does require, however, removal of the receiver.

The laser alignment approach was first implemented at the University of Minnesota solar furnace (Diver et al. 1983). In the University of Minnesota solar furnace, the concentrator facets all have the same radii of curvature and were therefore placed equal distance from the focus. Thus the calculated intersection of all 312 facet normals (aimed at the focal point) and the concentrator's axis were the same: one focal length behind the focus. To align the mirrors, a small neon laser was mounted behind the concentrator and aimed at the heliostat along the concentrator's z-axis. The laser defined the concentrator axis. A reference mark on the heliostat was used to ensure consistent alignment. A small, flat, front-silvered mirror mounted on a ball-and-socket swivel was then used to direct the laser beam to the center of each facet. (The ball and socket was designed so that the center of the mirror surface remained in the same position along the concentrator's axis as the mirror was swiveled.) The facet was then adjusted until the laser reflected back on itself. Masking of the alignment mirror with white paper, except for a small circular area in the center, was helpful for locating and adjusting the returned laser beam onto itself.

This approach has also been used to align test bed concentrator number 2 (TBC-2) at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM. Figure 6 shows the flat mirror at the target being adjusted to the TBC facet in the left-hand side of the photograph. A red filter monocle is being used to help locate the laser on the center of the facet. The reflected laser beam from the facet's center is adjusted to the calculated return points on the target. The mathematical principles used in the laser alignment technique have also been utilized to evaluate facet alignment at the NSTTF.

Distant Light Source Alignment

In the "distant light source" alignment technique, a light is placed at a distance of approximately 300 to 600 meters along the axis of the dish. A target is placed either in front of or behind the focal plane. If it is placed in front of the focal plane, alignment can be done with a receiver in place. The target is a montage of patterns drawn on paper or Mylar and supported on a flat, rigid structure. The exact location and shape of the patterns are calculated by the FACALGN computer program. At night, light reflected from the facets to the target produces patterns that

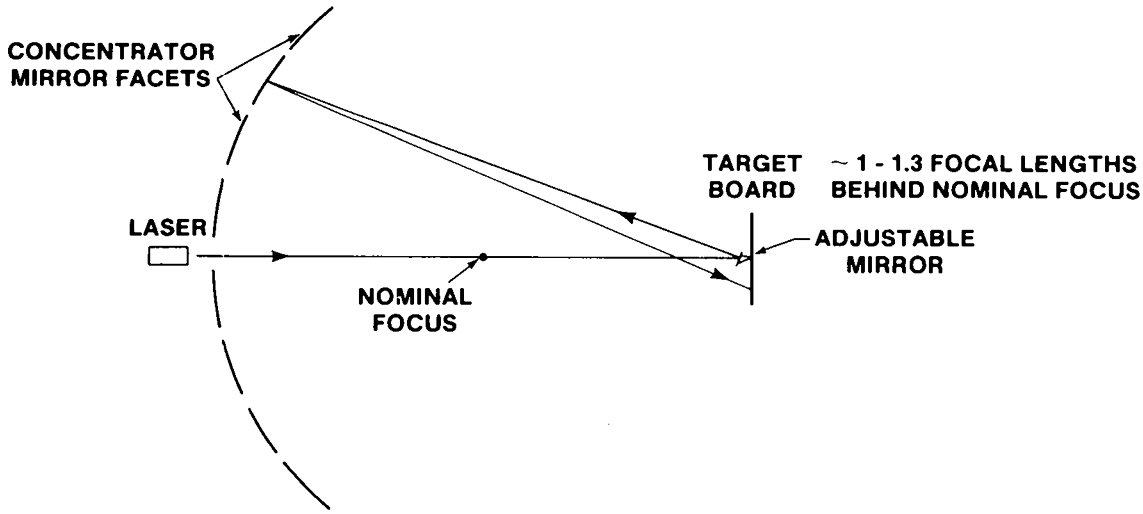

Figure 5. Schematic showing the laser alignment technique.

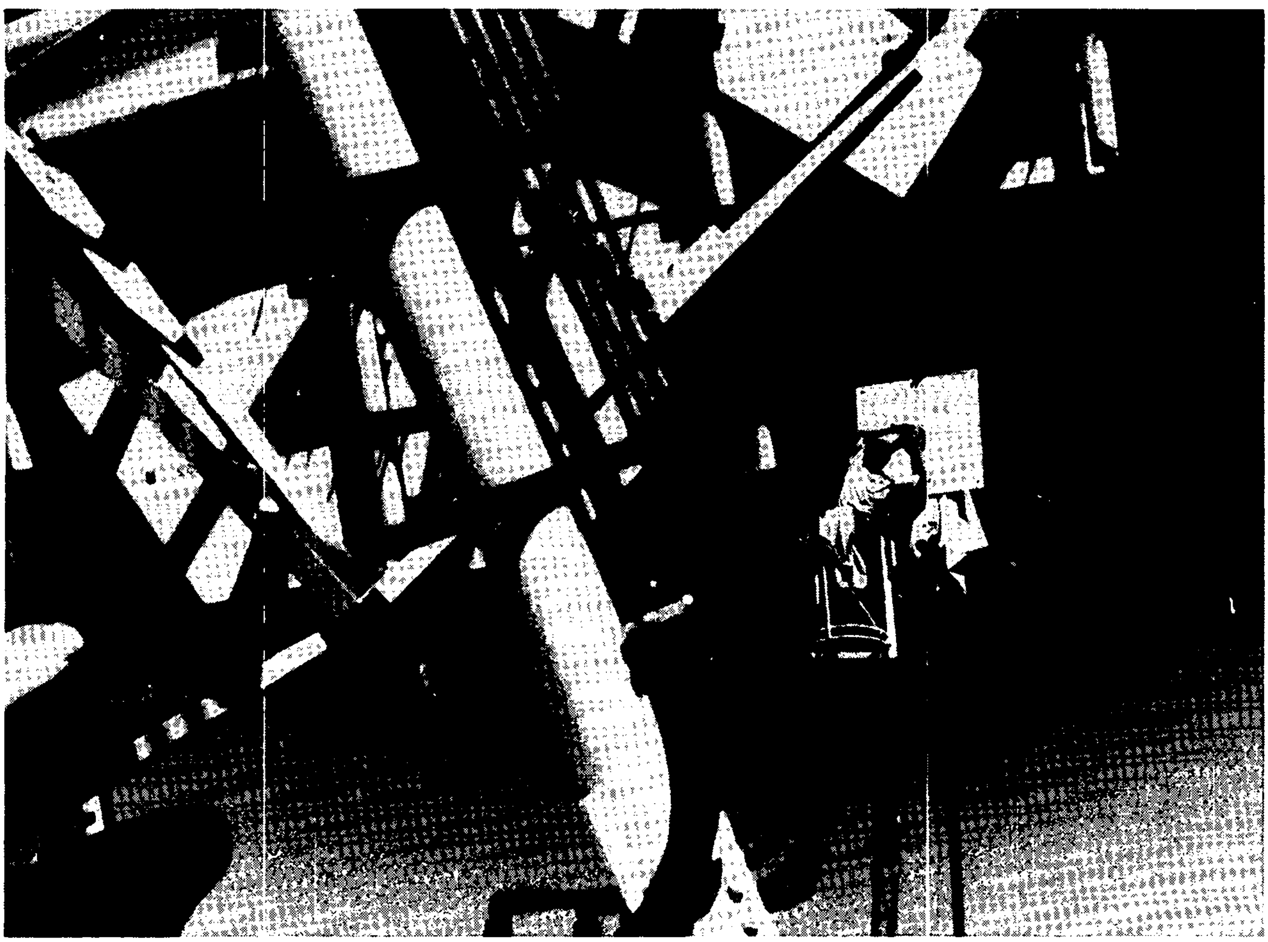

Figure 6. Photograph showing the laser alignment technique being implemented on TBC-2 at the National Solar Thermal Test Facility.

should match up with the computer-calculated patterns. Facets are adjusted to make the searchlight-reflected patterns overlap the computer-calculated patterns. The shape of the reflected images relative to the calculated patterns is a qualitative indication of the facet's optical quality. As with the laser alignment technique, it is useful to place a laser behind the vertex along the z-axis to define the concentrator optical axis. Fixtures at the receiver mounting ring, which further define the optical axis, are useful for maintaining a consistent reference axis and accurately pointing the dish's optical axis toward the light source. By placing the target behind the nominal focus, it is possible to create targets with no overlap of facet images.

This approach was developed by the Georgia Institute of Technology (GIT) and used by the Jet Propulsion Laboratory (JPL) at the Parabolic Dish Test Site at Edwards Air Force Base in California. The approach was further refined by Advanco Corp. at Rancho Mirage, CA, and was an important tool for reduction of peak flux intensities in the United Stirling tube receiver (Washom 1984).

This alignment technique is routinely used on the TBCs at the NSTTF. Figure 7 is an alignment target generated with the MIRROR7 program under illumination. An important advantage of this technique is the ability to see the alignment of all facets simultaneously. Good agreement has been observed between this and the laser alignment technique.

Near Light Source Alignment

A combination of the two techniques has been used by Cummins Power Generation, Inc. on the CPG-460 concentrator, Figs. 8 and 9. The light source and target are at one focal length behind the focal point, and the entire concentrator is illuminated.

As with the other techniques, accurate definition of the optical axis is critical to consistent alignment. In the Cummins approach, two neon lasers are used to accurately position the target along the concentrator's z-axis. A fixture plate near the receiver is used to help align the lasers parallel with the z-axis, and a measuring tape is used to place the target at the correct position along the z-axis. The use of two lasers ensures correct rotation of the target relative to the dish. The Cummins concentrator is pointed skyward to achieve a relatively neutral position for gravity-induced structural deflections and to make the facets accessible to adjustment from a ladder. By measuring the changes in the reflected image position as a function of dish orientation, this technique can be used to quantify structural deflections due to gravity. For stretched-membrane facets (like those used on the CPG-460), this technique can also be used to set focal lengths.

One of the advantages of the near alignment technique (relative to the distant light source) is that clear access to a distant light source is not necessary. Alignment can therefore be accomplished in a large field of dishes or where obstructions exist. On the other hand, it is not possible to achieve good pattern separation on a reasonably sized target (as with the distant light source technique). On the CPG-460 target, Fig. 9, the inner five mirrors overlap in the vicinity of the light source. The use of multiple targets and/or light sources is being considered to better resolve the inner mirror alignment.

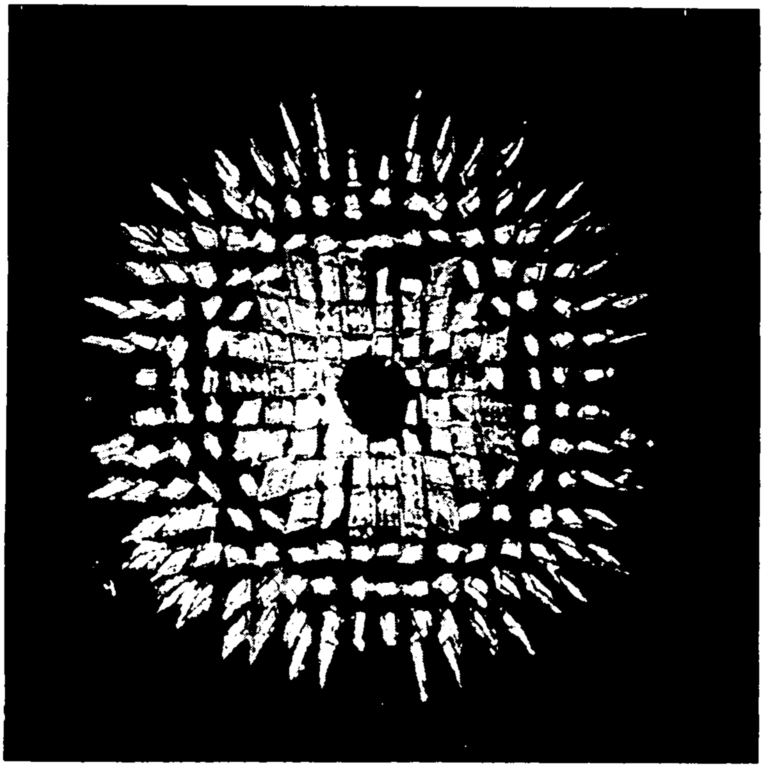

Figure 7. Photograph of a TBC-1 alignment target with illumination. With this alignment technique, the alignment of all of the mirrors can be seen at the same time. This high quality of the TBC mirror facets is apparent in the relatively good match of the predicted and measured shapes of the images.

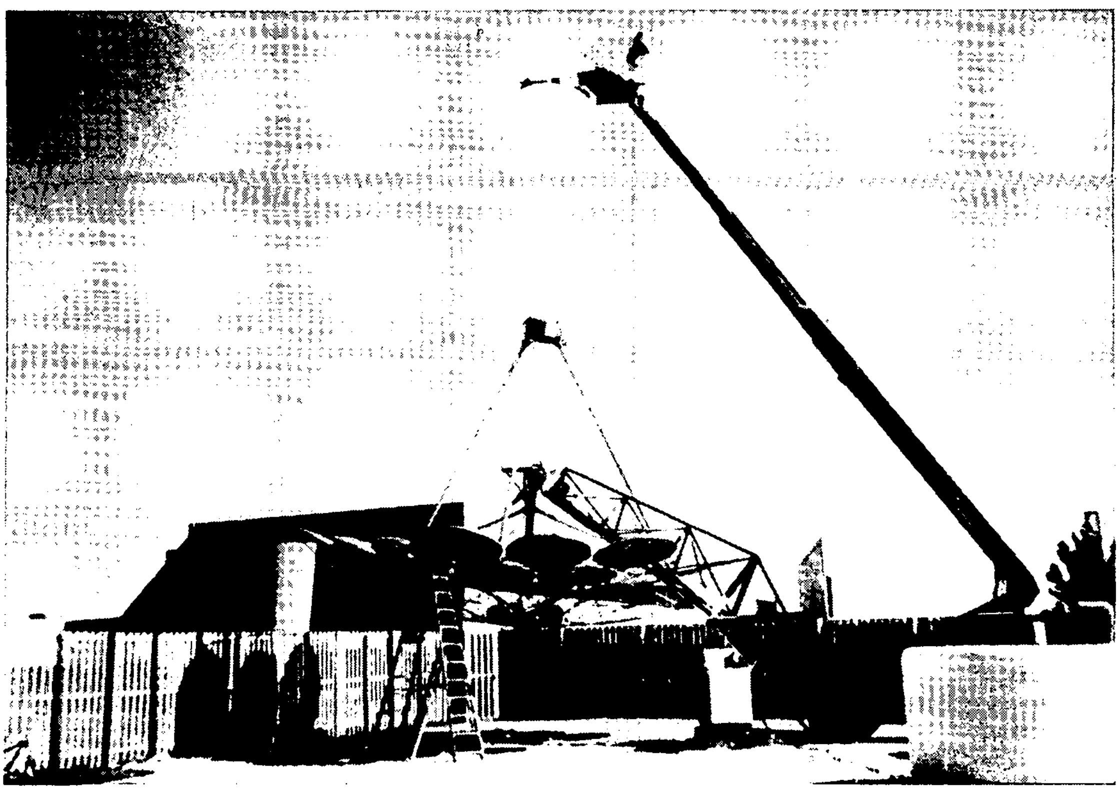

Figure 8. Photograph of the alignment technique adapted to the CPG-460 solar concentrator.

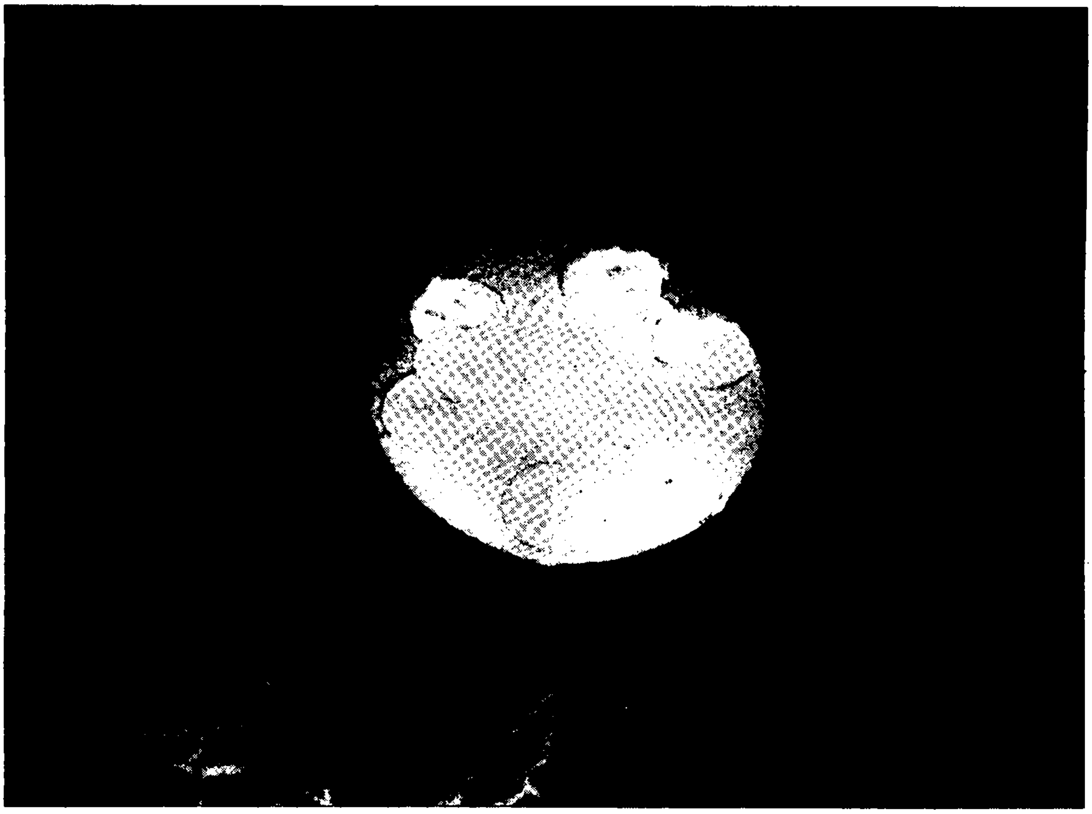

Figure 9. Photograph showing the CPG-460 alignment target with illumination. This technique facilitates focusing as well as alignment of the stretched-membrane facets.

CONCLUSIONS

Proper alignment and focus of faceted solar concentrators are important for improving collector performance and reducing peak flux intensities on solar receivers. Alignment techniques based on the use of a light source and theoretically developed targets have been used to align and focus solar concentrators. The equations that trace the rays from a light source to a facet and then to a target have been developed and implemented in computer software that can be used to produce alignment targets. Similar alignment software has been used on a variety of solar concentrators and adapted to specific alignment requirements. The theory, software, and techniques presented here are intended to provide developers of solar energy systems with practical tools and ideas for achieving high-quality alignment and focus of concentrating solar collectors.

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APPENDIX A

DISH OPTICAL ANALYSIS PROGRAM

Terry Hagen, P.E.

April 23, 1985

DESCRIPTION OF TARGET PATTERN PROGRAM

PROBLEM:

A remote light source is located on the (x-axis) optical center axis of the dish. A target is located perpendicular to the x-axis either behind or in front of the focal plane. A ray from the light source strikes the mirror facet and is then reflected. The reflected light ray strikes the target plane.

GIVEN:

1. Mirror Facet Center Coordinates (x,y,z)
2. Location of Light Source (x)
3. Location of Target Plane (x)
4. Facet aim Point
   Note: The coordinate system is established at this point. This is the Focal Point i.e., the point that a light ray from an infinite light source, reflected off the facet's center, would cross the x-axis.
5. The Mirror Radius of Curvature.
6. The Mirror Facets Shape (Square, Rectangular, or Round) and its Size.

FIND:

1. The Image Coordinates on the Target Plane of a reflected light source ray, from:

   a) The facet's center, and
   b) The facet's four (4) corners if square or rectangular, or
   c) The facet's edge if round at the 0, 90, 180, and 270 degree positions.

SOLUTION:

Lines: 10-130; 180-200; 250-270

Establish a coordinate system with the origin at the focal point, and the x-axis direction perpendicular to the dish (Fig. 1). This coordinate system is the same as Georgia Institute of the Technology's optical program. Input all given data.

Line: 140

Compute distance between facet center and focal point. This will be "MAG" (Fig. 2).

Note that vector BC (the facet's center of curvature axis) splits the angle between vector BS (an incoming light ray from the sun) and vector BF (the reflected ray to the focal point). Thus you have a Rhomus (Fig. 2), and the magnitude of vector BF (or MAG) is equal to the magnitude of vector FG.

Lines: 150-170

Compute the components of vector BG (i.e. from the facet's center to the point where its center of curvature vector crosses the x-axis at point G) (Fig. 3).

Note: That the components are called CX, CY and CZ for now.

Line: 210

Compute the magnitude of vector BG.

Lines: 220-240

Compute the coordinates of point C (the center of curvature for the facet) by scaling up the components of vector BG, and then adding these components to the coordinates of point B.

Lines: 280-350

Find the reflected vector BD, using vector BA (incoming vector from light source) and vector BC (vector normal to the mirror, i.e., the facet's center of curvature axis). From vector mathematics:

$$BD = 2 \left(\frac{BA * BC}{BC * BC} \right) BC - BA$$

where

BA = (AX - BX), (AY - BY), (AZ - BZ)

BC = (CX - BX), (CY - BY), (CZ - BZ)

In Line 290 we find the dot product of BA * BC, which we call "K". We defind the dot product of vectors U = (a,b,c) and V = (d,e,f) to be U * V = (a,b,c) * (d,e,f) = ad + be + cf.

In Line 310 we find the dot product of BC * BC, which we call "L". Finally in Lines 320-350 we use the above reflected vector equation to find the components (X1,Y1,Z1) of vector BD.

Lines: 360-400

Note that the magnitude of vector BD is the same as the magnitude of BA. However, what we want to know, are the coordinates of point E (on the target plane) where the ray of vector BD passes thru the target plane. If we could find a scale factor to multiply vector BD by, such that its X component is the same as the X component of the target plane, then we could compute the coordinates of point E (Fig. 4). To find the scale factor multiplier "M" we write the following equation:

EX = X1 * M + BX   and solve for "M", then EY and EZ.

These are the coordinates on the target of the ray from the light source striking the center of the mirror facet, and then reflected to the target.

Line: 410

Now we will determine the mirror facet corner coordinates. To do this, we first transfer the coordinate system to the center of curvature, with the x-axis along the vector BC (from the mirror facet center to its center of curvature). Maxtrix Transformations will be used. The equation of a sphere is used to compute the facet corner point coordinates in relations to the new coordinate system. We will combine the three transformations;

1. Trasnslation from point F to point C.
2. Rotation about the X-axis, and
3. Rotation about the Y-axis.

into one positive sequential transformation and then use the inverse maxtrix to move the coordinate system back to the focal point. The positive sequential transformation maxtrix (from point F to point C with the x-axis along vector BC) is not needed. Only its inverse is used. The following shows the positive translation matrix:

T * RZ

1	0	0	0		COSTHETA	SINTHETA	0	0
0	1	0	0	*	-SINTHETA	COSTHETA	0	0
0	0	1	0		0	0	1	0
-CX	-CY	-CZ	1		0	0	0	1

T * RZ

	COSTHETA	SINTHETA	0	0	
=	-SINTHETA	COSTHETA	0	0	*
	0	0	1	0	
	-CX	-CY	-CZ	1	

RY

COSPHI	0	-SINPHI	0	
0	1	0	0	=
SINPHI	0	COSPHI	0	
0	0	0	0	

T * RZ * RY

(COSTHETA) (COSPHI)	SINTHETA	-(COSTHETA) (SINPHI)	0
-(SINTHETA) (COSPHI)	COSTHETA	(SINTHETA) (SINPHI)	0
(SINPHI)	0	COSPHI	0
-(CX) (COSPHI)-(CZ) (SINPHI)	-CY	(CX) (SINPHI)-(CZ) (COSPHI)	1

The "inverse" sequential transformation matrix is:

INVERSE

(COSTHETA) (COSPHI)	-(SINTHETA) (COSPHI)	SINPHI	0
SINTHETA	COSTHETA	0	0
-(COSTHETA) (SINPHI)	-(SINTHETA) (SINPHI)	COSPHI	0
CX	CY	CZ	1

Note that due to the Georgia Institute of Technology coordinate system having the x-axis as the primary axis, rather than the z-axis, some confusion may arrise in getting the signs (+ or -) correct when using text book equations on 3-D Matrix Transformations. The above Inverse equation has the correct signs.

Line: 420

Sets array subscripts to start at 1.

Lines: 430-510

Sets up arrays for homogeneous coordinates (x,y,z,1) for points C and B.

Lines: 520-560

Determine (x,y,z) vector components for vector BC.

Lines: 570-680

Using conversion equations between a rectangular coordinate system and a polar coordinate system (Fig. 5), we find THETA and PHI for the two rotational transformations. Since you wish to rotate the x-axis into alignment with the vector BC, you then need to rotate the z-axis and y-axis away from its existing position by the amount calculated when using the above polar conversion equations. Thus you rotate the z and y axis by an amount of (THETA-90 Deg) and (90 Deg-PHI) respectively. Therefore:

SIN Z = SIN (THETA - 90 DEG) = - COSTHETA

SIN Y = SIN (90 DEG - PHI) = -COSPHI

Lines: 730-780

Set up on array for the Inverse Transformation Maxtris, and plug in the values.

Lines: 830-1390

Set up an array for the facet coners in both coordinate systems. Input the facet dimensions, and determine the corner coordinates in the new coordinate system at point C. Use the equation of a sphere to determine the coordinates. The program is set up for three (3) different shapes of facets; square, rectangular and round.

Lines: 1400-1460

Apply the Inverse Transformation Matrix to the above corner coordinates, to get the corner coordinates in the coordinate system at the focal point.

Lines: 1470-1670

Use the same technique as above in Lines 280-400 to determine the corner image coordinates on the target plane.

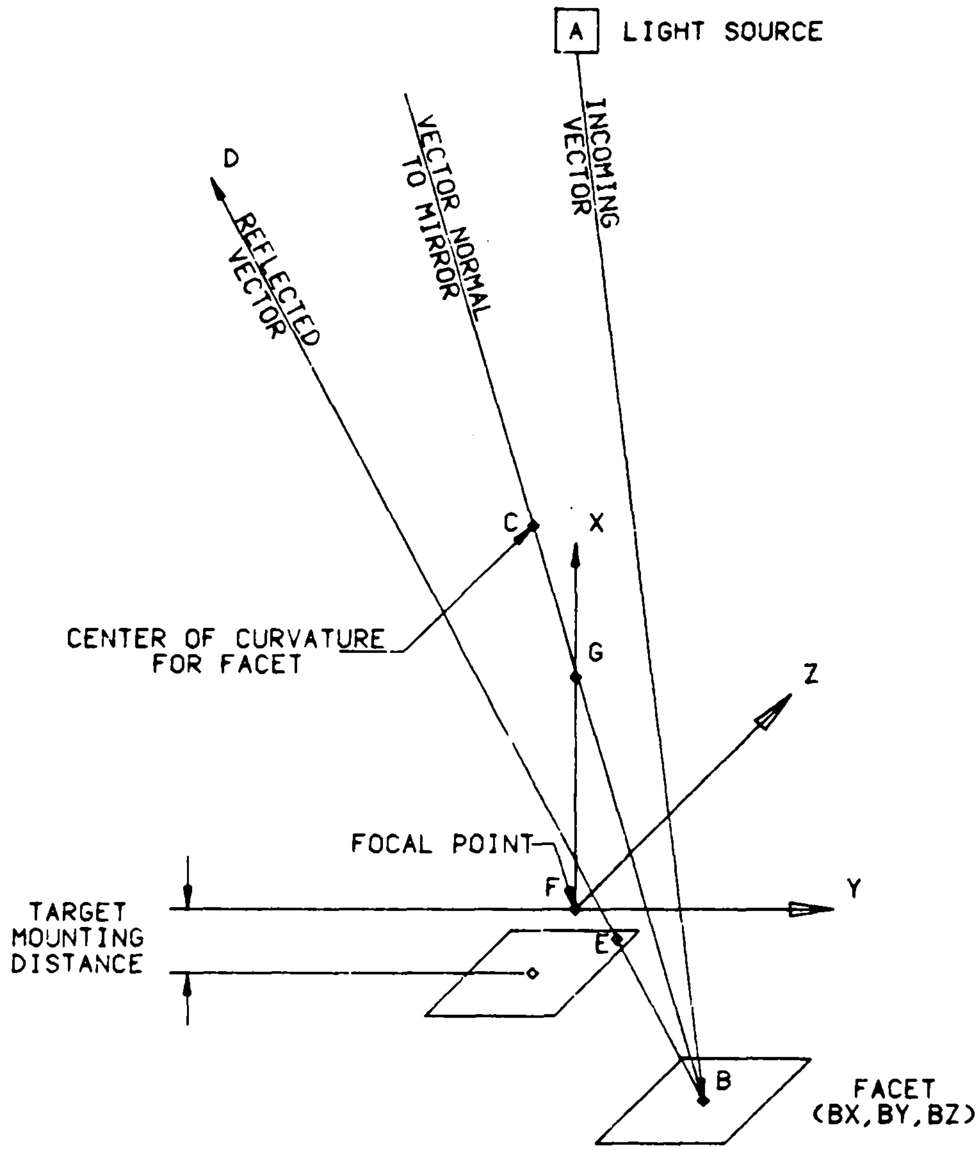

A
LIGHT SOURCE
INCOMING VECTOR
VECTOR NORMAL TO MIRROR
D
REFLECTED VECTOR
C
X
CENTER OF CURVATURE FOR FACET
G
Z
FOCAL POINT
F
Y
TARGET MOUNTING DISTANCE
E
B
FACET (BX,BY,BZ)

FIG 1

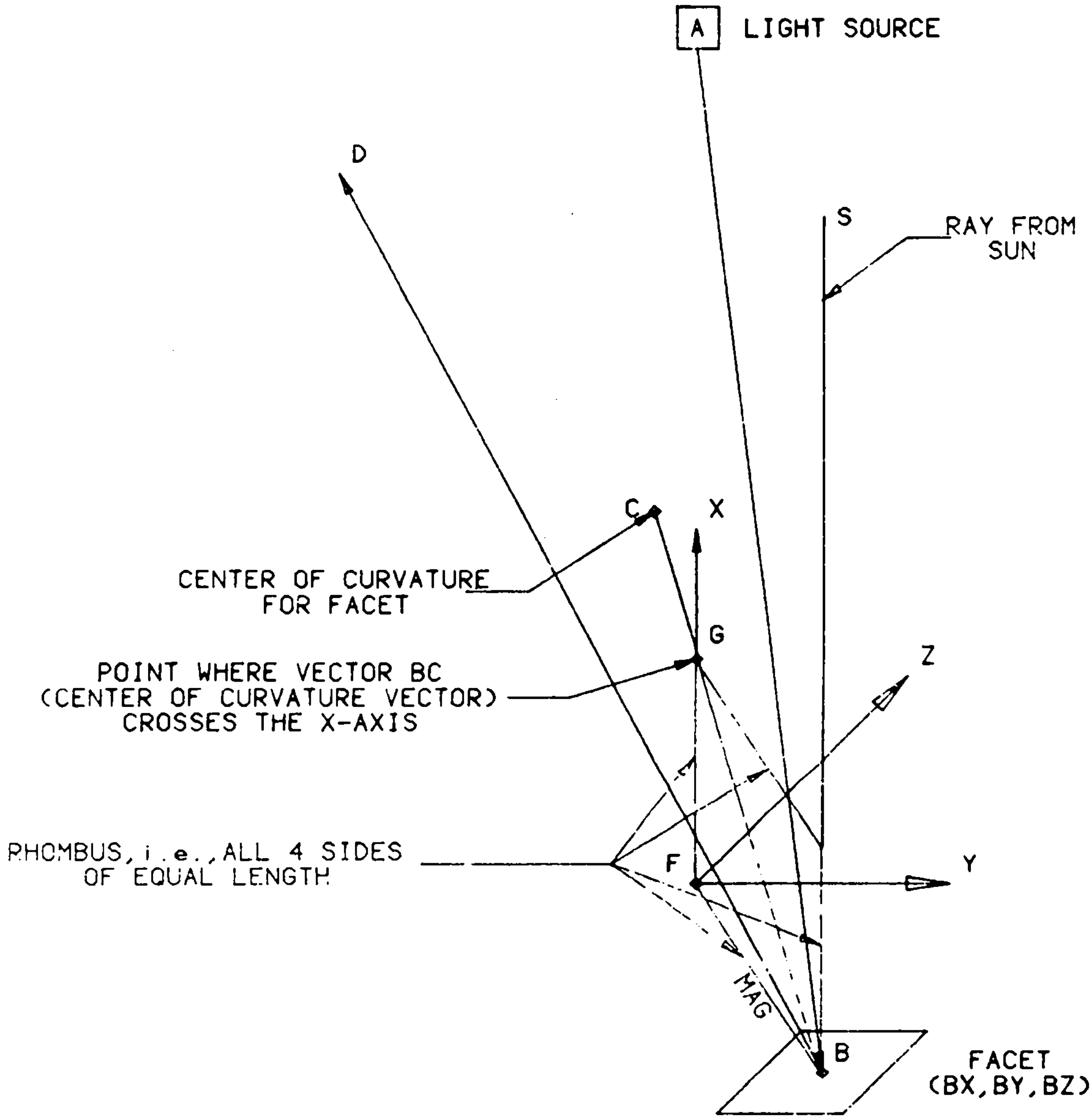

A
LIGHT SOURCE
D
S
RAY FROM SUN
C
X
CENTER OF CURVATURE FOR FACET
G
POINT WHERE VECTOR BC (CENTER OF CURVATURE VECTOR) CROSSES THE X-AXIS
Z
RHOMBUS, i.e., ALL 4 SIDES OF EQUAL LENGTH
F
Y
MAG
B
FACET (BX, BY, BZ)

FIG 2

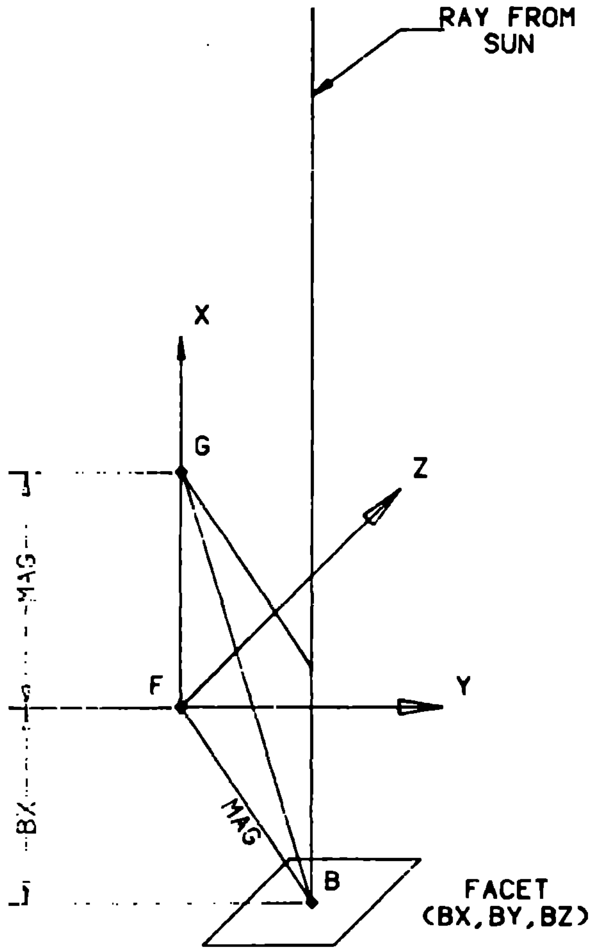


FIG 3

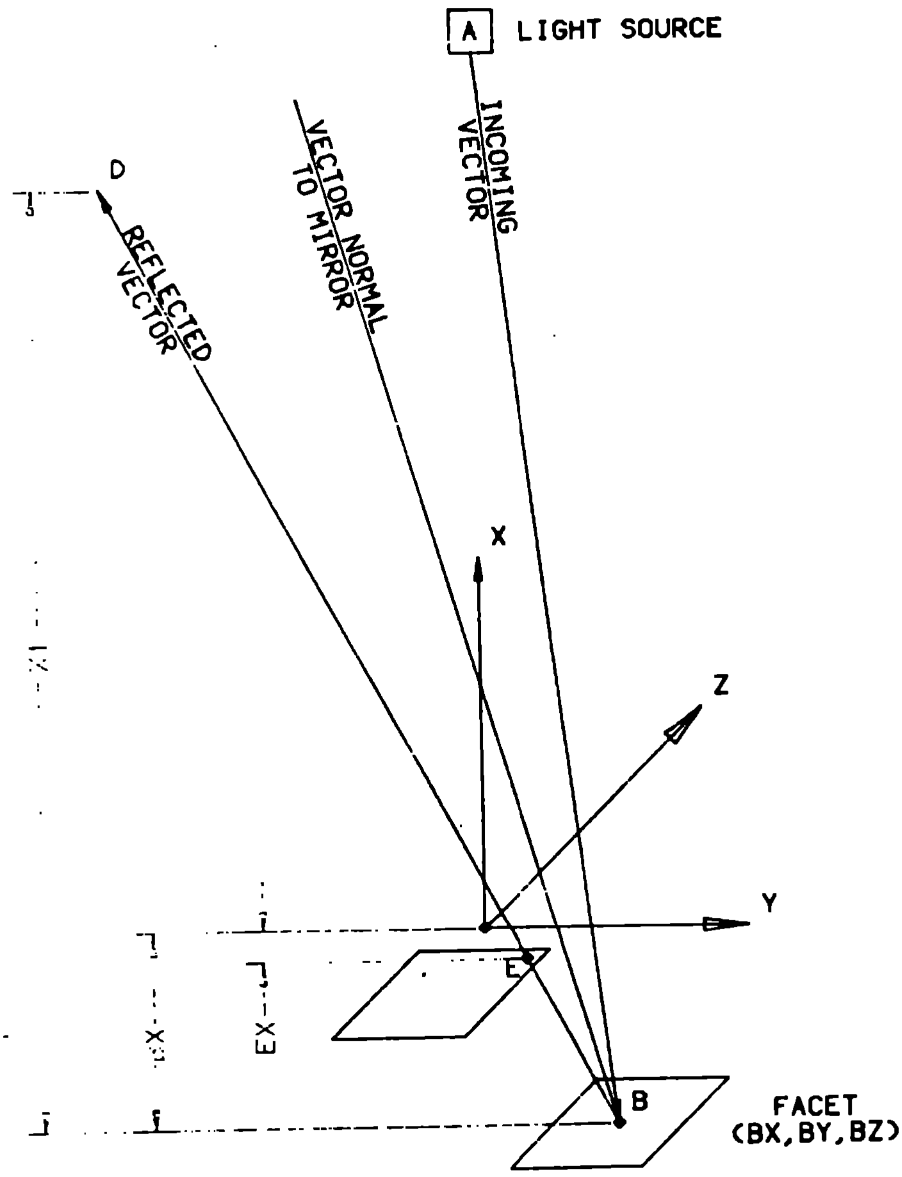
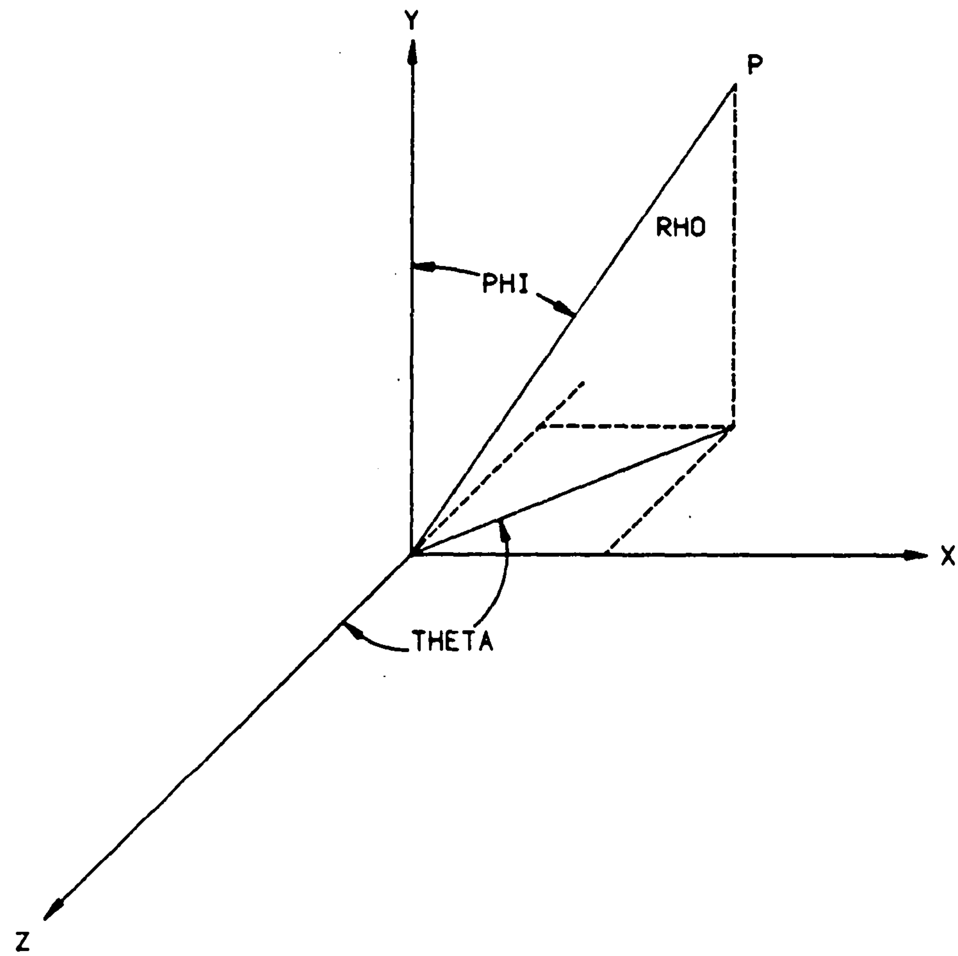

A
LIGHT SOURCE
INCOMING VECTOR
VECTOR NORMAL TO MIRROR
REFLECTED VECTOR
D
X
Z
Y
E
EX
B
FACET
(BX,BY,BZ)

FIG 4



Z = RHO*SIN(PHI)*COS(THETA)

X = RHO*SIN(PHI)*SIN(THETA)

Y = RHO*COS(PHI)

$RHO^2 = X^2 + Y^2 + Z^2$

FIG 5

```
10 REM "MIRROR7
20 REM PROGRAM TO CALCULATE TARGET PATTERN
30 INPUT "ENTER MIRROR NO.:",MIRNO
40 LPRINT "MIRROR NO. IS:";MIRNO
50 INPUT "ENTER ALIGNMENT LIGHT SOURCE DISTANCE IN FEET:",AX
60 LPRINT "DISTANCE TO ALIGNMENT LIGHT SOUCE IS:";AX;" FEET"
70 AX=AX*.3048
80 INPUT "ENTER MIRROR CENTER LOCATION,(INPUT X AS A NEGATIVE NUMBER),(X,Y,Z) IN
 INCHES:      ",BX,BY,BZ
90 LPRINT "MIRROR CENTER CORDINATES ARE: BX=";BX;"  BY=";BY;"  BZ=";BZ;" INCHES"

100 BX=BX*.0254
110 BY=BY*.0254
120 BZ=BZ*.0254
130 REM FACET AIM POINT PROGRAM
140 MAG=SQR(BX^2+BY^2+BZ^2)
150 CX=MAG-BX
160 CY=-BY
170 CZ=-BZ
180 INPUT "ENTER FACET RADIUS OF CURVATURE IN INCHES:",R
190 LPRINT "FACET RADIUS OF CURVATURE =";R;" INCHES"
200 R=R*.0254
210 MZ=SQR(CX^2+CY^2+CZ^2)
220 CX=CX/MZ*R+BX:REM LPRINT "CX=";CX;" METERS"
230 CY=CY/MZ*R+BY:REM LPRINT "CY=";CY;" METERS"
240 CZ=CZ/MZ*R+BZ:REM LPRINT "CZ=";CZ;" METERS"
250 INPUT "ENTER TARGET PLANE LOCATION IN INCHES ( - IF INSIDE FOCAL PLANE, + IF
 OUTSIDE OF FOCAL PLANE)  :",EX
260 LPRINT "TARGET LOCATION IN RELATION TO FOCAL PLANE IS:";EX;" INCHES"
270 EX=EX*.0254
280 REM NOW FIND DOT PRODUCT OF BA*BC
290 K=(AX-BX)*(CX-BX)+(AY-BY)*(CY-BY)+(AZ-BZ)*(CZ-BZ)
300 REM NOW FIND DOT PRODUCT OF BC*BC
310 L=(CX-BX)^2+(CY-BY)^2+(CZ-BZ)^2
320 REM NOW FIND COMPONENTS OF BD
330 X1=2*K/L*(CX-BX)-(AX-BX)
340 Y1=2*K/L*(CY-BY)-(AY-BY)
350 Z1=2*K/L*(CZ-BZ)-(AZ-BZ)
360 REM NOW FIND MAGNITUDE OF VECTOR
370 M=(EX-BX)/X1
380 EY=BY+M*Y1
390 EZ=BZ+M*Z1
400 LPRINT "CENTER OF REFLECTED MIRROR IMAGE ON TARGET IS: (INCHES)  Y=";EY/.025
4;"Z=";EZ/.0254
410 REM TRANSFER COORDINATE SYSTEM TO CENTER OF CURVATURE WITH -X AXIS ALONG MIR
ROR CENTER
420 OPTION BASE 1
430 DIM CENTCURV(4),BCENTER(4)
440 CENTCURV(1)=CX
450 CENTCURV(2)=CY
460 CENTCURV(3)=CZ
470 CENTCURV(4)=1
480 BCENTER(1)=BX
490 BCENTER(2)=BY
500 BCENTER(3)=BZ
510 BCENTER(4)=1
520 REM DETERMINE VECTOR BETWEEN BCENTER TO CENTCURV
530 DIM BCVEC(3)
540 FOR I=1 TO 3
550 BCVEC(I)=CENTCURV(I)-BCENTER(I)
```

```
560 NEXT I
570 REM NOW USE POLAR EQS TO GET THE 2 ROTATIONAL TRANSFORMATIONS ABOUT BOTH THE
 Y AND THE Z AXIS.
580 RHO=R
590 COSPHI=-BCVEC(3)/RHO
600 SINPHI=SQR(1-COSPHI^2)
610 COSTHETA=BCVEC(2)/(RHO*SINPHI)
620 REM DETERMINE INVERSE ROTATIONAL MATRIX ABOUT Z-AXIS
630 REM SUBTRACT 90 DEG FROM THETA TO GET CORRECT ROTATION FOR REGULAR MATRIX, T
HEN SOLVE FOR INVERSE MATRIX
640 SINZ=-COSTHETA
650 COSZ=SQR(1-SINZ^2)
660 REM SUBTRACT PHI FROM 90 DEG TO GET CORRECT ROTATION FOR REGULAR MATRIX, THE
N SOLVE FOR INVERSE MATRIX
670 SINY=-COSPHI
680 COSY=SQR(1-SINY^2)
690 REM LPRINT "SINZ,COSZ,SINY,COSY" ;SINZ;COSZ;SINY;COSY
700 REM FOR I=1 TO 3
710 REM LPRINT "BCVEC";I;"=";BCVEC(I)
720 REM NEXT I
730 REM SET UP FOR OVERALALL INVERSE MATRIX
740 DIM T(4,4)
750 T(1,1)=COSZ*COSY:  T(1,2)=-SINZ*COSY:  T(1,3)=SINY
760 T(2,1)=SINZ:  T(2,2)=COSZ
770 T(3,1)=-COSZ*SINY:  T(3,2)=-SINZ*SINY:  T(3,3)=COSY
780 T(4,1)=CX:  T(4,2)=CY:  T(4,3)=CZ:  T(4,4)=1
790 REM LPRINT "INVERSE MATRIX"
800 REM FOR I=1 TO 4
810 REM LPRINT T(I,1),T(I,2),T(I,3),T(I,4)
820 REM NEXT I
830 OPTION BASE 1
840 DIM COR(4,4),CORN(4,4),B(4)
850 INPUT "IS THE FACET SQUARE?       THEN ENTER  (1)
          IS THE FACET RECTANGULAR?  THEN ENTER  (2)
          IS THE FACET ROUND?        THEN ENTER  (3)             :",SHAPE
860 IF SHAPE = 1,GOTO 900
870 IF SHAPE = 2,GOTO 1070
880 IF SHAPE = 3,GOTO 1250
890 GOTO 850
900 INPUT "ENTER THE LENGTH (INCHES) ALONG ONE SIDE OF THE SQUARE FACET   :",S
910 LPRINT "LENGTH ALONG ONE SIDE OF SQUARE FACET IS";S;" INCHES"
920 S = (S*.0254)/2
930 REM COMPUTE CORNERS OF FACET WITH NEW COORD. SYSTEM USING EQU. FOR SPHERE
940 COR(1,1)=-SQR(R^2-2*(S^2)):REM LPRINT "COR(1,1)=";COR(1,1);" METERS"
950 COR(2,1)=COR(1,1)
960 COR(3,1)=COR(1,1)
970 COR(4,1)=COR(1,1)
980 COR(1,2)=-S:REM LPRINT "COR(1,2)=";COR(1,2);" METERS"
990 COR(2,2)=-S
1000 COR(3,2)=S
1010 COR(4,2)=S
1020 COR(1,3)=-S
1030 COR(2,3)=S
1040 COR(3,3)=S
1050 COR(4,3)=-S
1060 GOTO 1360
1070 INPUT "ENTER THE HEIGHT (INCHES) OF THE FACET   :",H
1080 LPRINT "HEIGHT OF FACET IS";H;"INCHES"
1090 H=(H*.0254)/2
1100 INPUT "ENTER THE WIDTH (INCHES) OF THE FACET   :",W
```

```
1110 LPRINT "WIDTH OF FACET IS";W;"INCHES"
1120 W=(W*.0254)/2
1130 COR(1,1)=-SQR(R^2-(H^2)-(W^2)):REM LPRINT "COR(1,1)=";COR(1,1);" METERS"
1140 COR(2,1)=COR(1,1)
1150 COR(3,1)=COR(1,1)
1160 COR(4,1)=COR(1,1)
1170 COR(1,2)=-W:REM LPRINT "COR(1,2)=";COR(1,2);" METERS"
1180 COR(2,2)=-W
1190 COR(3,2)=W
1200 COR(4,2)=W
1210 COR(1,3)=-H
1220 COR(2,3)=H
1230 COR(3,3)=H
1240 COR(4,3)=-H:GOTO 1360
1250 INPUT "ENTER THE RADIUS(INCHES) OF THE FACET   :",RAD
1260 LPRINT "RADIUS OF FACET IS";RAD;"INCHES"
1270 RAD=(RAD*.0254)
1280 COR(1,1)=-SQR(R^2-RAD^2)
1290 COR(2,1)=COR(1,1)
1300 COR(3,1)=COR(1,1)
1310 COR(4,1)=COR(1,1)
1320 COR(1,2)=RAD
1330 COR(2,2)=-RAD
1340 COR(3,3)=RAD
1350 COR(4,3)=-RAD
1360 COR(1,4)=1
1370 COR(2,4)=1
1380 COR(3,4)=1
1390 COR(4,4)=1
1400 REM NOW CONVERT CORNER POINTS TO ORIGINAL COORDINATE SYSTEM
1410 FOR J=1 TO 4
1420 FOR I=1 TO 4
1430 CORN(J,I)=COR(J,1)*T(1,I)+COR(J,2)*T(2,I)+COR(J,3)*T(3,I)+COR(J,4)*T(4,I)
1440 NEXT I
1450 REM LPRINT CORN(J,1),CORN(J,2),CORN(J,3),CORN(J,4)
1460 NEXT J
1470 REM NOW DO CORNERS
1480 FOR I=1 TO 4
1490 FOR J=1 TO 4
1500 B(J)=CORN(I,J)
1510 NEXT J
1520 K=(AX-B(1))*(CX-B(1))+(AY-B(2))*(CY-B(2))+(AZ-B(3))*(CZ-B(3))
1530 REM NOW FIND DOT PRODUCT OF BC*BC
1540 L=(CX-B(1))^2+(CY-B(2))^2+(CZ-B(3))^2
1550 REM NOW FIND COMPONENTS OF BD
1560 X1=2*K/L*(CX-B(1))-(AX-B(1))
1570 Y1=2*K/L*(CY-B(2))-(AY-B(2))
1580 Z1=2*K/L*(CZ-B(3))-(AZ-B(3))
1590 REM NOW FIND MAGNITUDE OF VECTOR
1600 M=(EX-B(1))/X1
1610 EY=B(2)+M*Y1
1620 EZ=B(3)+M*Z1
1630 IF SHAPE=3,GOTO 1650
1640 LPRINT "CORNER";I;"OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y=";EY/.0254;"Z
=";EZ/.0254:GOTO 1660
1650 LPRINT "POINT";I;"OF CIRCULAR REFLECTED MIRROR IMAGE ON TARGET IS:  Y=";EY/
.0254;"Z=";EZ/.0254
1660 NEXT I
1670 LPRINT "INCHES"
```

INPUT FOR SQUARE FACET

```
RUN
ENTER MIRROR NO.:1
ENTER ALIGNMENT LIGHT SOURCE DISTANCE IN FEET:1200
ENTER MIRROR CENTER LOCATION,(INPUT X AS A NEGATIVE NUMBER),(X,Y,Z) IN INCHES:
   -234.1,53.89,87.51
ENTER FACET RADIUS OF CURVATURE IN INCHES:518
ENTER TARGET PLANE LOCATION IN INCHES ( - IF INSIDE FOCAL PLANE, + IF OUTSIDE OF
 FOCAL PLANE)  :-22.83
IS THE FACET SQUARE?        THEN ENTER  (1)
IS THE FACET RECTANGULAR?  THEN ENTER  (2)
IS THE FACET ROUND?         THEN ENTER  (3)          :1
ENTER THE LENGTH (INCHES) ALONG ONE SIDE OF THE SQUARE FACET   :17.75
```

OUTPUT FOR SQUARE FACET

```
MIRROR NO. IS: 1
DISTANCE TO ALIGNMENT LIGHT SOUCE IS: 1200  FEET
MIRROR CENTER CORDINATES ARE: BX=-234.1   BY= 53.89   BZ= 87.51   INCHES
FACET RADIUS OF CURVATURE = 518  INCHES
TARGET LOCATION IN RELATION TO FOCAL PLANE IS:-22.83  INCHES
CENTER OF REFLECTED MIRROR IMAGE ON TARGET IS: (INCHES)  Y= 6.180584 Z=
 10.03643
LENGTH ALONG ONE SIDE OF SQUARE FACET IS 17.75  INCHES
CORNER 1 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 5.002238 Z= 8.99076
CORNER 2 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 4.877054 Z= 11.20808
CORNER 3 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 7.270547 Z= 10.97415
CORNER 4 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 7.475544 Z= 8.815029
INCHES
```

INPUT FOR RECTANGULAR FACET

```
RUN
ENTER MIRROR NO.:17
ENTER ALIGNMENT LIGHT SOURCE DISTANCE IN FEET:1200
ENTER MIRROR CENTER LOCATION,(INPUT X AS A NEGATIVE NUMBER),(X,Y,Z) IN INCHES:
   -234.1,53.89,87.51
ENTER FACET RADIUS OF CURVATURE IN INCHES:518
ENTER TARGET PLANE LOCATION IN INCHES ( - IF INSIDE FOCAL PLANE, + IF OUTSIDE OF
 FOCAL PLANE)  :-22.83
IS THE FACET SQUARE?        THEN ENTER  (1)
IS THE FACET RECTANGULAR?   THEN ENTER  (2)
IS THE FACET ROUND?         THEN ENTER  (3)          :2
ENTER THE HEIGHT (INCHES) OF THE FACET    :23.75
ENTER THE WIDTH (INCHES) OF THE FACET    :17.75
```

OUTPUT FOR RECTANGULAR FACET

```
MIRROR NO. IS: 17
DISTANCE TO ALIGNMENT LIGHT SOUCE IS: 1200  FEET
MIRROR CENTER CORDINATES ARE: BX=-234.1   BY= 53.89   BZ= 87.51   INCHES
FACET RADIUS OF CURVATURE = 518  INCHES
TARGET LOCATION IN RELATION TO FOCAL PLANE IS:-22.83  INCHES
CENTER OF REFLECTED MIRROR IMAGE ON TARGET IS: (INCHES)  Y= 6.180584 Z=
 10.03643
HEIGHT OF FACET IS 23.75 INCHES
WIDTH OF FACET IS 17.75 INCHES
CORNER 1 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 5.018233 Z= 8.594929
CORNER 2 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 4.850448 Z= 11.55924
CORNER 3 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 7.228617 Z= 11.31441
CORNER 4 OF REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 7.503319 Z= 8.428064
INCHES
```

INPUT FOR ROUND FACET

```
RUN
ENTER MIRROR NO.:3
ENTER ALIGNMENT LIGHT SOURCE DISTANCE IN FEET:1200
ENTER MIRROR CENTER LOCATION,(INPUT X AS A NEGATIVE NUMBER),(X,Y,Z) IN INCHES:
   -234.1,53.89,87.51
ENTER FACET RADIUS OF CURVATURE IN INCHES:518
ENTER TARGET PLANE LOCATION IN INCHES ( - IF INSIDE FOCAL PLANE, + IF OUTSIDE OF
 FOCAL PLANE)  :-22.83
IS THE FACET SQUARE?       THEN ENTER  (1)
IS THE FACET RECTANGULAR?  THEN ENTER  (2)
IS THE FACET ROUND?        THEN ENTER  (3)          :3
ENTER THE RADIUS(INCHES) OF THE FACET   :9
```

OUTPUT FOR ROUND FACET

```
MIRROR NO. IS: 3
DISTANCE TO ALIGNMENT LIGHT SOUCE IS: 1200  FEET
MIRROR CENTER CORDINATES ARE: BX=-234.1   BY= 53.89   BZ= 87.51   INCHES
FACET RADIUS OF CURVATURE = 518  INCHES
TARGET LOCATION IN RELATION TO FOCAL PLANE IS:-22.83  INCHES
CENTER OF REFLECTED MIRROR IMAGE ON TARGET IS: (INCHES)  Y= 6.180584 Z=
 10.03643
RADIUS OF FACET IS 9 INCHES
POINT 1 OF CIRCULAR REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 7.39865 Z=
 9.922334
POINT 2 OF CIRCULAR REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 4.928746 Z=
 10.12873
POINT 3 OF CIRCULAR REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 6.089497 Z=
 11.11739
POINT 4 OF CIRCULAR REFLECTED MIRROR IMAGE ON TARGET IS:  Y= 6.255658 Z=
 8.896242
INCHES
```

APPENDIX B

FACALGN COMPUTER PROGRAM LISTING

```
10 REM                    "FACET ALIGNMENT"
20 REM            PROGRAM TO CALCULATE TARGET PATTERN
30 REM          FOR LIGHT REFLECTED FROM A LIGHT SOURCE
40 REM
50 PI - 3.141592654#: NC - 4: COS30 - .866025403#
60 INPUT "ENTER MIRROR NO.:", MIRNO
70 PRINT "MIRROR NO. IS:"; MIRNO
80 INPUT "ENTER ALIGNMENT LIGHT SOURCE LOCATION, (X,Y,Z) METERS:", AX, AY, AZ
90 PRINT "LIGHT SOUCE LOCATION IS:"; AX, AY, AZ; " METERS"
100 INPUT "ENTER MIRROR CENTER LOCATION,(X,Y,Z) METERS:", BX, BY, BZ
110 PRINT "MIRROR CENTER CORDINATES ARE: BX-"; BX; "  BY-"; BY; "  BZ-"; BZ; " METERS"
120 INPUT "ENTER FACET AIM POINT, (X,Y,Z) (METERS):", FX, FY, FZ
130 REM     CALCULATE THE MAGNITUDE OF THE VECTOR BETWEEN
140 REM     THE FACET, B, AND THE FOCAL POINT, F.
150 MAG - SQR((FX - BX) ^ 2 + (FY - BY) ^ 2 + (FZ - BZ) ^ 2)
160 REM     DETERMINE THE LOCATION G, WHERE THE FACET NORMAL CROSSES
170 REM     THE LINE THROUGH THE FOCUS PARALLEL TO THE DISH AXIS
180 GX - FX
190 GY - FY
200 GZ - FZ + MAG
210 INPUT "ENTER FACET RADIUS OF CURVATURE IN METERS:", R
220 PRINT "FACET RADIUS OF CURVATURE -"; R; " METERS"
230 REM     DETERMINE THE MAGNITUDE OF THE VECTOR BETWEEN POINT B AND POINT G
240 MAGBG - SQR((GX - BX) ^ 2 + (GY - BY) ^ 2 + (GZ - BZ) ^ 2)
250 REM     DETERMINE THE FACET'S CENTER OF CURVATURE, C, BY MULTIPLYING
260 REM     THE DIRECTION COSINES BY THE RADIUS OF CURVATURE, R.
270 CX - ((GX - BX) / MAGBG) * R + BX
280 CY - ((GY - BY) / MAGBG) * R + BY
290 CZ - ((GZ - BZ) / MAGBG) * R + BZ
300 INPUT "ENTER TARGET PLANE LOCATION IN METERS:", EZ
310 PRINT "TARGET LOCATION ALONG Z-AXIS IS:"; EZ; " METERS"
320 REM     DETERMINE THE COMPONENTS OF THE REFLECTED VECTOR, BD.
330 REM     FIND THE DOT PRODUCT OF BA*BC
340 K - (AX - BX) * (CX - BX) + (AY - BY) * (CY - BY) + (AZ - BZ) * (CZ - BZ)
350 REM     FIND THE DOT PRODUCT OF BC*BC
360 L = (CX - BX) ^ 2 + (CY - BY) ^ 2 + (CZ - BZ) ^ 2
370 REM     FIND THE COMPONENTS OF BD
380 BDX - 2 * K / L * (CX - BX) - (AX - BX)
390 BDY = 2 * K / L * (CY - BY) - (AY - BY)
400 BDZ = 2 * K / L * (CZ - BZ) - (AZ - BZ)
410 REM     FIND THE RELATIVE MAGNITUDE, M, ALONG THE Z AXIS OF VECTORS EB AND BD.
420 M - (EZ - BZ) / BDZ
430 REM     SCALE THE X AND Y COMPONENTS BY M TO FIND TARGET INTERSECTION.
440 EX - BX + M * BDX
450 EY - BY + M * BDY
460 PRINT "CENTER OF REFLECTED IMAGE ON TARGET IS: (METERS)  X-"; EX; "Y-"; EY
470 REM     CALCULATE FACET CORNER/EDGE LOCATIONS
480 REM     TRANSFER COORDINATE SYSTEM TO CENTER OF CURVATURE
490 REM     WITH Z AXIS ALONG MIRROR NORMAL
500 OPTION BASE 1
510 DIM CENTCURV(3), BCENTER(3)
520 CENTCURV(1) - CX
530 CENTCURV(2) - CY
540 CENTCURV(3) - CZ
550 BCENTER(1) - BX
560 BCENTER(2) - BY
570 BCENTER(3) - BZ
580 REM     DETERMINE VECTOR BETWEEN BCENTER TO CENTCURV
590 DIM BCVEC(3)
600 FOR I - 1 TO 3
```

```
610 BCVEC(I) = CENTCURV(I) - BCENTER(I)
620 NEXT I
630 REM     USE POLAR EQS TO DETERMINE THE 2 ROTATIONAL TRANSFORMATIONS
640 REM     ABOUT THE X AND THE Y AXIS.
650 RHO = R
660 REM     DETERMINE THE ANGLE BETWEEN THE MIRROR NORMAL AND THE Y-AXIS, PHI.
670 COSPHI = -BCVEC(2) / RHO
680 PHI = -ATN(COSPHI / SQR(-COSPHI * COSPHI + 1)) + PI / 2
690 SINPHI = SIN(PHI)
700 REM     DETERMINE THE ANGLE OF ROTATION (ABOUT THE X-AXIS) NEEDED TO ALIGN
710 REM     THE MIRROR NORMAL AND Z-AXIS, Y = 90 - PHI.
720 Y = -(PI / 2 - PHI)
730 REM     DETERMINE THE ANGLE BETWEEN THE MIRROR NORMAL AND THE X-AXIS, THETA.
740 COSTHETA = -BCVEC(1) / (RHO * SINPHI)
750 THETA = -ATN(COSTHETA / SQR(-COSTHETA * COSTHETA + 1)) + PI / 2
760 REM     DETERMINE THE ANGLE OF ROTATION (ABOUT THE Y-AXIS) NEEDED TO ALIGN
770 REM     THE MIRROR NORMAL AND Z-AXIS, Z= -(90-THETA).
780 Z = -(PI / 2 - THETA)
790 REM     DETERMINE THE SINES AND COSINES OF THE ROTATIONAL ANGLES.
800 SINY = SIN(Y)
810 COSY = COS(Y)
820 SINZ = SIN(Z)
830 COSZ = COS(Z)
840 REM     DEFINE THE TERMS FOR THE INVERSE TRANSFORMATION MATRIX T(4,4).
850 DIM T(3, 3)
860 T(1, 1) = COSZ: T(1, 2) = 0: T(1, 3) = -SINZ
870 T(2, 1) = SINZ * SINY: T(2, 2) = COSZ: T(2, 3) = -COSZ * SINY
880 T(3, 1) = SINZ * COSY: T(3, 2) = SINY: T(3, 3) = COSY * COSZ
890 REM     ASK FOR FACET SHAPE AND DIMENSIONS.
900 DIM COR(8, 3), CORN(8, 3), B(3)
910 PRINT "IS THE FACET SQUARE?       THEN ENTER  (1)"
920 PRINT "IS THE FACET RECTANGULAR?  THEN ENTER  (2)"
930 PRINT "IS THE FACET ROUND?        THEN ENTER  (3)"
940 INPUT "IS THE FACET HEXAGONAL?    THEN ENTER  (4)", SHAPE
950 IF SHAPE = 1 THEN GOTO 1000
960 IF SHAPE = 2 THEN GOTO 1180
970 IF SHAPE = 3 THEN GOTO 1360
980 IF SHAPE = 4 THEN GOTO 1550
990 GOTO 910
1000 INPUT "ENTER THE LENGTH (METERS) ALONG ONE SIDE OF THE SQUARE FACET :", S
1010 PRINT "LENGTH ALONG ONE SIDE OF SQUARE FACET IS"; S; " METERS"
1020 S = S / 2
1030 REM     COMPUTE CORNERS OF FACET IN THE FACET COORDINATE
1040 REM     SYSTEM USING THE EQUATION OF A SPHERE
1050 COR(1, 3) = -SQR(R ^ 2 - 2 * (S ^ 2))
1060 COR(2, 3) = COR(1, 3)
1070 COR(3, 3) = COR(1, 3)
1080 COR(4, 3) = COR(1, 3)
1090 COR(1, 1) = -S
1100 COR(2, 1) = -S
1110 COR(3, 1) = S
1120 COR(4, 1) = S
1130 COR(1, 2) = -S
1140 COR(2, 2) = S
1150 COR(3, 2) = S
1160 COR(4, 2) = -S
1170 GOTO 1700
1180 INPUT "ENTER THE HEIGHT (METERS) OF THE FACET   :", H
1190 PRINT "HEIGHT OF FACET IS"; H; "METERS"
1200 H = H / 2
```

```
1210 INPUT "ENTER THE WIDTH (METERS) OF THE FACET   :", W
1220 PRINT "WIDTH OF FACET IS"; W; "METERS"
1230 W = W / 2
1240 COR(1, 3) = -SQR(R ^ 2 - (H ^ 2) - (W ^ 2))
1250 COR(2, 3) = COR(1, 3)
1260 COR(3, 3) = COR(1, 3)
1270 COR(4, 3) = COR(1, 3)
1280 COR(1, 1) = -W
1290 COR(2, 1) = -W
1300 COR(3, 1) = W
1310 COR(4, 1) = W
1320 COR(1, 2) = -H
1330 COR(2, 2) = H
1340 COR(3, 2) = H
1350 COR(4, 2) = -H: GOTO 1710
1360 INPUT "ENTER THE RADIUS (METERS) OF THE FACET   :", RAD
1370 PRINT "RADIUS OF FACET IS"; RAD; "METERS"
1380 COR(1, 3) = -SQR(R ^ 2 - RAD ^ 2)
1390 COR(2, 3) = COR(1, 3)
1400 COR(3, 3) = COR(1, 3)
1410 COR(4, 3) = COR(1, 3)
1420 COR(5, 3) = COR(1, 3)
1430 COR(6, 3) = COR(1, 3)
1440 COR(7, 3) = COR(1, 3)
1450 COR(8, 3) = COR(1, 3)
1460 COR(1, 1) = RAD
1470 COR(2, 1) = RAD / SQR(2): COR(2, 2) = -RAD / SQR(2)
1480 COR(3, 2) = -RAD
1490 COR(4, 1) = -RAD / SQR(2): COR(4, 2) = -RAD / SQR(2)
1500 COR(5, 1) = -RAD
1510 COR(6, 1) = -RAD / SQR(2): COR(6, 2) = RAD / SQR(2)
1520 COR(7, 2) = RAD
1530 COR(8, 1) = RAD / SQR(2): COR(8, 2) = RAD / SQR(2)
1540 NC = 8: GOTO 1710
1550 INPUT "ENTER THE LENGTH (METERS) ALONG ONE SIDE OF THE HEXAGONAL FACET ", L
1560 PRINT "LENGTH ALONG ONE SIDE OF THE HEXAGONAL FACET :"; L; "METERS"
1570 COR(1, 3) = -SQR(R ^ 2 - L ^ 2)
1580 COR(2, 3) = COR(1, 3)
1590 COR(3, 3) = COR(1, 3)
1600 COR(4, 3) = COR(1, 3)
1610 COR(5, 3) = COR(1, 3)
1620 COR(6, 3) = COR(1, 3)
1630 COR(1, 1) = L
1640 COR(2, 1) = L / 2: COR(2, 2) = -L * COS30
1650 COR(3, 1) = -L / 2: COR(3, 2) = -L * COS30
1660 COR(4, 1) = -L
1670 COR(5, 1) = -L / 2: COR(5, 2) = L * COS30
1680 COR(6, 1) = L / 2: COR(6, 2) = L * COS30
1690 NC = 6
1700 REM     CONVERT THE CORNER/EDGE POINTS TO ORIGINAL COORDINATE SYSTEM
1710 FOR J = 1 TO NC
1720 FOR I = 1 TO 3
1730 CORN(J, I) = COR(J, 1) * T(1, I) + COR(J, 2) * T(2, I) + COR(J, 3) * T(3, I)
1740 CORN(J, I) = CORN(J, I) + CENTCURV(I)
1750 NEXT I
1760 REM PRINT CORN(J, 1), CORN(J, 2), CORN(J, 3)
1770 NEXT J
1780 REM     DETERMINE CORNER REFLECTION INTERSECTIONS ON TARGET (LIKE ABOVE).
1790 FOR I = 1 TO NC
1800 FOR J = 1 TO 3
```

```
1810 B(J) = CORN(I, J)
1820 NEXT J
1830 REM      DETERMINE DOT PRODUCT OF BA*BC, K.
1840 K = (AX - B(1)) * (CX - B(1)) + (AY - B(2)) * (CY - B(2)) + (AZ - B(3)) * (CZ - B(3))
1850 REM      NOW FIND DOT PRODUCT OF BC*BC, L.
1860 L = (CX - B(1)) ^ 2 + (CY - B(2)) ^ 2 + (CZ - B(3)) ^ 2
1870 REM      NOW FIND COMPONENTS OF BD
1880 X1 = 2 * K / L * (CX - B(1)) - (AX - B(1))
1890 Y1 = 2 * K / L * (CY - B(2)) - (AY - B(2))
1900 Z1 = 2 * K / L * (CZ - B(3)) - (AZ - B(3))
1910 REM      NOW FIND MAGNITUDE OF VECTOR
1920 M = (EZ - B(3)) / Z1
1930 EX = B(1) + M * X1
1940 EY = B(2) + M * Y1
1950 IF SHAPE = 3 THEN GOTO 1970
1960 PRINT "CORNER"; I; "OF REFLECTED MIRROR IMAGE ON TARGET IS:  X="; EX; "Y="; EY: GOTO 1980
1970 PRINT "POINT"; I; "OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X="; EX; "Y="; EY
1980 NEXT I
1990 PRINT "METERS"
```

APPENDIX C

SAMPLE INPUT/OUTPUT
FOR THE FACALGN COMPUTER PROGRAM

SAMPLE INPUT/OUTPUT FOR A SQUARE FACET

```
                         ENTER MIRROR NO.:1
MIRROR NO. IS: 1
ENTER ALIGNMENT LIGHT SOURCE LOCATION, (X,Y,Z) METERS:0,0,371.70614
LIGHT SOUCE LOCATION IS: 0   0            371.7061  METERS
ENTER MIRROR CENTER LOCATION,(X,Y,Z) METERS:1.3688,2.2228,0
MIRROR CENTER CORDINATES ARE: BX= 1.3688   BY= 2.2228   BZ= 0  METERS
ENTER FACET AIM POINT, (X,Y,Z) (METERS):0,0,5.9461
ENTER FACET RADIUS OF CURVATURE IN METERS:13.1572
FACET RADIUS OF CURVATURE = 13.1572  METERS
ENTER TARGET PLANE LOCATION IN METERS:5.3662
TARGET LOCATION ALONG Z-AXIS IS: 5.3662  METERS
CENTER OF REFLECTED IMAGE ON TARGET IS: (METERS)  X= .156991 Y= .2549383
IS THE FACET SQUARE?       THEN ENTER  (1)
IS THE FACET RECTANGULAR?  THEN ENTER  (2)
IS THE FACET ROUND?        THEN ENTER  (3)
IS THE FACET HEXAGONAL?    THEN ENTER  (4)1
ENTER THE LENGTH (METERS) ALONG ONE SIDE OF THE SQUARE FACET :.45085
LENGTH ALONG ONE SIDE OF SQUARE FACET IS .45085  METERS
CORNER 1 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1271114 Y= .228154
CORNER 2 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1238136 Y= .2848665
CORNER 3 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1845851 Y= .2789173
CORNER 4 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1899576 Y= .2236969
METERS
```

SAMPLE INPUT/OUTPUT FOR A RECTANGULAR FACET

```
                         ENTER MIRROR NO.:17
MIRROR NO. IS: 17
ENTER ALIGNMENT LIGHT SOURCE LOCATION, (X,Y,Z) METERS:0,0,371.7061
LIGHT SOUCE LOCATION IS: 0   0             371.7061  METERS
ENTER MIRROR CENTER LOCATION,(X,Y,Z) METERS:1.3688,2.2228,0
MIRROR CENTER CORDINATES ARE: BX= 1.3688   BY= 2.2228   BZ= 0  METERS
ENTER FACET AIM POINT, (X,Y,Z) (METERS):0,0,5.9461
ENTER FACET RADIUS OF CURVATURE IN METERS:13.1572
FACET RADIUS OF CURVATURE = 13.1572  METERS
ENTER TARGET PLANE LOCATION IN METERS:5.3662
TARGET LOCATION ALONG Z-AXIS IS: 5.3662  METERS
CENTER OF REFLECTED IMAGE ON TARGET IS: (METERS)  X= .156991 Y= .2549382
IS THE FACET SQUARE?        THEN ENTER  (1)
IS THE FACET RECTANGULAR?  THEN ENTER  (2)
IS THE FACET ROUND?         THEN ENTER  (3)
IS THE FACET HEXAGONAL?     THEN ENTER  (4)2
ENTER THE HEIGHT (METERS) OF THE FACET   :.60325
HEIGHT OF FACET IS .60325 METERS
ENTER THE WIDTH (METERS) OF THE FACET   :.45085
WIDTH OF FACET IS .45085 METERS
CORNER 1 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1275322 Y= .2180134
CORNER 2 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1231125 Y= .2938288
CORNER 3 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1834847 Y= .2875998
CORNER 4 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1906838 Y= .2137834
METERS
```

SAMPLE INPUT/OUTPUT FOR A ROUND FACET

```
                         ENTER MIRROR NO.:3
MIRROR NO. IS: 3
ENTER ALIGNMENT LIGHT SOURCE LOCATION, (X,Y,Z) METERS:0,0,371.70614
LIGHT SOUCE LOCATION IS: 0   0          371.7061  METERS
ENTER MIRROR CENTER LOCATION,(X,Y,Z) METERS:1.3688,2.2228,0
MIRROR CENTER CORDINATES ARE: BX= 1.3688   BY= 2.2228   BZ= 0  METERS
ENTER FACET AIM POINT, (X,Y,Z) (METERS):0,0,5.9461
ENTER FACET RADIUS OF CURVATURE IN METERS:13.1572
FACET RADIUS OF CURVATURE = 13.1572  METERS
ENTER TARGET PLANE LOCATION IN METERS:5.3662
TARGET LOCATION ALONG Z-AXIS IS: 5.3662  METERS
CENTER OF REFLECTED IMAGE ON TARGET IS: (METERS)  X= .156991 Y= .2549383
IS THE FACET SQUARE?        THEN ENTER  (1)
IS THE FACET RECTANGULAR?   THEN ENTER  (2)
IS THE FACET ROUND?         THEN ENTER  (3)
IS THE FACET HEXAGONAL?     THEN ENTER  (4)3
ENTER THE RADIUS (METERS) OF THE FACET   :.2286
RADIUS OF FACET IS .2286 METERS
POINT 1 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1879313 Y= .2520404
POINT 2 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1806631 Y= .2326556
POINT 3 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .158961 Y= .225753
POINT 4 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1357722 Y= .2359896
POINT 5 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1251925 Y= .2572826
POINT 6 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1332104 Y= .2765463
POINT 7 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .1545972 Y= .282562
POINT 8 OF CIRCULAR REFLECTED IMAGE ON TARGET IS:  X= .177036 Y= .2724463
METERS
```

SAMPLE INPUT/OUTPUT FOR A HEXAGONAL FACET

```
                          ENTER MIRROR NO.:6
MIRROR NO. IS: 6
ENTER ALIGNMENT LIGHT SOURCE LOCATION, (X,Y,Z) METERS:0,0,371.7061
LIGHT SOUCE LOCATION IS: 0    0             371.7061  METERS
ENTER MIRROR CENTER LOCATION,(X,Y,Z) METERS:1.3688,2.2228,0
MIRROR CENTER CORDINATES ARE: BX= 1.3688   BY= 2.2228   BZ= 0  METERS
ENTER FACET AIM POINT, (X,Y,Z) (METERS):0,0,5.9461
ENTER FACET RADIUS OF CURVATURE IN METERS:13.1572
FACET RADIUS OF CURVATURE = 13.1572  METERS
ENTER TARGET PLANE LOCATION IN METERS:5.3662
TARGET LOCATION ALONG Z-AXIS IS: 5.3662  METERS
CENTER OF REFLECTED IMAGE ON TARGET IS: (METERS)  X= .156991 Y= .2549382
IS THE FACET SQUARE?        THEN ENTER  (1)
IS THE FACET RECTANGULAR?   THEN ENTER  (2)
IS THE FACET ROUND?         THEN ENTER  (3)
IS THE FACET HEXAGONAL?     THEN ENTER  (4)4
ENTER THE LENGTH (METERS) ALONG ONE SIDE OF THE HEXAGONAL FACET .2286
LENGTH ALONG ONE SIDE OF THE HEXAGONAL FACET : .2286 METERS
CORNER 1 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1879314 Y= .2520406
CORNER 2 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1745297 Y= .2285332
CORNER 3 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1427043 Y= .2308336
CORNER 4 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1251925 Y= .2572826
CORNER 5 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1393808 Y= .2803651
CORNER 6 OF REFLECTED MIRROR IMAGE ON TARGET IS:  X= .1702842 Y= .277402
METERS
```

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