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A Method for Calculating Shadows Cast by Two-Axis Tracking Solar Collectors

James K. Linn, John C. Zimmerman

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A METHOD FOR CALCULATING SHADOWS CAST BY TWO-AXIS TRACKING SOLAR COLLECTORS

James K. Linn
Systems Analysis Division 4744

John C. Zimmerman
Small Power Systems Applications Division 4725

Sandia Laboratories
Albuquerque, NM 87185

ABSTRACT

This report describes a method that quickly calculates the shadows cast from two-axis tracking solar collectors onto adjacent collectors. The solar collectors can have either circular or rectangular apertures.

CONTENTS

ILLUSTRATIONS

A METHOD FOR CALCULATING SHADOWS CAST BY TWO-AXIS TRACKING SOLAR COLLECTORS

Introduction

In most large solar collector fields internal shadowing occurs because of the proximity of adjacent collectors. This report describes the shadow program that calculates the measurable loss of available solar energy for two-axis tracking collectors having either circular or rectangular apertures. The program may be used separately or incorporated into existing codes. Coding has been optimized such that CDC 6600 computer time for an hourly calculation on an annual basis is 6 seconds.

The Shenandoah, GA, Large-Scale Experiment (LSE) illustrates the code's utility. In this application, optimized spacing in a land-locked area limits shadowing loss to ~15%. Nonoptimal spacing of the same collectors in the given area typically increased shadowing to as much as 20 to 25%.

Approach

This program evaluates the effect of all adjacent collectors on a single collector (neglecting collector field edge effects). Initially the sums of all individual adjacent collector shadows are derived. Any shadow overlaps or "double" shadows are then computed and the overlap used to reduce the net shadow. The net available collector area is the collector area minus the net shadowed area.

Geometry Layout

Calculating the location of shadows in a two-axis tracking solar collector field is greatly simplified when it is realized that each collector points at the sun; hence the collector aperture planes are parallel. As a result, all shadows cast in the plane of a shadowed collector are also the shape and size of the collector aperture.

The solar field layout was considered to be in one of two patterns: the diamond pattern, also known to metallurgists as the close-packed hexagonal pattern, and the rectangular pattern.

Figure 1 shows the configuration of the centers of each collector for a large diamond pattern field in which the diamond pattern is indicated by dashed lines. Figure 2 shows the configuration of the centers of each collector for a rectangular pattern field with the rectangular pattern indicated by dashed lines.

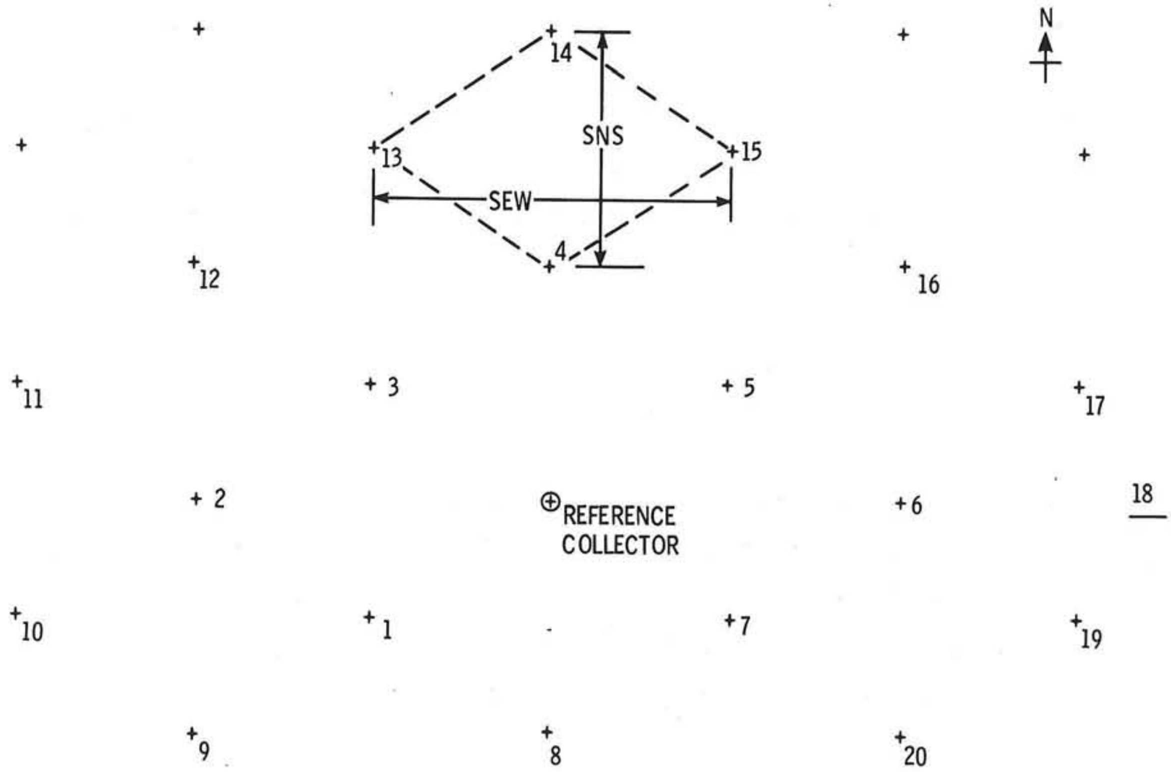


Figure 1. Two-Axis Tracking Solar Collector Field--Diamond Pattern

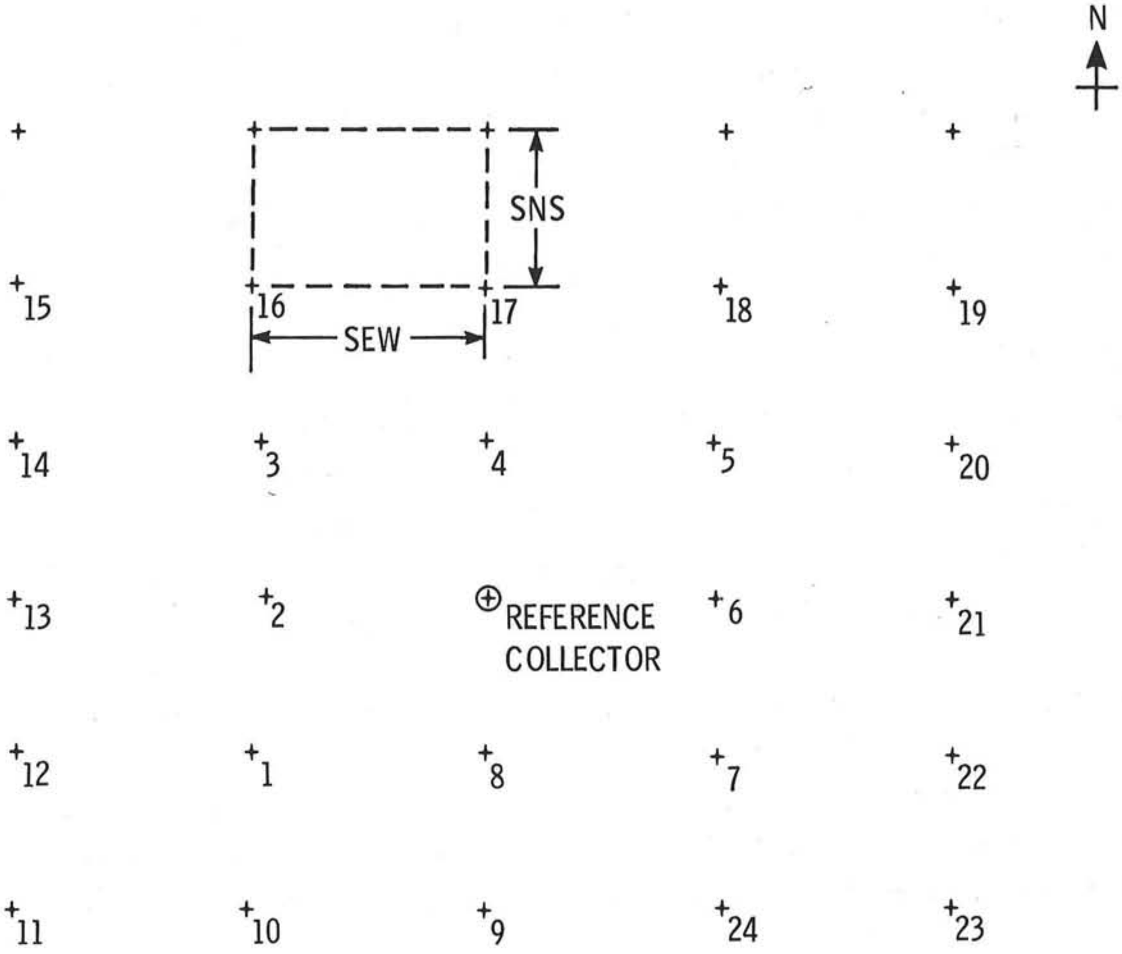


Figure 2. Two-Axis Tracking Solar Collector Field--Rectangular Pattern

North-south spacing between individual collectors is denoted by SNS, and east-west spacing is denoted by SEW for both patterns. In the coordinate system used, the X axis assumes east (+) and west (-), and the Y axis denotes north (+) and south (-). The reference collector has the coordinates (0,0).

Only seven shadowed locations are considered for each pattern. The reference solar collector casts a shadow on the numbered collectors for various times of the day throughout the year. No shadow is cast by the reference collector on Collector 8 since it is due south of the reference collector. In the diamond pattern, shadows cast by the reference collector on collectors that are in line but not adjacent to the reference collector (e.g., Collector 9) will necessarily be lower than the shadow cast by Collector 1 on Collector 9 because of the sun's elevation. Shadows cast by the reference collector on Collectors 10 and 11 during early morning (summer for No. 10 and winter for No. 11) are not considered because of their very small net effect. The same reasoning applies to the rectangular field. These are the only limitations to calculation of the shadowed area. All other calculations are exact.

Evaluation Method

Each potential shadowing collector is located in a peripheral position with respect to the reference collector. Because of the overall geometry of the array, each collector in the array receives equal shadowing (neglecting consideration of edge effects). It is therefore sufficient to calculate the total shadow cast on the reference collector.

Initially, shadowing or potential shadowing of each of the seven adjacent collectors is projected to be located in the plane of the reference collector. If the collector projection intersects the collector dimensions, a shadow is identified. The magnitude of the shadow depends on the collector's shadow projection distance and the collector or shadow dimensions.

The shadow, if any, from each adjacent collector is obtained in sequential numbering order. The possibility of shadow overlaps and thus overestimating the total shadow on the reference collector requires investigating the proximity of adjacent shadows.

If adjacent shadows overlap onto the reference collector, the magnitude of the overlap is determined and the total shadow is reduced appropriately.

The total shadow is the sum of the individual collector shadows, each properly reduced by any overlap with the previously analyzed collector. This approach justifies the need for investigating collectors in a prescribed order.

If a field is defined, some logic can then be added to the program to subtract the shadowed area from the number of outside collectors at the proper time for each side to obtain the correct solar input to the field.

Program Organization

The program listed in the Appendix is discussed in three sections--Array Projection, Rectangular Arrays, and Circular Arrays.

Array Projection

The first step in calculating shadows cast by two-axis tracking solar collectors is to determine the coordinates of each of the seven collector locations, depending on the north-south (SNS) and east-west (SEW) spacings and on the array configuration (diamond or rectangular). The reference collector, which is the one casting the shadow, is located at coordinates (0,0).

The first items calculated are the evaluation and azimuth of the sun for a particular day of the year and time of the day. Calculation in the subroutine ECBDAT takes local time (XNHR) and location on the earth's latitude (DLAT) and longitude (DLON) in degrees and then calculates a solar time. Next the sun's evaluation (ELANGR) and azimuth (AZANGR) angles (radians) are calculated using solar time. The method of computation assumes that the sun moves in a constant radius circle around the earth. For both azimuth and elevation the accuracy of calculation is slightly larger than ±1 degree. A more accurate sun-pointing program (±5 arc minutes) can be used and is available from the authors but the computation time would approximately double.

Figure 3 indicates the geometry of calculating the center of the shadow of the reference collector on the adjacent collector. YDISPO is the offset in the vertical dimension of the shadow center if the land is flat; however, for sloping land, YDISP (not shown) is calculated from

YDISPO by correcting the elevation coordinate for the land slope (i.e., YDISP = YDISPO - SBASE * LAND SLOPE).

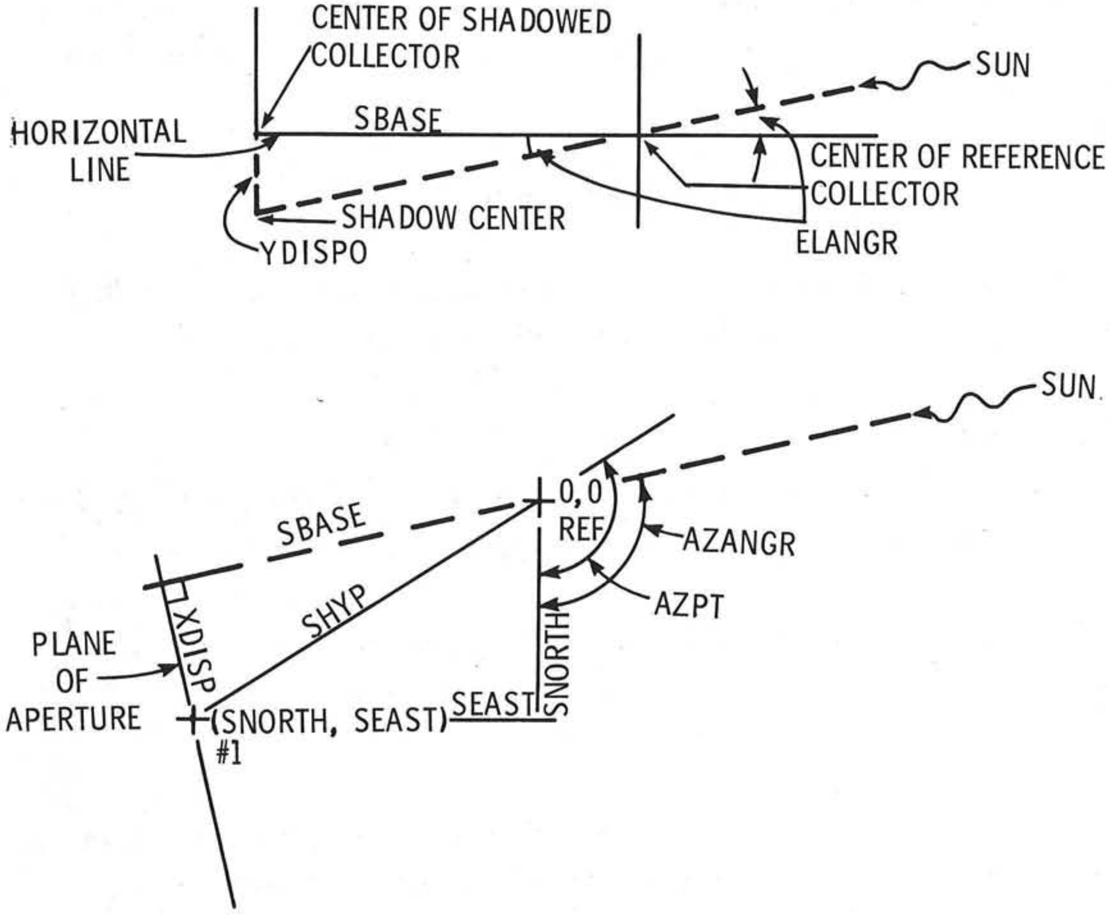


Figure 3. Geometry for Calculating the Center of the Shadow Cast by the Reference Collector Onto the Adjacent Collector

Rectangular Arrays

As discussed in the preceding section, the projected image location is calculated in the plane of the collector potentially being shadowed. The image appears to be true size under the simplifying assumption of parallel incident solar radiation.

The shadow cast on the reference collector is calculated by computing the product of the overlap in each axis (X and Y) (Figure 4).

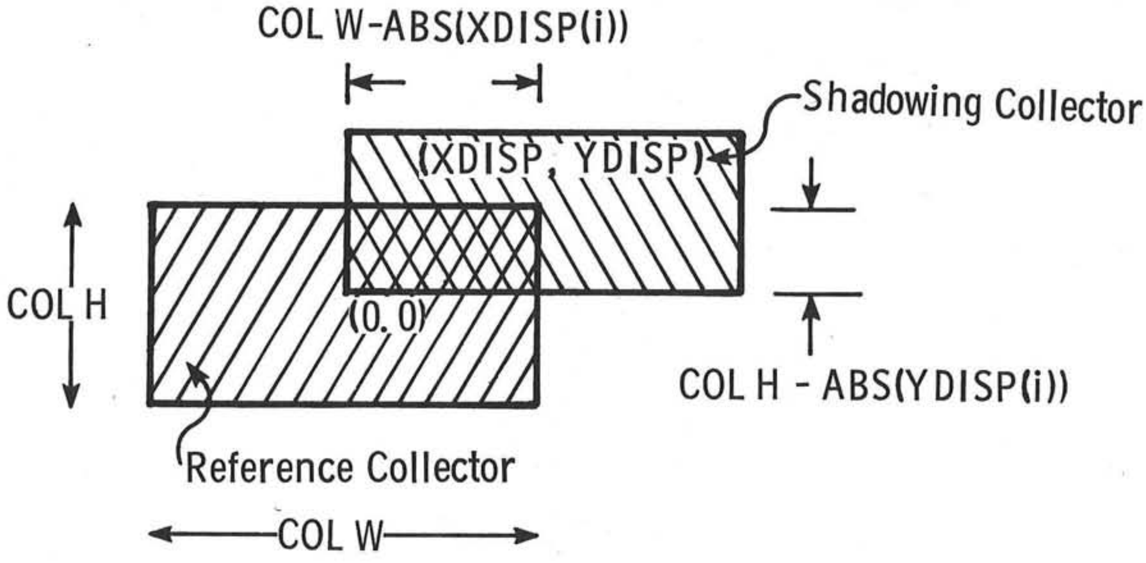


Figure 4. Rectangular Array Shadow

Total shadows of individual collectors are initially computed. In event of double shadowing (limited in this program to mean shadowing from adjacent collectors), the overlap is adjusted. Since all collector projections are equal in size, the necessary and sufficient conditions for double shadowing by two adjacent collectors are as follows:

- Each collector casts a shadow on the reference collector
- The shadows intersect

If double shadowing exists, one of two conditions occurs in each dimension; i.e., total overlap of one shadow, or only partial overlap of the shadow (Figure 5).

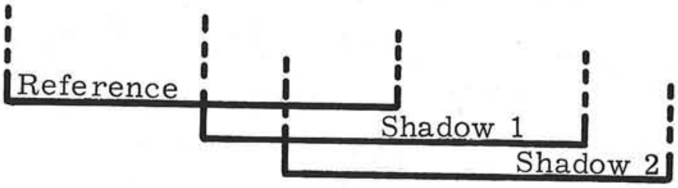
The magnitude of the overlap is given accordingly:

Total Overlap

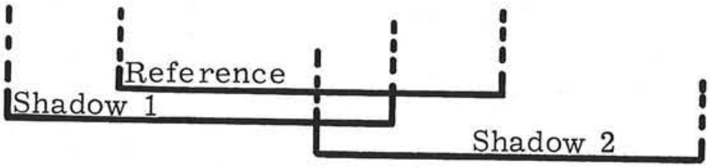
Overlap = COLW - MAXIMUM (XDISP(I) , XDISP(II)) (1)

Partial Overlap

Overlap = COLW - XDISP(1) - XDISP(II) (2)



Total Overlap (Shadow 1 totally overlaps Shadow 2)



Partial Overlap (Shadows 1 and 2 intersect)

Figure 5. One-Dimension Shadow Overlaps

where

COLW = collector width,

XDISP(i) = horizontal displacement of the midpoint of the <u>i</u>th collector

Conveniently, the minimum of the magnitude of the two overlap conditions properly identifies the condition; i.e.,

$$\text{Overlap} = \text{Minimum (total overlap, partial overlap)} \qquad (3)$$

The overlap, or double-shadowed, area is obtained as the product of the independent overlaps in each dimension. Deducting the double-shadowed area from the total shadowed area properly accounts for double shadowing.

Circular Arrays

The projected images of circular collectors in the shadow plane are true size--again, with the assumption of parallel incident solar radiation (Figure 6).

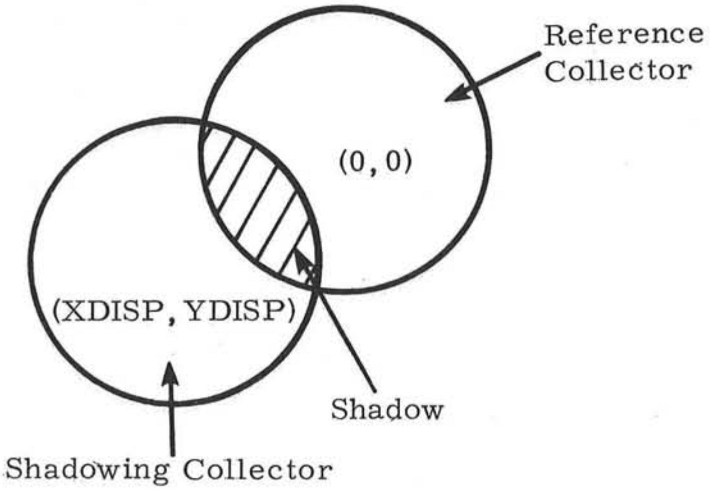


Figure 6. Circular Shadow Geometry

Shadow Area =

$$DISHR^2 - 2 \left[X \sqrt{DISHR^2 - X^2} + DISHR^2 * SIN^{-1}\left(\frac{X}{DISHR}\right) \right]$$

where

DISHR = DISH or Collector radius

X = One-half the distance between the two circle centers.

---

*R.C. Weast, ed., Handbook of Chemistry and Physics, 52d ed. (Cleveland: The Chemical Rubber Co., 1972).

The sum of the shadows from all shadowing collectors may overestimate the total shadow cast of the reference collector if double shadowing occurs.

Double shadows occur in three basic geometries, as shown in Figure 7.

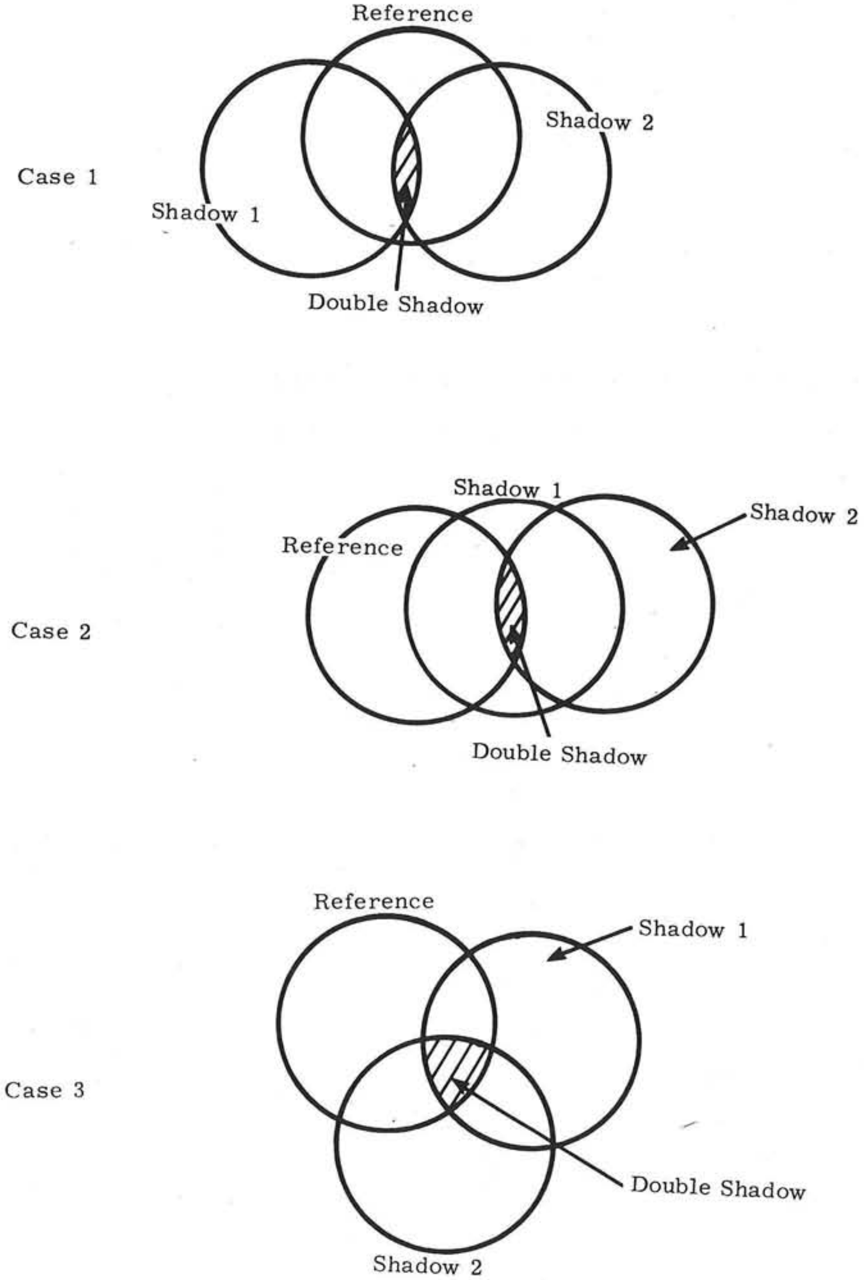


Figure 7. Three Geometries in Which Double Shadowing Occurs

The different conditions are identifiable from the location of the intersection points of two circles (i.e., either shadow circles or the reference circle) in relation to the third. Initially, however, in order to have double shadowing it is necessary for two adjacent collectors both to cast shadows and to have centers within a distance equal to the circle diameter.

Case 1 occurs if the intersection points between the two shadowing collectors fall within the reference collector circle.

Case 2 occurs if the intersection points of either shadowing collector and the reference collector fall within the other shadowing circle.

Case 3 occurs if and only if <u>one</u> intersection point between a shadowing collector and the reference collector is located within the other collector shadow.

The areas double-shadowed in Cases 1 and 2 are computed similarly to the area of the initial shadow (or simply recalled in Case 2) after proper case identification.

The double-shadowed area for Case 3 is computed as follows:

$$\begin{aligned}\text{Area} = {} & 1/2 \sum \text{Intersection areas of pairs of circles} \\ & + \text{Area in the triangle formed by the circle centers} \qquad (4) \\ & - \sum \text{Areas in the three circle segments formed by the} \\ & \qquad \text{triangle sides between circle centers}\end{aligned}$$

This is simplified, however, by noting that each circle segment formed by the triangle of the circle centers has equal radius (collector radius) and the sum of the internal angles totals π; i.e., the sum of the three circle-segments areas is

$$\frac{\pi \, DISHR^2}{2}$$

With the reference collector at (0,0), the area in the triangle is simply

$$\text{Triangle Area} = 1/2 \left| XDISP(1) * YDISP(2) - XDISP(2) * YDISP(1) \right| \quad (5)$$

where XDISP and YDISP are the centers of the other shadowing circles.

The sum of the intersection areas of all two circle combinations is computed by multiple use of the formula given previously. Subtracting the double-shadowed area from the total area shadowed then properly yields the correct shadowed area.

APPENDIX

Program FTSHADE

```
      PROGRAM FTSHADE(INPUT,OUTPUT,DATA,TAPE5=DATA)
C
C          SHADOWING OF FULLY TRACKING COLLECTORS DUE TO FIELD SPACING
C           SUBROUTINE ECBDATA IS USED TO CALCULATE THE SOLAR GEOMETRY
C           AND THE CENTER OF THE SHADOWING DISH IS PROJECTED ONTO THE
C           PLANE OF THE ADJACENT DISH, AND THE SHADOWED AREA CALCULATED.
C          COMMON SHADOWS FROM TWO ADJACENT COLLECTORS ARE CALCULATED
C          SO THAT NO DOUBLE ACCOUNTING OCCURRS.
C
      DIMENSION SNORTH(7),SEAST(7),XDISP(7),YDISP(7),ASHADE(7),X(7)
    3 FORMAT(A10)
   30 FORMAT(A4,1X,I2)
  131 FORMAT(I2,1X,A3,1X,I4)
C *************************************************************
C             CONSTANT INPUT DATA
C       THIS IS THE STANDARD INPUT FOR FAST RUNS
C*********************************************************************
      PRINT *,≠DO YOU WANT THE STANDARD INPUT≠,
      READ 3,NBUG
      IF(NBUG.EQ.2HNO) GO TO 1000
      IDENT=14HDISH SHADOWING
      ITYPE=1
      NDATE=21
      MON=3HJUN
      NDAYS=1
      IYR=1978
C          THE FOLLOWING LATITUDE AND LONGITUDE IS FROM THE SURVEY MARKER
C          NEAR THE CMTF AT SLA.  LATITUDE IS 35 DEGREES,3 MINUTES,15.7246
C          SECONDS; LONGITUDE IS 106 DEGREES,32 MINUTES,35.855 SECONDS.
      DLAT=35.054367944
      DLON=106.543293056
      HITE=5421.980
C          THE PRESSURE IS 837 MILLABARS FOR A STANDARD DAY ≤ ALBUQUERQUE
C          THE TEMPERATURE IS AVERAGE TEMP. ≤ ALBUQUERQUE IN DEGREES F.
      PRESSA=837.
      TA=57.
      ZONE=7.
        DISHDIA=22.966
      SNS=29.38
      SEW=60.43
      DLAT=33.40
      DWEST=1.00
      DNORTH=-1.73
      ANS1=4HHALF
      NANS2=24
      NSHAPE=7HDIAMOND
      NDINC=1
      LSTART=1
      GO TO 40
 1000 CONTINUE
C*********************************************************************
      LSTART=0
  100 PRINT *,≠1 IDENTIFICATION OF ANALYSIS (A10) =≠,
      READ 3,IDENT
      IF(LSTART.EQ.1)GO TO 40
  101 PRINT *,≠2 INPUT START DATE,AND MONTH≠,
      READ 131,NDATE,MON
```

```
      IF(LSTART.EQ.1)GO TO 40
  102 PRINT *,≠3 COLLECTOR TYPE; 1=DISH, 2=RECT↓≠,
      READ *,ITYPE
      IF(ITYPE .EQ. 2)GO TO 112
      PRINT *,≠    DIAMETER OF DISH(FEET)↓≠,
      READ *,DISHDIA
      GO TO 122
  112 PRINT *,≠    A) COLLECTOR HEIGHT↓≠,
      READ *,COLH
      PRINT *,≠    B) COLLECTOR WIDTH↓≠,
      READ *,COLW
  122 CONTINUE
      IF(LSTART.EQ.1)GO TO 40
  103 PRINT *,≠4 SPACING DISTANCE NORTH-SOUTH AND EAST-WEST (FEET)≠,
      READ *,SNS,SEW
      IF(LSTART.EQ.1)GO TO 40
  104 PRINT *,≠5 LATITUDE OF THE SITE LOCATION(DEGREES)≠,
      READ *,DLAT
      IF(LSTART.EQ.1)GO TO 40
  105 PRINT *,≠6 LONGITUDE OF THE SITE(DEGREES)≠,
      READ *,DLON
      IF(LSTART.EQ.1)GO TO 40
  106 PRINT *,≠7 WHAT TIME ZONE IS THE SITE LOCATED IN↓≠
      PRINT *,≠    THE TIME ZONE IS 7 FOR MOUNTAIN, 6 FOR CENTRAL, 5 FOR
     $ EASTERN AND 8≠
      PRINT *,≠    FOR PACIFIC, THE PROGRAM AUTOMATICALLY TAKES CARE O
     $F DAYLIGHT ≠
      PRINT *,≠    SAVINGS.≠
      READ *,ZONE
      IF(LSTART.EQ.1)GO TO 40
  107 PRINT *,≠8 SLOPE OF THE LAND TO THE WEST AND NORTH (FEET PER 100 F
     $EET)≠,
      READ *,DWEST,DNORTH
      IF(LSTART.EQ.1)GO TO 40
  108 PRINT *,≠9 DO YOU WANT HALF OR FULL HOUR INTERVALS (ANSWER HALF≠
      PRINT *,≠    OR FULL) FOR 12 HOURS OR 24 HOURS (ANSWER 12 OR 24)≠
      READ 30,ANS1,NANS2
      IF(LSTART.EQ.1)GO TO 40
  109 PRINT *,≠10 IS THE FIELD LAYOUT A DIAMOND OR RECTANGLE PATTERN≠,
      READ 3,NSHAPE
      IF(LSTART.EQ.1)GO TO 40
  110 PRINT *,≠11 HOW MANY DAYS DO YOU WANT CALCULATED AND IN WHAT INCRE
     $MENT≠,
      READ *,NDAYS,NDINC
      IF(LSTART.EQ.1)GO TO 40
    1 CONTINUE
C         CALCULATE DAY INTERVALS FOR NDAYS STARTING WITH NDAY
      CALL JULDAY(NDATE,MON,IYR,NDAY,JULDA0,TFLAG,FMO,NOUTANS)
      IF(TFLAG.NE.13.)GO TO 117
      PRINT *,≠THE MONTH WAS ENTERED WRONG; SELECT ONE OF THE FOLLOWING
     $ ≠
      PRINT *,≠JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DE
     $C.≠
      GO TO 101
  117 CONTINUE
      MDAYS=NDAY+NDAYS-1
      WW=3.141592654
```

```
      DLATR=(DLAT*(WW))/180
      IF(NSHAPE.EQ.9HRECTANGLE)GO TO 25
C         THIS DETERMINES THE LOCATION OF THE 7 SHADOWED COLLECTORS FOR A
C         DIAMOND LAYOUT.
      SNORTH(1)=-SNS/2
      SEAST(1)=(-SEW)/2
      SNORTH(2)=0.
      SEAST(2)=(-SEW)
      SNORTH(3)=SNS/2
      SEAST(3)=(-SEW)/2
      SNORTH(4)=SNS
      SEAST(4)=0.
      SNORTH(5)=SNS/2
      SEAST(5)=(SEW)/2
      SNORTH(6)=0.
      SEAST(6)=(SEW)
      SNORTH(7)=-SNS/2
      SEAST(7)=(SEW)/2
   25 CONTINUE
      IF(NSHAPE.EQ.7HDIAMOND)GO TO 26
C           THIS DETERMINES THE LOCATION OF THE 7 SHADOWED COLLECTORS FOR A
C           RECTANGULAR FIELD LAYOUT.
      SNORTH(1)=-SNS
      SEAST(1)=(-SEW)
      SNORTH(2)=0.
      SEAST(2)=(-SEW)
      SNORTH(3)=SNS
      SEAST(3)=(-SEW)
      SNORTH(4)=SNS
      SEAST(4)=0.
      SNORTH(5)=SNS
      SEAST(5)=(SEW)
      SNORTH(6)=0.
      SEAST(6)=(SEW)
      SNORTH(7)=-SNS
      SEAST(7)=(SEW)
   26 CONTINUE
      DISHR=DISHDIA/2
      ADISH=(WW)*(DISHR**2)
      XFACT=2.
      ILAST=48
      IF(ANS1.EQ.4HFULL)ILAST=24
      IF(ANS1.EQ.4HFULL)XFACT=1.
      IF(NANS2.EQ.12)ILAST=ILAST/2+1
      DO 10 J=NDAY,MDAYS,15
   44 FORMAT(///)
      PRINT 44
      CALL DATMDA(J,NDATE,FMO,IYR,MON)
      CALL JULDAY(NDATE,MON,IYR,NDAY,JULDA0,TFLAG,FMO,NOUTANS)
      PRINT 23,J,NDATE,MON
   23 FORMAT(5X,≠  **** NDAY = ≠,I3.9X,I2,2X,A3,2X,≠ ****≠)
      PRINT *,≠NORTH-SOUTH SPACING = ≠,SNS,≠  EAST-WEST SPACING = ≠,SEW
      PRINT *,≠SLOPE FROM EAST TO WEST IS ≠,DWEST,≠ AND SOUTH TO ≠
      PRINT *,≠     NORTH IS ≠,DNORTH,≠ IN FEET PER 100 FEET. ≠
   27 FORMAT(33HTHE COLLECTORS ARE ARRANGED IN A ,A10,8H LAYOUT.)
      IF(ITYPE.EQ.1)
     *PRINT *,≠ THE DISH DIAMETER IS ≠,DISHDIA
```

```
      IF(ITYPE.EQ.2)PRINT *,≠ COLLECTOR DIMENSIONS: ≠,COLH,
     A ≠ FEET HIGH BY ≠,COLW.≠ FEET WIDE≠
      PRINT 27,NSHAPE
   71 FORMAT(≠ THE LATITUDE IS ≠,F7.2,≠ AND THE LONGITUDE IS ≠.F7.2,≠ DE
     $GREES.≠)
      PRINT 71,DLAT,DLON
C
C           CALCULATE ONE HOUR TIME INTERVALS
      TIME=NDAY-172
      FIRTIM=1.
      DO 9 I=1,ILAST
      XNHR=(I-1)/XFACT
      CALL ECBDATA(J,XNHR,DLATR,AZANGR,ELANGR,TFLAG,DLON,ZONE,FRSTIM)
      IF(ELANGR.LE.0.)GO TO 9
C          IF THE SUN IS NOT SHINING, THERE IS NO SHADOW.
      ELANG=ELANGR*57.2957795
      AZANG=AZANGR*57.2957795
      PRINT 63,XNHR
   63 FORMAT(≠     NHR = ≠,F5.1)
      TASHAD=0.0
      TEFF=0.0
      DO 17 JJ=1,7
      ASHADE(JJ)=0.0
      XDISP(JJ)=1000000.
      YDISP(JJ)=0.0
      X(II)=0.
   17 CONTINUE
      DO 13 II=1,7
C          LOOK AT 7 POSSIBLE LOCATIONS THAT MAY BE SHADOWED.
C          THE NEXT FOUR STEPS ELIMINATE IMPOSSIBLE SHADOWING SITUATIONS.
      IF(XNHR.LT.12 .AND. II.GT.4)GO TO 13
      IF(XNHR.EQ.12 .AND. II.LE.2)GO TO 13
      IF(XNHR.EQ.12 .AND. II.GT.6)GO TO 13
      IF(XNHR.GT.12 .AND. II.LT.4)GO TO 13
      IF(SEAST(II).LT.0.)AZPT=ATAN(SNORTH(II)/SEAST(II))+(WW/2.)
      IF(SEAST(II).EQ.0.)AZPT=0.
      IF(SEAST(II).GT.0.)AZPT=ATAN(SNORTH(II)/SEAST(II))-(WW/2.)
      SHYP=((SEAST(II)**2)+(SNORTH(II)**2))**.5
      AZDEL=AZANGR-AZPT
      AAZDEL=ABS(AZDEL)
      IF(AAZDEL.GE.(WW/2))GO TO 13
C          IF THE SUN AZIMUTH IS GREATER THAN 90 DEGREES FROM THE AZIMUTH
C          BETWEEN THE SHADOWING DISH AND THE SHADOWED DISH, THERE CAN BE NO
C          INTERSECTION OF THE SHADOW ON THE SHADOWED DISH PLANE.
      XDISP(II)=-SHYP*SIN(AZDEL)
      SBASE=SQRT(SHYP**2-XDISP(II)**2)
      DELNOR=(SNORTH(II)/100)*DNORTH
      DELWES=-(SEAST(II)/100.)*DWEST
      DEL=DELNOR+DELWES
      YDISPO=-SBASE*TAN(ELANGR)
      YDISP(II)=YDISPO-DEL
      IF(ITYPE.EQ.1)GO TO 31
      IF(ABS(YDISP(II)).GE.COLH)GO TO 13
      IF(ABS(XDISP(II)).GE.COLW)GO TO 13
C  IF COLLECTOR CENTERS ARE SUFFICIENTLY REMOTE IN THE
C  X AND Y DIMENSION, THERE IS NO SHADOW.
      ASHADE(II)=(COLH-ABS(YDISP(II)))*(COLW-ABS(XDISP(II)))
```

```
      PEREFF=1.-ASHADE(II)/(COLW*COLH)
      TASHAD=TASHAD+ASHADE(II)
      PRINT 4,SNORTH(II),SEAST(II),II
      PRINT 5,ELANGR,AZANGR,ASHADE(II)
      PRINT 305,ELANG,AZANG
      PRINT 6,XDISP(II),YDISP(II),PEREFF
C         AT THIS POINT THE TOTAL SHADOWS CAST ON THE SHADOWED RECT HAVE
C         BEEN CALCULATED; BUT THERE MAY HAVE BEEN DOUBLE ACCOUNTING AND
C         THE FOLLOWING STEPS THROUGH ≠31 CONTINUE≠ CHECK FOR THIS POSSIBILI
C         AND SUBTRACT ANY DOUBLE SHADOWS.
      IF(II.EQ.1)GO TO 13
C  IF THE HORIZONTAL OR VERTICAL DIMENSION OF TWO COLLECTORS ARE
C  SUFFICIENTLY REMOTE, THERE WILL BE NO DOUBLE ACCOUNTING.
      IF(ASHADE(II-1).EQ.0.)GO TO 16
      IF(ABS(YDISP(II)-YDISP(II-1)).GE.COLH)GO TO 16
      IF(ABS(XDISP(II)-XDISP(II-1)).GE.COLW)GO TO 16
C  BOTH COLLECTORS SHADOW THE SHADOWED COLLECTOR
C  AND THEIR SHADOW INTERSECT, HENCE THEIR IS DOUBLE ACCOUNTING
      X1=COLW-ABS(XDISP(II)-XDISP(II-1))
      X2=AMAX1(ABS(XDISP(II)),ABS(XDISP(II-1)))
      X3=AMIN1(X1,(COLW-X2))
      Y1=COLH-ABS(YDISP(II)-YDISP(II-1))
      Y2=AMAX1(ABS(YDISP(II)),ABS(YDISP(II-1)))
      Y3=AMIN1(Y1,(COLH-Y2))
      TASHAD=TASHAD-X3*Y3
      GO TO 16
   31 CONTINUE
      DHYP=((XDISP(II)**2)+(YDISP(II)**2))**.5
      X(II)=DHYP/2
      IF(DHYP.GE.DISHDIA)GO TO 13
C         IF CENTERS OF THE SHADOWED DISH AND THE SHADOW ARE FARTHER APART
C         THAN THE DIAMETER OF THE DISH, THERE IS NO SHADOW ON THE SHADOWED
C         DISH.
      ASEG=(((WW)*(DISHR**2))/2)-(X(II)*(DISHR**2-X(II)**2)**.5+
     $(DISHR**2)*ASIN(X(II)/DISHR))
      ASHADE(II)=2*ASEG
      PEREFF=1.-(ASHADE(II)/ADISH)
      TASHAD=TASHAD+ASHADE(II)
      PRINT 4,SNORTH(II),SEAST(II),II
      PRINT 5,ELANGR,AZANGR,ASHADE(II)
      PRINT 305,ELANG,AZANG
      PRINT 6,XDISP(II),YDISP(II),PEREFF
C         AT THIS POINT THE TOTAL SHADOWS CAST ON THE SHADOWED DISH HAVE
C         BEEN CALCULATED; BUT THERE MAY HAVE BEEN DOUBLE ACCOUNTING AND
C         THE FOLLOWING STEPS THROUGH ≠16 CONTINUE≠ CHECK FOR THIS POSSIBILI
C         AND SUBTRACT ANY DOUBLE SHADOWS.
      IF(II.EQ.1)GO TO 13
      IF(ASHADE(II).EQ.0.)GO TO 13
      IF(ASHADE(II-1).EQ.0.)GO TO 16
      XHYP=SQRT((XDISP(II)-XDISP(II-1))**2+(YDISP(II)-YDISP(II-1))**2)
      IF(XHYP.GE.DISHDIA)GO TO 16
      IF(XHYP.EQ.0.0)GO TO 65
C  IF THE DISTANCE BETWEEN ADJACENT SHADOWS ON THE SHADOWED PLANE
C  IS GREATER THAN THE DISH DIAMETER, THERE IS NO DOUBLE ACCOUNTING
      IF(DHYP.EQ.0.)GO TO 66
      DIHYP=2.*X(II-1)
      IF(DIHYP.EQ.0.) GO TO 65
```

```
      V=SQRT(DISHR**2-X(II)**2)
      XCORD=XDISP(II)/2.-V*(YDISP(II)/DHYP)
      YCORD=YDISP(II)/2.+V*XDISP(II)/DHYP
      XXCORD=XDISP(II)/2.+V*YDISP(II)/DHYP
      YYCORD=YDISP(II)/2.-V*XDISP(II)/DHYP
      HCORD=SQRT((XDISP(II-1)-XCORD)**2+(YDISP(II-1)-YCORD)**2)
      HHCORD=SQRT((XDISP(II-1)-XXCORD)**2+(YDISP(II-1)-YYCORD)**2)
      IF(HCORD.LT.DISHR.AND.HHCORD.LT.DISHR)GO TO 65
      IF(HCORD.LT.DISHR.AND.HHCORD.GE.DISHR) GO TO 39
      IF(HCORD.GE.DISHR.AND.HHCORD.LT.DISHR) GO TO 39
      V=SQRT(DISHR**2-X(II-1)**2)
      XCORD=XDISP(II-1)/2. - V*YDISP(II-1)/DIHYP
      YCORD=YDISP(II-1)/2. + V*XDISP(II-1)/DIHYP
      XXCORD=XDISP(II-1)/2. +V*YDISP(II-1)/DIHYP
      YYCORD=YDISP(II-1)/2. -V*XDISP(II-1)/DIHYP
      HCORD=SQRT((XDISP(II)-XCORD)**2+(YDISP(II)-YCORD)**2)
      HHCORD=SQRT((XDISP(II)-XXCORD)**2+(YDISP(II)-YYCORD)**2)
      IF(HCORD.LT.DISHR.AND.HHCORD.LT.DISHR)GO TO 66
      DDIHYP=(DISHR**2-(XHYP/2)**2)**.5
      XCORD=(XDISP(II)+XDISP(II-1))/2.-DDIHYP*(YDISP(II-1)-YDISP(II))/
     A XHYP
      YCORD=(YDISP(II)+YDISP(II-1))/2.+DDIHYP*(XDISP(II-1)-XDISP(II))/
     A XHYP
      XXCORD=(XDISP(II)+XDISP(II-1))/2.+DDIHYP*(YDISP(II-1)-YDISP(II))/
     A XHYP
      YYCORD=(YDISP(II)+YDISP(II-1))/2.-DDIHYP*(XDISP(II-1)-XDISP(II))/
     A XHYP
      HCORD=SQRT(XCORD**2+YCORD**2)
      HHCORD=SQRT(XXCORD**2+YYCORD**2)
      IF(HCORD.LE.DISHR.AND.HHCORD.LE.DISHR)GO TO 68
      GO TO 16
C  THE DISH HAS A CONFIRMED DOUBLE ACCOUNTING.
   65 ACOM=ASHADE(II)
      GO TO 67
   66 ACOM=ASHADE(II-1)
      GO TO 67
  68  ACOM=WW*DISHR**2-2.*((XHYP/2.)*(DISHR**2-(XHYP/2.)**2)**.5+
     A DISHR**2*ASIN((XHYP/2.)/DISHR))
      GO TO 67
   39 AASEG=((WW*DISHR**2)/2.)-(XHYP/2.*(DISHR**2-(XHYP/2.)**2)
     A **.5+DISHR**2*ASIN(XHYP/2./DISHR))
      ACOM=-WW*DISHR**2/2.+.5*ABS(XDISP(II)*YDISP(II-1)-XDISP(II-1)*
     A  YDISP(II))+AASEG+ASHADE(II)/2.+ASHADE(II-1)/2.
   67 TASHAD=TASHAD-ACOM
   16 CONTINUE
    4 FORMAT(5X,9HSNORTH = ,F6.2,2X,9HSEAST   = ,F6.2,
     A 17H  COLLECTOR NO.= ,I2)
    5 FORMAT(5X,9HELANGR=  ,F6.4,2X,9HAZANGR=  ,F7.4,1X,10HASHADE =  ,
     $F6.2)
    6 FORMAT(5X,9HXDISP =  ,F6.2,2X,9HYDISP =  ,F6.2,2X,10HPEREFF =  ,
     $F6.4)
    7 FORMAT(21H TOTAL AREA SHADED = ,F6.2,19H  EFFECTIVE AREA = ,
     $F5.1,9H PER CENT)
  305 FORMAT(5X,9HELANG =  ,F7.2,1X,9HAZANG =  ,F7.2)
   13 CONTINUE
      TEFF=(1.-(TASHAD/ADISH))*100.
      PRINT 7,TASHAD,TEFF
```

```
    9 CONTINUE
   10 CONTINUE
      LSTART=1
      ANS=2HNO
      PRINT *,≠DO YOU WISH TO CHANGE INPUT DATA≠,
      READ 3, ANS
      IF(ANS.EQ.3HYES) GO TO 40
      GO TO 41
   40 PRINT *,≠TYPE LINE NUMBER OF INPUT(TYPE 0 TO EXECUTE) --≠,
      READ *,LINE
      IF(LINE.EQ.0) GO TO 1
      GO TO(100,101,102,103,104,105,106,107,108,109,110)LINE
   41 CONTINUE
      STOP
      END
```

```
C*****************************************************************
      SUBROUTINE ECBDATA(NDAY,XNHR,DLATR,AZANGR,ELANGR,TFLAG,DLONO,ZONE,
     $FRSTIM)
      DATA A,B,C,D,E,F,G,H,XI,XJ
     $/-4.688888997,.3641099890,0.3108332386E-02
     $,0.6046251052E-04,0.2812149530E-05,0.3896121774E-07
     $,0.2432655444E-09,0.7775214651E-12,0.1246203767E-14
     $,0.7965959848E-18/
      IF(FRSTIM.EQ.0.)GO TO 10
      D2=NDAY*NDAY
      D3=D2*NDAY
      D4=D3*NDAY
      D5=D4*NDAY
      D6=D5*NDAY
      D7=D6*NDAY
      D8=D7*NDAY
      D9=D8*NDAY
      ECOR=A-B*NDAY+C*D2-D*D3+E*D4-F*D5+G*D6-H*D7+XI*D8-XJ*D9
      FRSTIM=0.
   10 CONTINUE
      XNHOR=XNHR-TFLAG
      SOLTIM=XNHOR+(ECOR+4*(15.*ZONE-DLONO))/60.
      PSIR=0.40927971
      GAMMAR=DLATR
      PI=3.14159265
      TIME=NDAY-172.
      PHIR=TIME*0.01720242384
      ALPHAR=ASIN(SIN(PSIR)*COS(PHIR))
      NSEC=0
      THETAR=(SOLTIM-12.+NSEC/3600.)*.2618
      CG=COS(GAMMAR)
      SG=SIN(GAMMAR)
      CT=COS(THETAR)
      ST=SIN(THETAR)
      CA=COS(ALPHAR)
      SA=SIN(ALPHAR)
      SDI=CG*CT*CA+SG*SA
      EAR=PI/2.-ACOS(SDI)
      X=CA-SDI*CG*CT
      Y=SA-SDI*SG
      Z=-SDI*ST*CG
      AAR=ACOS((X*SG*CT-Y*CG+Z*ST*SG)/SQRT(X**2+Y**2+Z**2))
      IF(THETAR.GT.0)AAR=-AAR
      AZANGR=AAR
      ELANGR=EAR
  500 CONTINUE
      RETURN
      END
```

```
   IF(IDOW.GE.1)LSM=LDM-IDOW
   PRINT *,≠LSM= ≠,LSM
   IF(NDATE.GE.LSM)GO TO 15
   IF(FMO.EQ.4.)GO TO 13
   GO TO 14
15 CONTINUE
   IF(FMO.EQ.4.)GO TO 14
13 TFLAG=0
   GO TO 16
14 TFLAG=1
16 CONTINUE
   RETURN
   END
```

```
C*****************************************************************
      SUBROUTINE JULDAY(NDATE,MON,IYR,NDAY,JULDA0,TFLAG,FMO,NOUTANS)
C
C          THIS SUBROUTINE TAKES THE INPUT DAY IN THE FORM OF DATE(NDATE)
C          MONTH(MON) AND YEAR(IYR)AND CALCULATES THE DAY OF THE YEAR
C          (NDAY), THE JULIAN DAY NUMBER OF THAT DAY(JULDA0), AND IF
C          STANDARD TIME (TFLAG=0)OR IF DAYLIGHT SAVINGS TIME(TFLAG=1)
C          SHOULD BE USED.
C
      DIMENSION IDATE(12),IMO(12)
      DATA IDATE/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA (IMO(I),I=1,12)/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HA
     $UG,3HSEP,3HOCT,3HNOV,3HDEC/
      IF(((MOD(IYR,100).NE.0) .AND. (MOD(IYR,4).EQ.0))
     $ .OR.((MOD(IYR,400).EQ.0))) IDATE(2)=29
      NDAY=0
      J=1
   10 CONTINUE
      IF(MON.EQ.IMO(J))GO TO 11
      NDAY=NDAY+IDATE(J)
      J=J+1
      IF(J.NE.13)GO TO 10
      TFLAG=13
      RETURN
   11 CONTINUE
      NDAY=NDAY+NDATE
      FMO=J
      CALL JULDA(IYR,FMO,NDATE,JULDA0,NOUTANS)
      IF((FMO.EQ.4) .OR. (FMO.EQ.10))GO TO 12
      IF((FMO.LT.4) .OR. (FMO.GT.10))GO TO 13
      GO TO 14
   12 CONTINUE
      IF((FMO.EQ.4) .AND. (NDATE.LE.23))GO TO 13
      IF((FMO.EQ.10) .AND. (NDATE.LE.24))GO TO 14
      IF(FMO.EQ.4.)LDM=30
      IF(FMO.EQ.10.)LDM=31
      CALL JULDA(IYR,FMO,LDM,JULDAL,NOUTANS)
      XLDMDAN=JULDAL-1720982
      IF(NOUTANS.NE.3HYES)GO TO 17
      PRINT *,≠XLDMDAN = ≠,XLDMDAN,≠ JULDAL= ≠,JULDAL
   17 CONTINUE
      XLDMDAN=(XLDMDAN+5.)/7.
      LDMDAN=XLDMDAN
      FRAC=XLDMDAN-LDMDAN
      IF(FRAC.GT.0.99)FRAC=FRAC-0.99
      IF(NOUTANS.NE.3HYES)GO TO 18
      PRINT *,≠FRAC= ≠,FRAC,≠ XLDMDAN=≠,XLDMDAN,≠ LDMDAN=≠,LDMDAN
   18 CONTINUE
      DOW=FRAC*7.
      IDOW=DOW
      IF((DOW-IDOW).GT.0.5)IDOW=IDOW+1
      JDOW=IDOW-1
      IF(NOUTANS.NE.3HYES)GO TO 19
      PRINT *,≠DOW= ≠,DOW,≠ IDOW= ≠,IDOW,≠ JDOW= ≠,JDOW
   19 CONTINUE
C          IDOW=0 ^ JDOW=1 WHEN SUNDAY IS THE LAST DAY OF THE MONTH.
      IF(IDOW.EQ.0)LSM=LDM
```

```
C*****************************************************
      SUBROUTINE JULDA(IYR,FMO,NDATE,JULDA0,NOUTANS)
C
C          THE SUBROUTINE CALCULTES THE JULIAN DAY FOR THE INPUT DATE.
C
      IF(IYR.LT.100)IYR=IYR+1900
      YR=IYR
      IF(FMO.LE.2.)GO TO 15
      FMOP=FMO+1.
      YRP=YR
      GO TO 16
   15 CONTINUE
      FMOP=FMO+13
      YRP=YR-1.
   16 CONTINUE
      JULDA0=AINT(365.25*YRP)+AINT(30.6001*FMOP)+NDATE+1720982
      IF(NOUTANS.NE.3HYES)GO TO 18
      PRINT *,≠JULDA0=≠,JULDA0,≠ YRP=≠,YRP,≠ FMOP=≠,FMOP,≠ NDATE=≠,NDATE
   18 CONTINUE
      RETURN
      END
```

```
C************************************************************
      SUBROUTINE DATMDA(NDAY,NDATE,FMO,IYR,MON)
C
C         THIS SUBROUTINE TAKES THE INPUT DAY IN THE FORM OF THE DAY OF
C          THE YEAR(NDAY) AND CALCULATES THE DATE(NDATE), MONTH(FMO).
C
      DIMENSION IDATE(12),IMO(12)
      DATA IDATE/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA (IMO(I),I=1,12)/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HA
     $UG,3HSEP,3HOCT,3HNOV,3HDEC/
      IF(((MOD(IYR,100).NE.0) .AND. (MOD(IYR,4).EQ.0))
     $ .OR.((MOD(IYR,400).EQ.0))) IDATE(2)=29
      J=1
      NDAYN=NDAY
   10 CONTINUE
      NDAYO=NDAYN
      NDAYN=NDAYO-IDATE(J)
      J=J+1
      IF(NDAYN.GT.0)GO TO 10
      FMO=J-1
      NDATE=NDAYO
      MON=IMO(J-1)
      RETURN
      END
```

```
C************************************************
C         THIS FUNCTION FINDS THE COSINE OF AN ANGLE WHOSE ARGUMENT
C         IS IN DEGREES.
C
      FUNCTION COSD(A)
      DPR=180./3.141592653589793
      R=A/DPR
      COSD=COS(R)
      RETURN
      END
```

```
C*************************************************
C         THIS FUNCTION FINDS THE SINE OF AN ANGLE WHOSE ARGUMENT
C         IS IN DEGREES.
C
      FUNCTION SIND(A)
      DPR=180./3.141592653589793
      R=A/DPR
      SIND=SIN(R)
      RETURN
      END
```

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