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Sun-Pointing Programs and Their Accuracy

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SUN-POINTING PROGRAMS AND THEIR ACCURACY

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ABSTRACT

This paper describes several sun-pointing programs and their accuracy. FORTRAN program listings are given. Program descriptions are given for both Hewlett-Packard (HP-67) and Texas Instruments (TI-59) hand-held calculators.

ACKNOWLEDGMENT

The author acknowledges the following contributions:

The SUNAE program that was provided by Grover Hughes of SNLA, along with many subroutines that gave the base with which to compare the other sun-pointing programs.

The ECBDAT program that was provided by Eldon Boes of SNLA.

The RLAMB program that was provided by Ray Lamb of GE-VF.

The PLUTUS program that was provided by Paul Lutus, a consultant of ILC Technology.

The SUNAEP program that was provided by Robert Walraven of UC, Davis.

The SUNPOS program that was provided by Dr. R. Turner and D. R. Hinds of SNLA.

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Introduction

Where is the sun? Anyone can point to the sun on a clear day, but to predict with any accuracy the sun's location at some future time (hours, days, years from now) is a difficult task.

Renewed interest in solar energy has stimulated development of new sun-pointing programs. A large number of these programs are available, with varying claims of accuracy. This document reviews several sun-pointing programs, reports on their accuracy, and provides detailed programming instructions. In several instances, the programs are adaptable to hand-held, programmable calculators, and, in these instances, the program instructions for both Hewlett-Packard and Texas Instruments products are given.

Ephemeris Programs

The most accurate astronomical pointing programs are those used by the United States Naval Observatory and H.M. Nautical Almanac Office for generating the data printed in The American Ephemeris and Nautical Almanac (in Great Britain, The Astronomical Ephemeris). These data are accurate to approximately 0.1 arc second. Using the ephemeris equations, Grover Hughes of Sandia National Laboratories, Albuquerque (SNLA), has developed a computer program (SUNAE) which is the base from which sun-pointing programs for pointing the heliostats at the Central Receiver Test Facility and for pointing the parabolic troughs and paraboloidal dishes at the Midtemperature Solar Systems Test Facility (MSSTF) were developed. The SUNAE program has been verified in actual use by comparison with other sun-pointing programs and by astronomical and satellite tracking tests. The SUNAE program is accurate to approximately 1 arc second (0.00028 degree).

The ephemeris programs and the SUNAE program are too complicated and too slow-running for most applications, but they can be used to verify the accuracy of simpler sun-pointing programs. The author has used the SUNAE program to evaluate the accuracy of several sun-pointing programs, which are described in the following paragraphs. The method used was to execute the program under test for each sunlight hour of the day for every 15th day for a period of at least 1 year. Concurrently, the SUNAE program was used to calculate the same functions (e.g., sun's elevation and azimuth). The differences between the test program output and the SUNAE output were then tabulated. The accuracies reported below are the maximum differences appearing in these tabulations.

ECBDATA Program

The ECBDATA program is the simplest program in use at SNLA. The model upon which the program is based assumes that the sun moves in a circular path about the earth. The program calculates the elevation and azimuth of the sun. The time coordinate is solar time with no correction for the "equation of time" or for longitude. Comparing the ECBDATA output in solar time against the SUNAE output in local time yields errors of ± 10 degrees in azimuth and ± 4.5 degrees in elevation. Correcting for the difference between solar time and local time reduces the errors to 2 to 4 degrees. The ECBDATA program listing as shown in Appendix A.

RLAMB Program

Ray Lamb of General Electric-Valley Forge developed a similar program to give tracking data for an equatorial mount. The program includes corrections for the equation of time and longitude so that the output is in terms of local time. The maximum error in polar azimuth (hour angle) is ±1 degree and in declination is ±1 degree. The RLAMB program listing is shown is Appendix B.

PLUTUS Program

Paul Lutus, a consultant with ILC Technology, Sunnyvale, California, developed a program for the HP-67 calculator which was published in the July 1977 issue of Optical Spectra. The program includes corrections for the equation of time and longitude. The maximum error is ±2.0 degrees in azimuth and ±1.2 degrees in elevation. The FORTRAN program listing is given in Appendix C.

SUNAEP Program

Robert Walraven of the University of California, Davis, developed a program using modified ephemeris equations. The modification allows the calculation of the sun's longitude if the number of days since 31 December 1979 is known. In the basic ephemeris equations this calculation is based upon the number of Julian ephemeris centuries (36,525 days) since 1 January 1900. The maximum error for this program is ±0.06 degree in azimuth and ±0.013 degree in elevation for the period 1979 to 1986. Robert Walraven's program is sufficiently accurate to use for the computer-directed tracking of short-focus concentrating collectors, such as parabolic troughs and some paraboloidal dishes. The FORTRAN program listing is given in Appendix D.

None of the previous programs includes a correction for the refraction of the sun's rays by the atmosphere. For high sun elevations, the correction is not very large. However, at elevations of 60° or less, the refraction correction is significant, as shown in Table 1.

Table 1

Refraction Correction

Sun Elevation (degrees)	Refraction Correction (degrees)
60	0.01
10	0.1
0	0.5

Grover Hughes developed a series of equations to correct for the refraction errors. Input data for the correction are the ground level temperature (°F) and pressure (millibars) at the observation point. The algorithm for the refraction correction is included in the latter part of Appendix D and is marked for identification.

The HP-67 version of the SUNAEP program is described in Appendix E. The HP-67 program for the correction of the sun's elevation angle due to atmospheric refraction is given in Appendix F. The TI-59 version of the SUNAEP program is given in Appendix G. This latter program includes the correction for refraction.

SUNPOS Program

The SUNPOS program is used at SNLA for pointing the heliostats at the Central Receiver Test Facility (CRTF). The computer program was constructed by D. R. Turner and D. R. Hinds with equations furnished by Grover Hughes (all from SNLA). The program includes a refraction correction, but it is a less accurate one than that described in the preceding paragraphs. The program is accurate to ± 5 arc minutes (± 0.08 degree). If the more accurate refraction correction is used, the error drops to ± 2 arc minutes (± 0.03 degree). The larger refraction errors in SUNPOS occur only at the lower sun elevations and hence are not too noticeable. The SUNPOS program listing is given in Appendix H.

Conversions

The conversion from azimuth-elevation to polar-declination coordinates is required in order to calculate the position of any equatorial mount. In order to correct for the refraction of the earth, the elevation must be known. Hence, it is easier to calculate the azimuth-elevation, correct for refraction, and then convert to polar-declination. If it is necessary to convert from polar declination to azimuth-elevation, this calculation can also be performed.

Figure 1 illustrates the geometry. The North Pole, the zenith point, and the sun are the vertices of a spherical triangle on the celestial sphere. If any three parts of a spherical triangle are known, the magnitudes of the unknown parts can be calculated. If the latitude of the zenith point (local latitude) and the sun's elevation and azimuth are known, then the sun's polar angle and declination can be calculated. Conversely, if the latitude of the zenith point (local latitude) and the sun's solar angle and declination are known, then the sun's elevation and azimuth can be calculated.

Equations Used (AZ-EL to P-δ)

Symbols:

ϕ = the latitude

E = the sun's elevation

A = the sun's azimuth (measured from south, positive to the west)

δ = the sun's declination

For conversion from azimuth-elevation to polar-declination:

1. $\sin \delta = \sin E \cdot \sin \phi - \cos E \cdot \cos \phi \cdot \cos A$
2. $\tan P = \sin A / (\cos \phi \cdot \tan E + \sin \phi \cdot \cos A)$

For conversion from polar-declination to azimuth-elevation:

3. $\sin E = \sin \delta \cdot \sin \phi + \cos \delta \cdot \cos \phi \cdot \cos P$
4. $\tan A = \sin P / (\cos \phi \cdot \tan \delta - \sin \phi \cdot \cos P)$

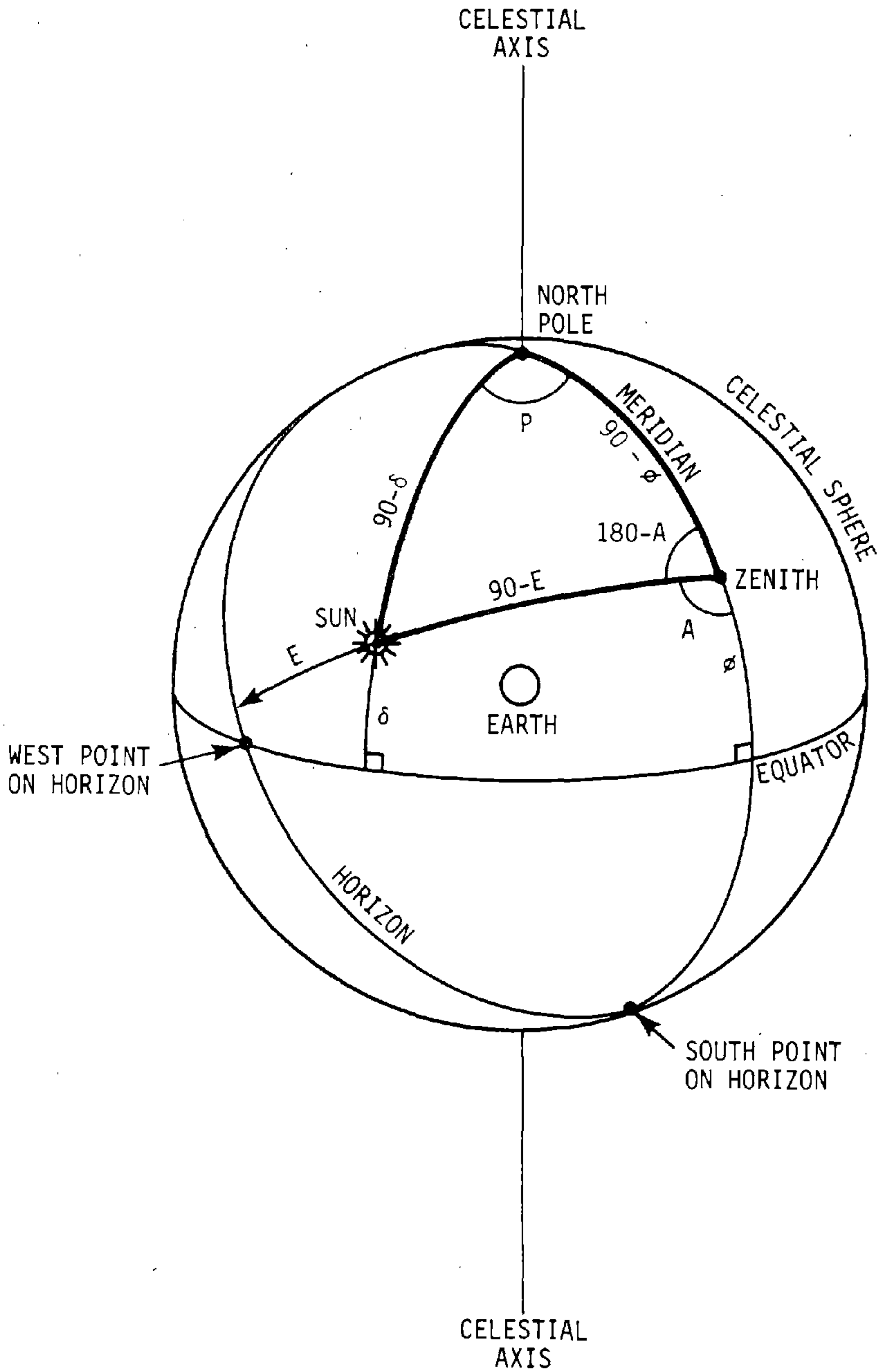


Figure 1. Geometry of Azimuth-Elevation and Polar-Declination Coordinates

See Appendix I for a detailed derivation of the formulas and a program for these conversions for the HP-67 calculator. An equivalent program for the TI-59 calculator is given in Appendix J.

Another useful conversion is the computation of the tracking and incidence angles for parabolic trough collectors when the sun's azimuth and elevation angles are given. Conversions for both east-west (E-W) oriented and north-south (N-S) oriented troughs are given.

The geometry and nomenclature are shown in Figure 2. Note that, for this program, the azimuth angle, A, is measured from due north toward the east. Given the sun's azimuth and elevation angles, this program computes the angle of incidence of the sun's rays on the collector aperture plane and the collector tracking angle for both E-W- and N-S-oriented collectors. The collector is a line-focusing, trough type with the focal line parallel to the horizontal plane. It is assumed that the collector is symmetric about a central plane, as is true for parabolic troughs in which the central plane is defined by the focal line and the apex line of the reflector surface (these two lines are parallel and hence define a plane). When the collector is "in focus," the extended central plane passes through the sun. In Figure 2, the intersection of the central plane and the celestial sphere is shown.

<u>Equations Used (AZ-EL to T-i)</u>

Symbols:

i = angle of incidence

T = tracking angle

$T = 90° - \tau$

For E-W troughs:

1. $\sin i = -\cos E \cdot \sin A$
2. $\tan \tau = -\dfrac{\cos A}{\tan E}$

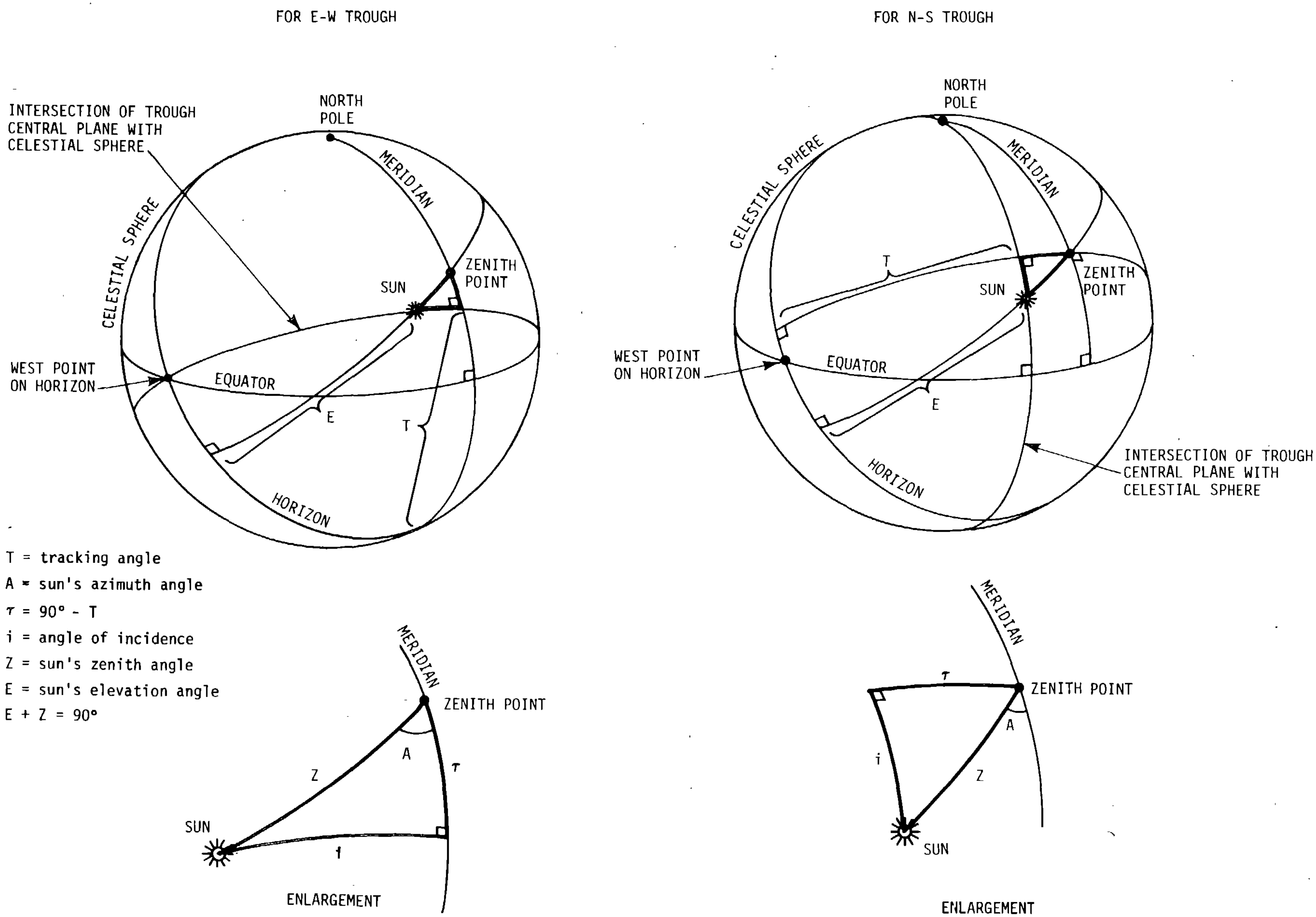


Figure 2. Geometry for Calculation of Tracking and Incidence Angles from the Sun's Azimuth-Elevation Coordinates

For N-S troughs:

3. $\sin \iota = -\cos E \cdot \sin A$

4. $\tan \tau = -\dfrac{\sin A}{\tan E}$

See Appendix K for a detailed derivation of the formulas and a program for these conversions for the HP-67 calculator. An equivalent program for the TI-59 calculator is given in Appendix L.

For anyone who might want to program any of the aforementioned programs to a computer, Appendix M contains listings for the hourly azimuth-elevation with each program for 21 March 1981 and a printout of many of the variables for several hours of that day.

APPENDIX A

FORTRAN Listing for the ECBDATA Program

```
C*****************************************************************
      SUBROUTINE ECBDATA(NDAY,XNHR,DLATR,AZANGR,ELANGR)
C**********************************************************************
C                    SOLAR GEOMETRY CALCULATIONS
C**********************************************************************
      SOLTIM=XNHR
      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
      TWOPI=2*PI
      AZANGR=AAR
      ELANGR=EAR
      IF(AZANGR.GE.O.)AZANGR=PI-AZANGR
      IF(AZANGR.LT.O.)AZANGR=PI+ABS(AZANGR)
      IF(SOLTIM.LT.O.)AZANGR=TWOPI-AZANGR
500   CONTINUE
      RETURN
      END
```

Input:

NDAY	Day of the year, e.g., for 21 June 1981, NDAY = 172
XNHR	24-hour decimal time of the day, e.g., for 1:30 p.m., XNHR = 13.50
DLATR	Observer's latitude in radians, e.g., for the MSSTF at SNLA, DLATR = 0.611814138 radians.

Output:

AZANGR	Sun's azimuth angle in radians
ELANGR	Sun's elevation angle in radians

APPENDIX B

FORTRAN Listing for the RLAMB Program

For an Output of the Sun's Polar Angle and Declination in Radians

```
C*********************************************************************
      SUBROUTINE RLAMB(NDAY,XNHR,DLAT,RLMAZR,RLMDCR,DLON,TFLAG,ZONE,NDFEB
      RLMDCR=0.4093*SIN(6.283*284.0+NDAY/(365+NDFEB-28))
      X=0.01717*NDAY
      EQOFTM=0.007*COS(X)-0.05*COS(2*X)-0.0015*COS(3*X)
     $ -0.122*SIN(X)-0.156*SIN(2*X)-0.005*SIN(3*X)
      SOLTIM=XNHR-TFLAG+EQOFTM+(4.*(15.*ZONE-DLON))/60.
      STIM=(4.*(15.*ZONE-DLON))/60.
      SOLTIME=SOLTIM-12.
      POLAZ=15*SOLTIME
      RLMAZR=-POLAZ/DPR
      RETURN
      END
```

Input

NDAY	Day of the year, e.g., for 21 June 1981, NDAY = 172
XNHR	24-hour decimal time of the day, e.g., for 1:30 p.m., XNHR = 13.50
DLAT	Observer's latitude in degrees, e.g., for the MSSTF at SNLA, DLAT = 35°.054368
DLON	Observer's longitude, e.g., for the MSSTF at SNLA, DLON = 106°.543293
TFLAG	0 if Standard Time, 1 if Day Light Savings Time.
ZONE	Hours from Greenwich Time, see Table E-1
NDFEB	Number of days in February for the year in question

Output

RLMAZR	Sun's polar angle in radians
RLMDCR	Sun's declination angle in radians

Notes: 1. SIND and COSD are sine and cosine functions that use degrees as an argument.

2. ATAN2 is an arctangent function that selects the correct quadrant and returns an angle in the range of $\pm 180°$.

APPENDIX C

FORTRAN Listing for the PLUTUS Program

```
C***************************************************
      SUBROUTINE PLUTUS(NDAY,TFLAG,FLONO,FLATO,XNHR,ZONE,
     $AZANGR,ELANGR)
      DPR=180./3.141592654
C
C         THIS SUBROUTINE WAS MODIFIED FROM A HP-67 PROGRAM BY PAUL
C         LUTUS THAT WAS PUBLISHED IN THE JULY,1977 EDITION OF
C         ≠OPTICAL SPECTRA≠.
C
      XHANG=NDAY*0.986
C         360 DEGREE/365.25 DAYS = .985626
      Q31=XHANG-80.5
      Q32=SIND(Q31+2*COSD(Q31))
      Q5=0.4338*Q32
      Q33=15*(12.+XNHR+ZONE-TFLAG)
      Q34=1.8*SIND(XHANG-3.)
      Q35=2.46*SIND(19.+2*XHANG)+Q34
      Q36=SIND(29+XHANG*3.)
      Q37=Q35+0.1*(Q36)
      QE=Q37-0.22
      Q6=Q33-QE-FLONO
      Q38=Q5*COSD(FLATO)
      QA=(-SIND(FLATO))*(COSD(Q6))+Q38
      QC=Q5*SIND(FLATO)+COSD(FLATO)*COSD(Q6)
      QB=-SIND(Q6)
      AZANGR=ATAN2(QB,QA)
      IF(AZANGR.LT.0.0)AZANGR=AZANGR+6.283185308
      AZANG=AZANGR*DPR
      POLAR2=SQRT(QB**2+QA**2)
      ELANGR=ATAN2(QC,POLAR2)
      ELANG=ELANGR*DPR
      RETURN
      END
```

Input

NDAY	Day of the year, e.g., for 21 June 1981, NDAY = 172
XNHR	24-hour decimal time of the day, e.g., for 1:30 p.m., XNHR = 13.50
FLATO	Observer's latitude in degrees, e.g., for the MSSTF at SNLA, DLAT = 35°.054368
FLOND	Observer's longitude, e.g., for the MSSTF at SNLA, DLON = 106°.543293
TFLAG	0 if Standard Time, 1 if Day Light Savings Time.
ZONE	Hours from Greenwich Time, see Table E-1

Output

AZANG	Sun's azimuth angle in degrees
ELANG	Sun's elevation angle in degrees

Notes:

1. SIND and COSD are sine and cosine functions that use degrees as an argument.
2. ATAN2 is an arctangent function that selects the correct quadrant and returns an angle in the range of $\pm\pi$ radians.

APPENDIX D

FORTRAN Listing for the SUNAEP Program

```
C***********************************************************************
      SUBROUTINE SUNAEP(YEAR,DAY,XNHR,MIN,SEC,ZONE,DASVTM,LAT,LONG,AZANG
     $R,ELANGR,NOUTANS,PRESSA,TA,PAZANS,POAZPR,PODCPR)
C
C         THIS SUBROUTINE CALCULATES THE LOCAL AZIMUTH AND ELEVATION OF
C         THE SUN AT A SPECIFIED LOCATION AND TIME USING AN APPROXIMA-
C         TION TO THE EQUATIONS USED TO GENERATE THE NAUTICAL ALMANAC.
C
C         THIS IS COPIED FROM AN ARTICLE BY ROBERT WALRAVEN OF THE
C         UNIVERSITY OF CALIFORNIA,DAVIS IN SOLAR ENERGY VOL 20 NO.5-C
C         PUBLISHED IN NOVEMBER OF 1978.
C
C         INPUT PARAMETERS
C           YEAR         - THE YEAR NUMBER(E.G., 1977).
C           DAY          - THE DAY NUMBER OF THE YEAR STARTING WITH 1 FOR
C                          JANUARY 1,EXCEPT IN LEAP YEARS WHEN 1 SHOULD BE
C                          SUBTRACTED FROM THE DAY NUMBER BEFORE MARCH 1.
C           HR,MIN,SEC - THE TIME OF THE DAY
C           ZONE         - THE LOCAL INTERNATIONAL ZONE TIME(E.G., PST=8)
C                          (SEE TABLE E1)
C           DASVTM       - =1 IF DAYLIGHT SAVINGS TIME IN EFFECT,ELSE = 0.
C           LAT          - THE LOCAL LATITUDE IN DEGREES(NORTH IS
C                          POSITIVE)
C           LONG         - THE LOCAL LONGITUDE IN DEGREES WEST OF
C                          GREENWICH.
C           PRESSA       - THE LOCAL AIR PRESSURE IN MILLIBARS
C           TA           - THE LOCAL AMBIENT TEMPERATURE IN DEGREES F
C           NOUTANS      - IF YES, LONG OUTPUT IS PRINTED
C           PAZANS       - IF YES, POLAR AZIMUTH AND DECLINATION ARE
C                          CALCULATED
C
C         OUTPUT PARAMETERS
C           A            - AZIMUTHAL ANGLE OF THE SUN (POSITIVE IS EAST
C                          OF SOUTH)
C           E            - ELEVATION OF THE SUN
C           AZANGR       - AZIMUTHAL ANGLE OF THE SUN IN RADIANS
C           ELANGR       - ELEVATION ANGLE OF THE SUN IN RADIANS
C           POLAZ        - POLAR AZIMUTH ANGLE OF THE SUN IN DEGREES
C           POLDEC       - DECLINATION OF THE SUN IN DEGREES
C
C-----------------------------------------------------------------------
C
```

```
      REAL MIN,LAT, LONG
      DATA TWOPI,RAD/6.2831853, 0.017453293/
      DELYR = YEAR-1980
      LEAP=INT(DELYR/4.)
      T=XNHR+(MIN+SEC/60.)/60.+ZONE-DASVTM
      TIME=DELYR*365.+LEAP+DAY-1.+T/24.
      IF(DELYR.EQ.LEAP*4.)TIME=TIME-1.
      IF((DELYR.LT.0.) .AND. (DELYR.NE.LEAP*4)) TIME=TIME-1.
      THETA=(360.*TIME/365.25)*RAD
      G=- 0.031271 - 4.53963E-7*TIME + THETA
      EL=4.900968+3.67474E-7*TIME+(0.033434-2.3E-9*TIME)*SIN(G)
     $  +0.000349*SIN(2.*G) + THETA
      EPS= 0.409140 - 6.2149E-9*TIME
      SEL = SIN(EL)
      A1= SEL*COS(EPS)
      A2=COS(EL)
      RA=ATAN2(A1,A2)
      IF(RA.LT.0.)RA=RA+TWOPI
      DECL=ASIN(SEL*SIN(EPS))
      ST=1.759335+TWOPI*(TIME/365.25-DELYR)+3.694E-7*TIME
      IF(ST.GE.TWOPI)ST=ST-TWOPI
      S=ST+(T*15.-LONG)*RAD
      IF(S.GE.TWOPI) S=S-TWOPI
      H=RA-S
      PHI=LAT*RAD
      ER=ASIN(SIN(PHI)*SIN(DECL)+COS(PHI)*COS(DECL)*COS(H))
      A=ASIN(COS(DECL)*SIN(H)/COS(ER))/RAD
      IF(SIN(ER).GE.SIN(DECL)/SIN(PHI))GO TO 15
      IF(A.LT.0)A=A+360.
      A=180.-A
   15 E=ER/RAD                                                   }
C      FIND THE MEAN REFRACTION (R) IN ARC-SECONDS FOR A         }
C      GIVEN ELEVATION ANGLE (E) IN DEGREES.                     }
      IF(E.LT.-0.575) GO TO 20                                   }
      IF(E.LT.5.)     GO TO 10                                   }
      TANE=TAND(E)                                               }
      R=58.1/TANE-.070/TANE**3+.000086/TANE**5                   }
      GO TO 30                                                   }   REFRACTION
   10 R=1735.+E*(-518.2+E*(103.4+E*(-12.79+E*0.711)))            }   CORRECTION
      GO TO 30                                                   }
   20 R=-20.774/TAND(E)                                          }
   30 CONTINUE                                                   }
      RFAC=(PRESSA*510.)/(1013.*(460.+TA))                       }
      RC=R*RFAC                                                  }
      RC=RC/3600.                                                }
      EC=E+RC                                                    }
      A=180.-A
      AZANGR=A*RAD
      ELANGR=EC*RAD
```

```
      IF(PAZANS.NE.3HYES)GO TO 23
      Z=SIN(ELANGR)
      E=SIN(AZANGR)*COS(ELANGR)
      XN=COS(AZANGR)*COS(ELANGR)
      XNROF=XN*COSD(LAT)+Z*SIND(LAT)
      ZROF=-XN*SIND(LAT)+Z*COSD(LAT)
      POAZPR=ATAN2(E,ZROF)
      TEMP=SQRT((ZROF**2)+(E**2))
      PODCPR=ATAN2(XNROF,TEMP)
      POLAZ=POAZPR*DPR
      POLDEC=PODCPR*DPR
      IF(NOUTANS.NE.3HYES)GO TO 11
      PRINT *,≠ Z= ≠,Z,≠ E= ≠,E,≠ XN= ≠,XN,≠ XNROF= ≠,XNROF,≠
     $ZROF= ≠,ZROF,≠ POLAZ= ≠,POLAZ,≠ POLDEC= ≠,POLDEC
   23 CONTINUE
      IF(NOUTANS.NE.3HYES)GO TO 11
      PRINT *,≠ A= ≠,A,≠ E= ≠,E,≠ LEAP= ≠,LEAP,≠ T = ≠,T,≠
     $TIME= ≠,TIME,≠ DELYR= ≠,DELYR,≠ THETA= ≠,THETA,≠ G= ≠,G,≠
     $EL= ≠,EL,≠ EPS= ≠,EPS
      PRINT *,≠SEL= ≠,SEL,≠ RA= ≠,RA,≠ DECL= ≠,DECL,≠ ST= ≠ST,≠
     $S = ≠,S,≠ H= ≠,H
      PRINT *,≠ER= ≠,ER,≠ E= ≠,E,≠ EC= ≠,EC,≠ R= ≠,R,≠ RC= ≠,RC,≠
     $RFAC= ≠,RFAC
   11 CONTINUE
      RETURN
      END
```

CONVERSION FROM AZIMUTH-ELEVATION TO POLAR DECLINATION (DIFFERENT FROM APPENDICES I AND J)

Notes: 1. ATAN2 is an arc-tangent function that selects the correct quadrant and returns an angle in the range of $\pm\pi$ radians.

2. TAND is a tangent function that uses degrees as an argument.

APPENDIX E

HP-67 Version of the SUNAEP Program

Program Description

This program was developed from the algorithms provided by Robert Walraven of the University of California, Davis. The basic ephemeris equations have been modified to measure the time from midnight, 0 January 1980 (actually 31 December 1979) at Greenwich, England. The program has been checked through the year 1986 and is accurate to ± 0.05 degree in azimuth and ± 0.02 degree in elevation if refraction is ignored. Refraction causes errors of 0.574 degree at apparent sunrise, 0.09 degree at approximately 10° elevation, and 0.009 degree at approximately 60° elevation. Corrections for refraction must be computed separately.

Equations Used

1. DELYR = YEAR - 1980, the number of years since 1980.
2. $T = T_{LOCAL} + ZONE$, where T is Greenwich mean time in decimal hours. T_{LOCAL} is local standard time (corrected for daylight saving time). ZONE is listed in Table E1.

Table E1

The Value of ZONE for Several International Time Zones

International Time Zone	ZONE (hours)
Atlantic Standard Time	4
Eastern Standard Time	5
Central Standard Time	6

Table E1 (Continued)

International Time Zone	ZONE (hours)
Mountain Standard Time	7
Pacific Standard Time	8
Hawaii Standard Time	10

3. TIME = DELYR x 365 + DAY^{-1} + T/24, the number of days, expressed as a decimal, since 31 December 1979. DAY is the day number of the year (e.g., DAY = 1 for 1 January). T is Greenwich mean time expressed in decimal hours. Each leap year is accounted for in the calculator routine in computing TIME.

4. $\theta = \frac{2\pi}{365.25} \times \text{TIME}$, the number of sidereal years since 31 December 1979 expressed in radians.

5. $g = -0.031271 - 4.53963 \times 10^{-7} \times \text{TIME} + \theta$, the mean anomaly of the earth in radians.

6. $$L = 4.900968 + 3.67474 \times 10^{-7} \times \text{TIME} + \theta$$

$$+ (0.033434 - 2.3 \times 10^{-9} \times \text{TIME}) \sin g$$

$$+ 0.000349 \times \sin 2g,$$ the longitude of the sun in radians.

7. $\xi = 0.40914 - 6.2149 \times 10^{-9} \times \text{TIME}$, the obliquity of the ecliptic in radians.

8. $\tan \alpha = \cos \xi \cdot \tan L$, where α is the right ascension of the sun in radians.

9. $\sin \delta = \sin \xi \cdot \sin L$, where δ is the declination of the sun in radians.

10. $SG = 1.759335 + 3.694 \times 10^{-7} \times TIME$

$+ 2\pi(TIME/365.25 - DELYR)$,

where SG is Greenwich sidereal time expressed in radians.

11. $S = SG + \frac{2\pi}{360}(15 \times TIME - LONG)$, where S is local sidereal time expressed in radians. LONG is local longitude in decimal degrees.

12. $H = \alpha - S$, the polar angle (or hour angle) expressed in radians.

13. $\sin E = \sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\delta \cdot \cos H$, where E is the elevation angle of the sun in radians. ϕ is the local latitude in radians.

14. $\sin A = \frac{\cos\delta \cdot \sin H}{\cos E}$, where A is the azimuth angle of the sun in radians. Due north is zero with positive angles toward the east. (Note: This differs from Walraven's method of measuring the azimuth angle as given in Appendix D.)

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
001	*LBLA	051	X=Y?	101	P≷S
002	RCL0	052	GT01	102	COS
003	1	053	RCLE	103	RCLD
004	9	054	1	104	SIN
005	8	055	-	105	x
006	0	056	STOE	106	RCLD
007	-	057	*LBL1	107	COS
008	ST06	058	P≷S	108	R►P
009	4	059	RCLE	109	X≷Y
010	÷	060	RCL0	110	STOA
011	INT	061	x	111	Pi
012	STOA	062	D►R	112	2
013	RCL2	063	STOA	113	x
014	RCL3	064	RCLE	114	STOB
015	+	065	RCL2	115	RCLA
016	ST07	066	x	116	X>0?
017	2	067	+	117	GT02
018	4	068	RCL1	118	+
019	÷	069	+	119	STOA
020	RCL1	070	STOB	120	*LBL2
021	+	071	RCL3	121	RCLI
022	1	072	RCL4	122	SIN
023	-	073	RCLE	123	RCLD
024	RCLA	074	x	124	SIN
025	+	075	+	125	x
026	RCL6	076	RCLE	126	SIN^{-1}
027	3	077	RCL6	127	STOI
028	6	078	x	128	RCLE
029	5	079	RCL5	129	RCL9
030	x	080	+	130	÷
031	+	081	RCLB	131	RCL6
032	STOE	082	SIN	132	-
033	RCL6	083	x	133	RCLB
034	RCLA	084	+	134	x
035	4	085	RCLB	135	RCLE
036	x	086	2	136	RCL8
037	X≠Y?	087	x	137	x
038	GT00	088	SIN	138	+
039	RCLE	089	RCL7	139	RCLC
040	1	090	x	140	+
041	-	091	+	141	GSB9
042	STOE	092	RCLA	142	RCL7
043	*LBL0	093	+	143	1
044	RCL6	094	STOD	144	5
045	X>0?	095	RCL8	145	x
046	GT01	096	RCL9	146	RCL4
047	RCL6	097	RCLE	147	-
048	RCLA	098	x	148	D►R
049	4	099	-	149	+
050	x	100	STOI	150	GSB9

Step	Key Entry	Step	Key Entry
151	RCLA	201	*LBL4
152	RCLE	202	RCLA
153	-	203	R►D
154	STOE	204	STOA
155	RCL5	205	~x~
156	COS	206	RCL7
157	RCLI	207	R►D
158	COS	208	STOE
159	x	209	RTN
160	RCLE	210	*LBL9
161	COS	211	RCLB
162	x	212	X≷Y
163	RCLI	213	X≤Y?
164	SIN	214	GTO8
165	RCL5	215	-
166	SIN	216	CHS
167	x	217	*LBL8
168	+	218	STOE
169	SIN	219	RTN
170	STO7	220	*LBLa
171	RCLE	221	RCL5
172	SIN	222	D►R
173	RCLI	223	STO5
174	COS	224	RTN
175	x	225	R/S
176	RCL7		
177	COS		
178	÷		
179	SIN		
180	STOA		
181	RCL7		
182	SIN		
183	RCLI		
184	SIN		
185	RCL5		
186	SIN		
187	÷		
188	X>Y?		
189	GTO3		
190	Pi		
191	RCLA		
192	-		
193	STOA		
194	GTO4		
195	*LBL3		
196	RCLB		
197	RCLA		
198	X<0?		
199	+		
200	STOA		

Operating Instructions

Step	Instruction	Enter	Press
1	Enter YEAR (e.g., 1981) Store 0	1981	STO 00
2	Enter DAY (e.g., 21 March 1981 = 80) Store 1	80	STO 01
3	Enter HOUR (decimal hour, local standard time, e.g., 1:30 p.m. = 13.50 hours) Store 2	13.5	STO 02
4	Enter ZONE (e.g., from Table E1, Mountain Standard Time is Zone 7, Mountain Daylight Saving Time is Zone 6) Store 3	7	STO 03
5	Enter LONG in decimal degrees (e.g., MSSTF at Albuquerque, NM, is at 106°.54329 W.) Store 4	106.54	STO 04
6	Enter ϕ (latitude) in decimal degrees (e.g., Albuquerque, NM, is at 35°.054368 N.) Store 5	35.05	STO 05
7	With latitude in decimal degrees showing on display, press f LBL A Stores latitude in radians in storage register 5.		f a
8	Start program		A

Output: Azimuth measured in degrees clockwise from north, flashing. Elevation in degrees is stored in E. Declination in radians is stored in I.

Limits

$1975 \leq \text{YEAR} \leq 1986$ (verified over this range)

$1 < \text{DAY} < 366$

$0 < \text{TIME} < 24$

$-180° < \text{LONG} < 180°$ (west to east)

$-90° < \phi < 90°$

Memory Listing

Where a memory is used more than once, the contents of the memory are listed in the order in which they appear. The last item listed for each memory remains after completion of the calculation.

Memory	Item	Remarks
0	YEAR	--
1	DAY	The day number of the year, e.g., for 23 October on a leap year, DAY = 295 and on a NON-leap year, DAY = 294.
2	Local Time	In decimal hours
3	ZONE	See Table E1. (-1 if Daylight Saving Time)
4	Longitude	In degrees
5	Latitude	In radians
6	DELYR	Computed
7	T; ER	T = Greenwich standard time ER = sun's elevation in radians
8	3.694×10^{-7}	Fixed data
9	365.25	Fixed data
S0	360/365.25	Fixed data
S1	-0.031271	Fixed data
S2	-4.53963×10^{-7}	Fixed data
S3	4.900968	Fixed data
S4	3.67474×10^{-7}	Fixed data
S5	0.033434	Fixed data
S6	-2.3×10^{-9}	Fixed data
S7	0.000349	Fixed data
S8	0.40914	Fixed data
S9	6.2149×10^{-9}	Fixed data
A	LEAP;ϕ;RA;A	LEAP = INTEGER OF DELYR/4 θ = sidereal year since 31 December 1979 in radians RA = sun's right ascension angle in radians A = sun's azimuth angle in degrees
B	G;2	G = mean anomaly of the earth in degrees

Memory	Item	Remarks
C	1.759335	Fixed data
D	L	L = sun's longitude in radians
E	TIME;ST;S;H;E	TIME = number of days (a decimal) since 31 December 1979. ST = Greenwich sidereal time S = local sidereal time H = polar angle (hour angle) E = sun's elevation angle in degrees
I	ξ; δ	ξ = obliquity of the ecliptic δ = sun's declination

APPENDIX F

HP-67 Program for the Correction of the Sun's Elevation Angle Due to Atmospheric Refraction

Program Description

This program calculates the angle through which a ray of sunlight is refracted during its passage through the atmosphere. By adding this correction to the elevation angle, as computed with the ephemeris equations, the elevation angle of the sun as actually observed is obtained. The atmospheric pressure and the ambient temperature at the point of observation are required as inputs to this program (although average values will not cause too large an error).

Equations Used

Symbols:

E = The sun's elevation angle in degrees, as calculated from the ephemeris equations

R = The refraction angle in seconds of arc for a standard atmosphere

RC = The refraction angle in degrees, corrected for variations in atmospheric pressure and ambient temperature

P = Atmospheric pressure in millibars

T_a = Ambient temperature in °F

E_c = The sun's elevation angle in degrees, corrected for refraction

1. For $5° < E \leq 90°$

$$R = \frac{58.1}{\tan E} - \frac{0.07}{\tan^3 E} + \frac{0.000086}{\tan^5 E}$$

2. For $-0.575° < E \geq 5°$

$$R = 1735 + E \quad -518.2 + E[103.4 + E(-12.79 + 0.711E)]$$

3. For $-0.575° \geq E$

$$R = \frac{-20.774}{\tan E}$$

Note: Equation 3 provides a smooth function for elevation angles below the horizon.

4. $$RC = \frac{510 \cdot P \cdot R}{1013 \cdot 3600(460 + T_a)}$$

5. $E_c = E + RC$

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
001	*LBLB	033	6	065	+
002	RCLE	034	EEX	066	RCLE
003	TAN	035	6	067	x
004	STO6	036	CHS	068	5
005	.	037	RCL6	069	1
006	5	038	X^2	070	8
007	7	039	X^2	071	.
008	5	040	RCL6	072	2
009	CHS	041	x	073	-
010	RCLE	042	÷	074	RCLE
011	X≤Y?	043	+	075	x
012	GTO9	044	GTO7	076	1
013	5	045	*LBL8	077	7
014	RCLE	046	RCLE	078	3
015	X≤Y?	047	.	079	5
016	GTO8	048	7	080	+
017	5	049	1	081	GTO7
018	8	050	1	082	*LBL9
019	.	051	x	083	2
020	1	052	1	084	0
021	RCL6	053	2	085	.
022	÷	054	.	086	7
023	.	055	7	087	7
024	0	056	9	088	4
025	7	057	-	089	CHS
026	RCL6	058	RCLE	090	RCL6
027	X^2	059	x	091	÷
028	RCL6	060	1	092	*LBL7
029	x	061	0	093	STO7
030	÷	062	3	094	RCLD
031	-	063	.	095	5
032	8	064	4	096	1

Step	Key Entry
097	0
098	x
099	RCLB
100	4
101	6
102	0
103	+
104	1
105	0
106	1
107	3
108	x
109	÷
110	3
111	6
112	0
113	0
114	÷
115	RCL7
116	x
117	STO6
118	RCLE
119	+
120	STOE
121	~x~
122	RCLA
123	RTN

Operating Instructions

Step	Instruction	Enter	Press
1	Store sun's elevation angle in decimal degrees in Memory E	E	STO E
2	Store atmospheric pressure in millibars in Memory D	P	STO D
3	Store ambient temperature in °F in Memory B	T_a	STO B
4	Initiate program		B

The sun's elevation angle as corrected for refraction will be flashed and stored in Memory E. The angle of refraction will be stored in Memory 06.

Memory Listing

Memory	Item	Remarks
6	tan E, RC	RC remains in store.
7	R	Computed
B	T_a	Input
D	P	Input
E	E, E_c	E is input. E_c is output and remains in store.

APPENDIX G

TI-59 Version of the SUNAEP Program, Including the Correction of the Elevation Angle for Atmospheric Refraction

Program Description

This program is similar to the Robert Walraven program used for SUNAEP but differs in the algorithms used for the mean anomaly of the earth, g, and for the longitude of the sun, L. The program operates in the degree mode rather than in the radian mode, and this forces further changes in some of the equations and values of constants. Accuracy of the program has been checked only by comparing the value of the computed L with that listed in the ephemeris for 1 day of each month in the years 1979 and 1980. The maximum deviation was +0.0014 degree. The program includes a provision for computing the correction for refraction as listed in Appendix D. All computed values of possible interest are stored and can be recalled. A short print routine is included in case a PC-100 printer is available. The print routine is separate under Label C and can easily be changed to suit the specific needs of the user.

Partitioning is set at 479.59.

The Master Library Module must be used.

Equations Used

1. T = HOUR + ZONE, where T is Greenwich mean time, HOUR is local standard time, and both are in decimal hours. ZONE is the value listed in Table G1 for the local International Time Zone.

Table G1

The Value of ZONE for Several International Time Zones

International Time Zone	ZONE (hours)
Atlantic Standard Time	4
Eastern Standard Time	5
Central Standard Time	6
Mountain Standard Time	7
Pacific Standard Time	8
Hawaii Standard Time	10

2. $g = 0.9856(N + T/24) - 3.7628$, where g is the mean anomaly of the earth in decimal degrees. N is the number of days since 31 December 1979 and is automatically calculated and stored (Memory 24) in case the user is curious.

3. $$L = 282.587 + 1.000045972\ g + 1.9156748 \sin g + 0.020015 \sin 2g - 0.003018 \sin g/2 - 0.001110613 \cos\left[(g - 207)\frac{120}{77}\right],$$

   where L is the longitude of the sun in decimal degrees.

4. $$SG = 98.82586667 + 0.04106864(24)(N) + 15.04106864\ T,$$

   where SG is Greenwich sidereal time in decimal degrees.

5. $S = SG + LONG$, where S is local sidereal time in decimal degrees. LONG is local longitude in decimal degrees.

6. $\xi = 23.441884 - 3.5616 \times 10^{-7}$ N, where ξ is the obliquity of the ecliptic in decimal degrees.

7. $\tan \alpha = \cos \xi \cdot \tan L$, where α is the right ascension of the sun.

8. $\sin \delta = \sin \xi \cdot \sin L$, where δ is the declination of the sun.

9. $H = \alpha - S$, where H is the hour angle in decimal degrees.

10. $\cos Z = \sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos H$, where Z is the zenith angle of the sun, ϕ is the local latitude, and both are in decimal degrees.

11. $E = 90 - Z$ where E is the elevation of the sun in decimal degrees.

12. $\sin A = \dfrac{\cos \delta \cdot \sin H}{\sin Z}$, where A is the sun's azimuth measured east from due south in decimal degrees.

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
000	R/S	022	24	044	RCL
001	LBL	023	(	045	33
002	A	024	(	046	)
003	STO	025	RCL	047	STO
004	56	026	55	048	50
005	R/S	027	+	049	(
006	STO	028	RCL	050	RCL
007	55	029	22	051	35
008	RCL	030	)	052	+
009	31	031	STO	053	RCL
010	PGM	032	28	054	34
011	20	033	÷	055	x
012	A	034	2	056	RCL
013	RCL	035	4	057	50
014	56	036	+	058	+
015	PGM	037	RCL	059	RCL
016	20	038	24	060	36
017	B	039	)	061	x
018	PGM	040	x	062	RCL
019	20	041	RCL	063	50
020	C	042	32	064	SIN
021	STO	043	-	065	+

Step	Key Entry	Step	Key Entry	Step	Key Entry
066	RCL	118	INV	170	STO
067	37	119	INT	171	27
068	x	120	x	172	-
069	(	121	RCL	173	RCL
070	RCL	122	24	174	26
071	50	123	x	175	)
072	x	124	2	176	STO
073	2	125	4	177	57
074	)	126	+	178	(
075	SIN	127	RCL	179	RCL
076	-	128	43	180	29
077	RCL	129	x	181	SIN
078	38	130	RCL	182	x
079	x	131	28	183	RCL
080	(	132	-	184	51
081	RCL	133	RCL	185	SIN
082	50	134	54	186	)
083	÷	135	)	187	INV
084	2	136	SBR	188	SIN
085	)	137	LOG	189	STO
086	SIN	138	STO	190	58
087	-	139	26	191	(
088	RCL	140	(	192	RCL
089	39	141	RCL	193	53
090	x	142	44	194	SIN
091	(	143	-	195	x
092	(	144	RCL	196	RCL
093	RCL	145	45	197	58
094	50	146	x	198	SIN
095	-	147	RCL	199	+
096	2	148	24	200	RCL
097	0	149	)	201	53
098	7	150	STO	202	COS
099	)	151	29	203	x
100	x	152	(	204	RCL
101	1	153	(	205	58
102	2	154	CE	206	COS
103	0	155	COS	207	x
104	÷	156	x	208	RCL
105	7	157	RCL	209	57
106	7	158	51	210	COS
107	)	159	SIN	211	)
108	COS	160	)	212	INV
109	)	161	X≷T	213	COS
110	STO	162	RCL	214	STO
111	51	163	51	215	59
112	(	164	COS	216	(
113	RCL	165	X≷T	217	RCL
114	42	166	INV	218	58
115	+	167	P/R	219	COS
116	RCL	168	SBR	220	x
117	43	169	LOG	221	RCL

Step	Key Entry	Step	Key Entry	Step	Key Entry
222	57	274	52	326	(
223	SIN	275	RCL	327	RCL
224	÷	276	52	328	59
225	RCL	277	RST	329	TAN
226	59	278	LBL	330	x
227	SIN	279	LOG	331	5
228	)	280	÷	332	8
229	INV	281	3	333	.
230	SIN	282	6	334	1
231	STO	283	0	335	-
232	52	284	)	336	RCL
233	CP	285	INV	337	59
234	(	286	INT	338	TAN
235	RCL	287	x	339	Y^X
236	59	288	3	340	3
237	COS	289	6	341	x
238	—	290	0	342	.
239	RCL	291	)	343	0
240	58	292	INV	344	7
241	SIN	293	GE	345	+
242	÷	294	B'	346	RCL
243	RCL	295	RTN	347	59
244	53	296	LBL	348	TAN
245	)	297	B'	349	Y^X
246	INV	298	+	350	5
247	GE	299	3	351	x
248	EE	300	6	352	RCL
249	RST	301	0	353	46
250	LBL	302	)	354	)
251	EE	303	RTN	355	LBL
252	RCL	304	LBL	356	ENG
253	52	305	C	357	(
254	INV	306	(	358	CE
255	GE	307	9	359	x
256	A'	308	0	360	RCL
257	+/-	309	-	361	47
258	+	310	RCL	362	x
259	1	311	59	363	RCL
260	8	312	)	364	48
261	0	313	STO	365	÷
262	)	314	23	366	RCL
263	STO	315	X⇄T	367	49
264	52	316	.	368	)
265	RCL	317	5	369	STO
266	52	318	7	370	30
267	RST	319	5	371	RST
268	LBL	320	+/-	372	LBL
269	A'	321	GE	373	$\bar{x}$
270	3	322	Σ+	374	(
271	6	323	5	375	1
272	0	324	GE	376	7
273	SUM	325	$\bar{x}$	377	3

Step	Key Entry	Step	Key Entry
378	5	430	TAN
379	+	431	x
380	RCL	432	2
381	23	433	0
382	x	434	.
383	(	435	7
384	5	436	7
385	1	437	4
386	8	438	)
387	.	439	+/-
388	2	440	GTO
389	+/-	441	ENG
390	+	442	LBL
391	RCL	443	D
392	23	444	RCL
393	x	445	52
394	(	446	PRT
395	1	447	(
396	0	448	RCL
397	3	449	59
398	.	450	-
399	4	451	RCL
400	+	452	30
401	RCL	453	PRT
402	23	454	)
403	x	455	PRT
404	(	456	RST
405	1	457	0
406	2	458	0
407	.	459	0
408	7	460	0
409	9	461	0
410	+/-	462	0
411	+	463	0
412	.		
413	7		
414	1		
415	1		
416	x		
417	RCL		
418	23		
419	)		
420	)		
421	)		
422	)		
423	GTO		
424	ENG		
425	LBL		
426	Σ+		
427	(		
428	RCL		
429	59		

Operating Instructions

Step	Instruction	Enter	Press
1	Enter month, day, year in the form MMDD.YYYY, e.g., 31 December 1979 = 1231.1979 1 January 1980 = 101.1980	MMDD.YYYY	A
2	Enter standard time in decimal hours, e.g., 8:15 a.m. = 8.25 2:45 p.m. = 14.75	HOUR	R/S

NOTE: It is assumed that all data, fixed and variable, has been entered into memory; see Memory Listing.

Memory Listing

Memory	Item	Units	Remarks
22	Time zone	Integer	Variable data
23	Sun's elevation	Degrees	Computed
24	Days since 31 Dec. 1979	Days	Computed
25	Not used	--	--
26	Local sidereal time	Decimal degrees	Computed
27	Sun's right ascension	Decimal degrees	Computed
28	Greenwich Standard Time	Decimal Hours	Computed
29	Obliquity of the ecliptic	Decimal degrees	Computed
30	Refraction correction	Decimal degrees	Computed
31	1231.1979	--	Fixed data
32	0.9856	--	Fixed data
33	3.7628	--	Fixed data
34	1.000045972	--	Fixed data
35	282.587	--	Fixed data
36	1.9156748	--	Fixed data
37	0.020015	--	Fixed data
38	0.003018	--	Fixed data
39	0.0011106127	--	Fixed data
40	Not used	--	--

Memory	Item	Units	Remarks
41	Not used	--	--
42	98.82586667	--	Fixed data
43	15.04106864	--	Fixed data
44	23.4411884	--	Fixed data
45	0.0000003562	--	Fixed data
46	0.000086	--	Fixed data
47	0.0001398486	--	Fixed data
48	Atmospheric pressure	Millibars	Variable data
49	Air temperature	Kelvin	Variable data
50	Mean anomaly of earth	Decimal degrees	Computed
51	Sun's longitude	Decimal degrees	Computed
52	Sun's azimuth	Decimal degrees measured eastward from south	Computed
53	Local latitude	Decimal degrees	Variable data
54	Local longitude	Decimal degrees	Variable data
55	Local standard time	Decimal hours	Step 2 entry
56	Date	--	Step 1 entry
57	Hour (or polar) angle	Decimal degrees	Computed
58	Sun's declination	Decimal degrees	Computed
59	Sun's zenith angle	Decimal degrees	Computed

NOTE: The most commonly used output data are stored in Memories 52 through 59 and can be printed by pressing 52 INV 2D List. If this suffices, no other print routine is required.

APPENDIX H

FORTRAN Listing for the SUNPOS Program

```
C********************************************************************
      SUBROUTINE SUNPOS(NDATE,FMO,IYR,XNHR,MIN,XSEC,TFLAG,AZANGR,
     $ELANGR,FLONO,FLATO,FJDI,ZONE,DELPSI,DELOBL,NDAY,NOUTANS,PRESSA,
     $TA)
C
C         THIS SUBROUTINE IS ADAPTED FROM A SUN AZIMUTH AND ELEVATION
C         PROGRAM(/SUNPOS≠) WRITTEN BY D. R. TURNER AND D. R. HINDS,
C         DIV. 9344,SANDIA LABS. REVISION B ---2/23/77 DRH
C
      DPR=180./3.141592653589793
      HYR=IYR-1900
      YRI=HYR
      IF(NOUTANS.NE.3HYES)GO TO 12
      PRINT *,≠     ***** INSIDE SUNPOS *****≠
      PRINT *,≠NDATE= ≠,NDATE,≠ FMO= ≠,FMO,≠ IYR= ≠,IYR,≠ YRI= ≠,YRI,≠
     $XNHR= ≠,XNHR,≠ MIN= ≠,MIN,≠ XSEC ≠,XSEC,≠ TFLAG= ≠,TFLAG
      PRINT *,≠FLONO= ≠,FLONO,≠ FLATO= ≠,FLATO,≠ FJDI= ≠,FJDI,≠ ZONE=
     $≠,ZONE,≠ DELPSI= ≠,DELPSI,≠ DELOBL= ≠,DELOBL,≠ NDAY= ≠,NDAY
   12 CONTINUE
      FMIN=FLOAT(MIN)+XSEC/60.
      T=(365.*YRI+INT((YRI-1.)/4.)+NDAY-0.5)/36525.
      SEC=23925.836+8640184.5*T+.0929*T*T
      GMSTOD=360.*((AMOD(SEC,86400.))/86400.)
C
C         SOME DEFINITIONS
C         T---THE NUMBER OF JULIAN CENTURIES OF 36525 DAYS WHICH,AT
C         MIDNIGHT BEGINNING THE DAY,HAVE ELAPSED SINCE MEAN NOON ON
C         1900 JANUARY 0 AT THE GREENWICH MERIDIAN.
C
C         SEC---THE MEAN SIDEREAL TIME,SECONDS ELAPSED SINCE 1900, AT
C         0 HOUR ON THE DATE SPECIFIED.
C
C         GMSTOD---THE GREENWICH MEAN SIDEREAL TIME FOR 0 HOUR ON THE
C         SPECIFIED DAY.
C
C         SUNM---MEAN ANOMALY OF THE SUN
C         SUNECC---ECCENTRICITY
C         OOBLIQ--MEAN OBLIQUITY OF THE ECLIPTIC
C         SUNOMG---MEAN LONGITUDE OF PERIGEE
C         ESUN---ECCENTRIC ANOMALY
C         TRUANS---TRUE ANOMALY OF THE SUN
C         SOPNU---ANGULAR DISTANCE FROM ASCENDING NODE TO SUN
```

```
C         GMLON---GREENWICH MEAN LONGITUDE(ECLIPTIC LONGITUDE)
C         GTLON---GREENWICH MEAN LONGITUDE CORRECTED FOR NUTATION
C         RSUN---MEAN DISTANCE EARTH TO SUN IN ASTRONOMICAL UNITS
C         GALON--GREENWICH MEAN LONGITUDE CORRECTED FOR ABERRATION
C         GARA---GREENWICH APPARENT RIGHT ASCENSION
C         DEC-DECLINATION
C
      TI=T+((XNHR+ZONE-TFLAG)/24.+FMIN/1440.)/36525.
      Q15=TI*TI
      Q16=TI*Q15
      SUNM=358.47583+35999.04975*TI-.00015*Q15-.000003*Q16
      SUNM=AMOD(SUNM,360.0)
      SUNECC=.01675104-.0000418*TI-.000000126*Q15
      OOBLIQ=23.452294-.0130125*TI-.00000164*Q15+.000000503*Q16
      SUNOMG=281.22083+1.71917331*TI+.000453*Q15+.000003*Q15
      ESUN=SUNM
      N=0
  320 ETEMPS=ESUN
      N=N+1
      IF(N.GT.10)GO TO 330
      ESUN=SUNM+DPR*SUNECC*SIN(ETEMPS/DPR)
      IF(ABS(ESUN-ETEMPS).GT.0.00000001)GO TO 320
  330 TRUANS=DPR*ATAN2(SIN(ESUN/DPR)*SQRT(1.-SUNECC*SUNECC)
     $,COS(ESUN/DPR)-SUNECC)
      CALL FCV(TRUANS)
      SOPNU=SUNOMG+TRUANS
      CALL FCV(SOPNU)
      GMLON=SOPNU
C
C         FIND THE NUTATION
C
  360 GTLON=GMLON+DELPSI/3600.
      RSUN=1.00000023*(1.-SUNECC*COS(ESUN/DPR))
      GALON=GTLON-20.47/(3600.*RSUN)
      OOBLIQ=OOBLIQ+DELOBL/3600.
      Q32=COS(OOBLIQ/DPR)*SIN(GALON/DPR)
      Q33=COS(GALON/DPR)
      GARA=QADAT(Q32,Q33)
      Q17=SIN(OOBLIQ/DPR)*SIN(GALON/DPR)
      Q34=SQRT(1.-Q17*Q17)
      DEC=DPR*ATAN2(Q17,Q34)
C
C         FIND THE GMST AND THE LAST PREDICTION EPOCH
C
C         DEFINITIONS
C         UT---UNIVERSAL TIME
C         GMSTI---GREENWICH MEAN SIDERIAL TIME AT THIS INSTANT
C         EOE---EQUATION OF THE EQUINOXES
C         GASTI---GREENWICH APPARENT SIDEREAL TIME AT THIS INSTANT
C         FLAST---LOCAL APPARENT SIDEREAL TIME
C
      UT=XNHR+FMIN/60.+ZONE-TFLAG
      GMSTI=GMSTOD+15.04106864*UT
      EOE=DELPSI*COS(OOBLIQ/DPR)/3600.
```

```
      GASTI=GMSTI+EOE
      FLAST=GASTI-FLONO
      CALL FCV(FLAST)
C
C         FIND THE AZIMUTH AND ELEVATION OF THE SUN
C
C         DEFINITIONS
C         FLHA---LOCAL HOUR ANGLE
C         AZ---AZIMUTH
C         EL---ELEVATION
C
      FLHA=FLAST-GARA
      FNUM=-SIN(FLHA/DPR)
      DENOM=COS(FLATO/DPR)*TAN(DEC/DPR)-
     $SIN(FLATO/DPR)*COS(FLHA/DPR)
      AZ=QADAT(FNUM,DENOM)
      SINEL=SIN(FLATO/DPR)*SIN(DEC/DPR)+COS(FLATO/DPR)*
     $COS(DEC/DPR)*COS(FLHA/DPR)
      EL=DPR*ATAN(SINEL/(SQRT(1.-(SINEL*SINEL))))
      ELP=EL
      CALL REFRA(EL,REFC)
      PRLX=(8.794/RSUN)*COSD(EL)
      ELV=EL-PRLX/3600.
      RFAC=(PRESSA*510.)/(1013.*(460.+TA))
      REFC=REFM*RFAC/3600.
      EL=ELV+REFC
      AZANGR=AZ/DPR
      ELANGR=EL/DPR
      IF(NOUTANS NE.3HYES)GO TO 11
      PRINT *,≠ T= ≠,T,≠ SEC= ≠,SEC,≠ GMSTOD= ≠,GMSTOD,≠ TI= ≠,TI≠
     $SUNM= ≠,SUNM,≠ SUNECC= ≠,SUNECC,≠ OOBLIQ= ≠,OOBLIQ,≠ SUNOMG= ≠,
     $SUNOMG
      PRINT *,≠ TRUANS= ≠,TRUANS,≠ GMLON= ≠,GMLON,≠ GTLON= ≠,GTLON,≠
     $RSUN= ≠,RSUN,≠ GALON= ≠,GALON,≠ OOBLIQ= ≠,OOBLIQ,≠ GARA= ≠,GARA,≠
     $DEC= ≠,DEC
      PRINT *,≠ UT= ≠,UT,≠ GMSTI= ≠,GMSTI,≠ EOE= ≠,EOE, ≠ GASTI= ≠,
     $GASTI,≠ FLAST= ≠,FLAST,≠ FLHA= ≠,FLHA,≠ AZ= ≠,AZ,≠ EL= ≠,EL,≠
     $REFC= ≠,REFC,≠ ELP= ≠,ELP
   11 CONTINUE
      RETURN
      END
```

Input:

IYR	The year, e.g., 1981
NDAY	Day of the year, e.g., for 21 June 1981, NDAY = 172
XNHR, MIN, XSEC,	Local time in hours, minutes, and decimal seconds
FLONO	Observer's longitude in degrees
FLATO	Observer's latitude in degrees
TFLAG	0 if Standard Time, 1 if Daylight Saving Time
ZONE	Hours from Greenwich Time, see Table E1
PRESSA	Ambient pressure in millibars
TA	Ambient temperature in °F
NOUTANS	If YES, long output is printed
DELPSI	Calculated once using subroutine NUTATE (see Appendix M) for noon of the day of interest
DELDBL	Calculated once using subroutine NUTATE (see Appendix M) for noon of the day of interest

Output:

AZANGR	Sun's azimuth angle in radians
ELANGR	Sun's elevation angle in radians

Notes:

1. ATAN2 is an arc-tangent function that selects the correct quadrant and returns an angle in the range of $\pm 180°$. Equivalent to Function QADATN*.
2. FCV* is a full-circle value function that returns an angle value between 0° and 360° for any angle.
3. QADATN* determines the correct quadrant for an angle found through the arc-tangent.
4. For subroutine REFRA, see Appendix M.

APPENDIX I

HP-67 Program for the Conversion of the Sun's Azimuth-Elevation Coordinates to Its Polar-Declination Coordinates and the Inverse

Program Description

Figure I-1 illustrates the geometry. The North Pole, the zenith point, and the sun are the vertices of a spherical triangle on the celestial sphere. If any three parts of a spherical triangle are known, the magnitudes of the unknown parts can be calculated. If the latitude of the zenith point (local latitude) and the sun's elevation and azimuth are known, then the sun's polar angle and declination can be calculated. Conversely, with the latitude and the sun's polar angle and declination known, the sun's elevation and azimuth can be calculated.

Equations Used

Symbols:

ϕ = the latitude

E = the sun's elevation

A = the sun's azimuth (measured from south, positive to the west)

P = the sun's polar angle (measured from south, positive to the west)

δ = the sun's declination

For conversion from azimuth-elevation to polar-declination, using the Law of Cosines spherical trigonometry:

1. $\cos(90° - \delta) = \cos(90° - E)\cdot\cos(90° - \phi) +$
   $\sin(90° - E)\cdot\sin(90° - \phi)\cdot\cos(180° - A)$ which reduces to:

2. $\sin\delta = \sin E\cdot\sin\phi - \cos E\cdot\cos\phi\cdot\cos A$

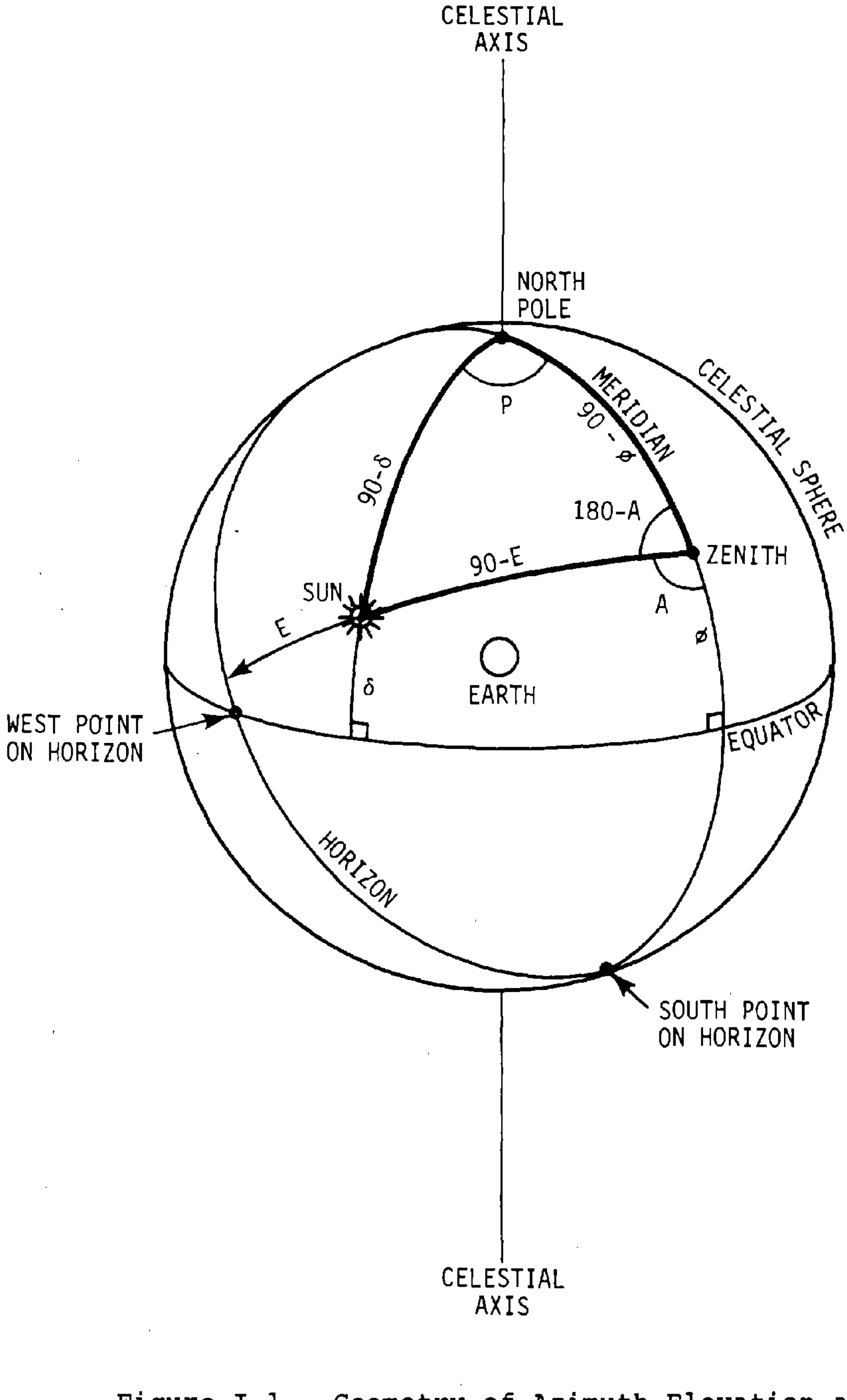


Figure I-1. Geometry of Azimuth-Elevation and Polar-Declination Coordinates

Using the four consecutive parts formula for spherical trigonometry:

3. $$\tan P = \frac{\sin(180° - A)}{\dfrac{\sin(90° - \phi)}{\tan(90° - E)} - \cos(90° - \phi)\cdot\cos(180° - A)}$$

which reduces to:

4. $\tan P = \sin A/(\cos\phi \cdot \tan E + \sin\phi \cdot \cos A)$

For conversion from polar-declination to azimuth-elevation, using the Law of Cosines from spherical trigonometry:

5. $\cos(90° - E) = \cos(90° - \delta)\cdot\cos(90° - \phi) +$
$\sin(90° - \delta)\cdot\sin(90° - \phi)\cdot\cos P$

6. $\sin E = \sin\delta \cdot \sin\phi + \cos\delta\cdot\cos\phi\cdot\cos P$

Using the four consecutive parts formula from spherical trigonometry:

7. $$\tan(180° - A) = \frac{\sin P}{\dfrac{\sin(90° - \phi)}{\tan(90° - \delta)} - \cos(90° - \phi)\cos P}$$

which reduces to:

8. $\tan A = \sin P/(\cos\phi\cdot\tan\delta - \sin\phi\cdot\cos P)$

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
001	*LBLA	016	x	031	x
002	ST01	017	-	032	+
003	R▼	018	SIN^{-1}	033	R►P
004	ST00	019	STOD	034	R▼
005	SIN	020	RCL1	035	STOC
006	RCL2	021	SIN	036	~x~
007	SIN	022	RCL2	037	RCLD
008	x	023	COS	038	RTN
009	RCL0	024	RCL0	039	*LBLD
010	COS	025	TAN	040	ST06
011	RCL1	026	x	041	R▼
012	COS	027	RCL2	042	ST07
013	x	028	SIN	043	SIN
014	RCL2	029	RCL1	044	RCL2
015	COS	030	COS	045	SIN

Step	Key Entry
046	x
047	RCL2
048	COS
049	RCL7
050	COS
051	x
052	RCL6
053	COS
054	x
055	+
056	SIN^{-1}
057	STOE
058	RCL6
059	SIN
060	RCL2
061	COS
062	RCL7
063	TAN
064	x
065	RCL2
066	SIN
067	RCL6
068	COS
069	x
070	-
071	R►P
072	R▼
073	1
074	8
075	0
076	STO9
077	+
078	CHS
079	STOA
080	RCL9
081	CHS
082	X≤Y?
083	GTO0
084	3
085	6
086	0
087	RCLA
088	+
089	STOA
090	*LBL0
091	RCLA
092	~x~
093	RCLE
094	RTN
095	R/S

Operating Instructions

For azimuth-elevation to polar-declination:

Step	Instruction	Enter	Press
1	Store latitude in Memory 2	ϕ	STO 02
2	Enter elevation	E	ENTER
3	Place azimuth on display and start program	A	A

P is flashed and stored in Memory C.

δ is left on display and stored in Memory D.

For polar-declination to azimuth-elevation:

Step	Instruction	Enter	Press
1	Store latitude in Memory 2	ϕ	STO 02
2	Enter declination	δ	ENTER
3	Place polar angle on display and start program	P	D

A is flashed and stored in Memory A.

E is left on display and stored in Memory E.

Limits

The angles, A and P, are measured from south (the solar noon position), negative to the east (before noon) and positive to the west (after noon). The angle E is measured from the horizontal plane. The declination, δ , is measured negative below the equator and positive above the equator. The angles, A, P, E, and δ have the following limits:

$$0 \le A \le 360$$
$$-180 \le P \le 180$$
$$-90 \le E \le 90$$
$$-23.5 \le \delta \le 23.5 \text{ (approx.)}$$

Memory Listing

Memory Register	Use
0	Elevation (input)
1	Azimuth (input)
2	Latitude (input)
6	Polar angle (input)
7	Declination (input)
9	180
A	Azimuth (output)
C	Polar angle (output)
D	Declination (output)
E	Elevation (output)

APPENDIX J

TI-59 Program for the Conversion of the Sun's Azimuth-Elevation Coordinates to Its Polar-Declination Coordinates and the Inverse

Program Description

Figure J-1 illustrates the geometry. The North Pole, the zenith point, and the sun are the vertices of a spherical triangle on the celestial sphere. If any three parts of a spherical triangle are known, the magnitudes of the unknown parts can be calculated. If the latitude of the zenith point (local latitude) and the sun's elevation and azimuth are known, then the sun's polar angle and declination can be calculated. Conversely, with the latitude and the sun's polar angle and declination known, the sun's elevation and azimuth can be calculated.

Equations Used

Symbols:

ϕ = the latitude

E = the sun's elevation

A = the sun's azimuth (measured from south, positive to the west)

P = the sun's polar angle (measured from south, positive to the west)

δ = the sun's declination

For conversion from azimuth-elevation to polar-declination, using the Law of Cosines spherical trigonometry:

1. $\cos(90° - \delta) = \cos(90° - E) \cdot \cos(90° - \phi) + \sin(90° - E) \cdot \sin(90° - \phi) \cdot \cos(180° - A)$ which reduces to:

2. $\sin \delta = \sin E \cdot \sin \phi - \cos E \cdot \cos \phi \cdot \cos A$

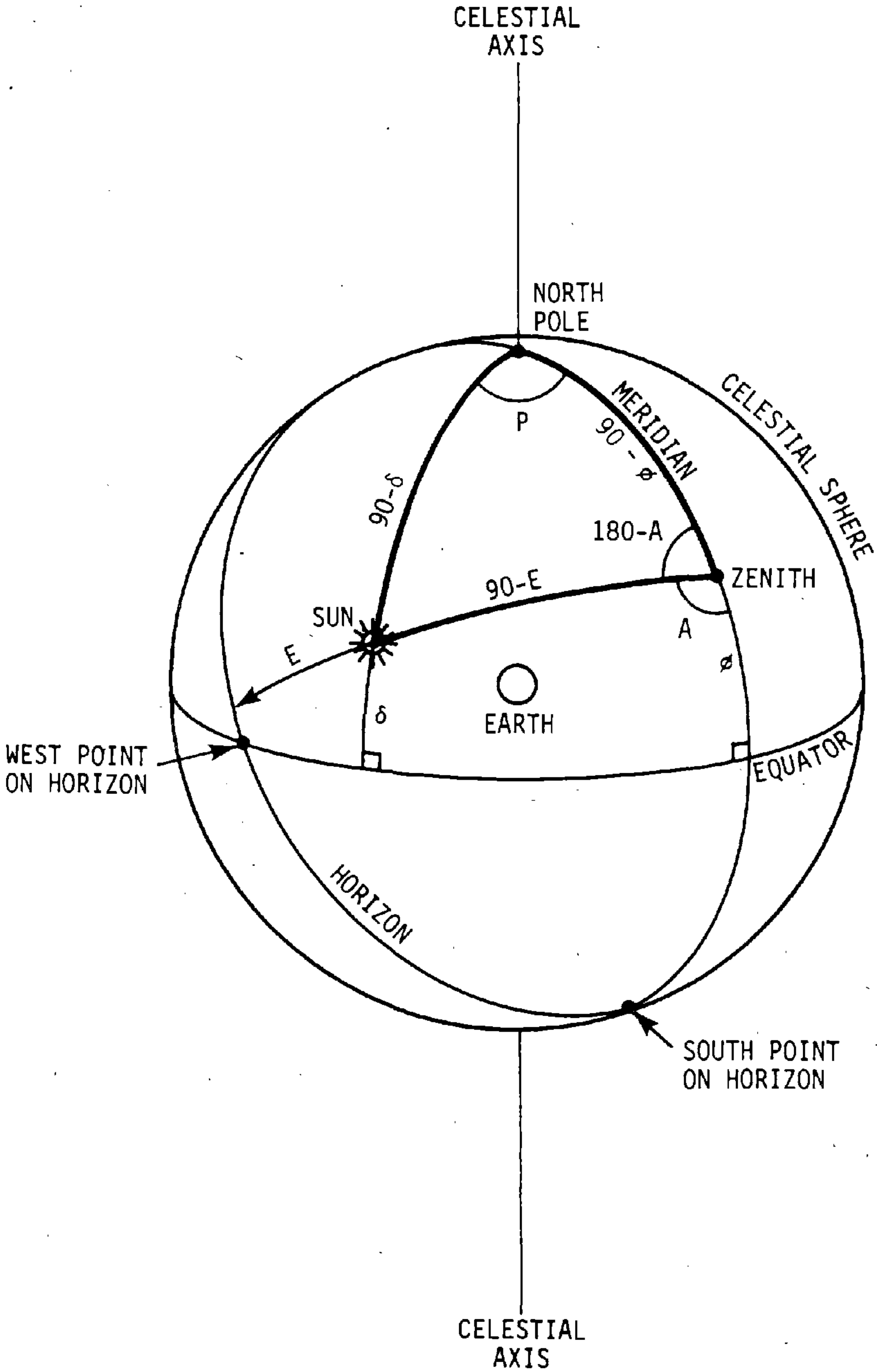


Figure J-1. Geometry of Azimuth-Elevation and Polar-Declination Coordinates

Using the four consecutive parts formula for spherical trigonometry:

3. $$\tan P = \frac{\sin(180° - A)}{\dfrac{\sin(90° - \phi)}{\tan(90° - E)} - \cos(90° - \phi)\cdot\cos(180° - A)}$$

which reduces to:

4. $\tan P = \sin A/(\cos\phi\cdot\tan E + \sin\phi\cdot\cos A)$

For conversion from polar-declination to azimuth-elevation, using the Law of Cosines from spherical trigonometry:

5. $\cos(90° - E) = \cos(90° - \delta)\cdot\cos(90° - \phi) +$
$\sin(90° - \delta)\cdot\sin(90° - \phi)\cdot\cos P$

6. $\sin E = \sin\delta\cdot\sin\phi + \cos\delta\cdot\cos\phi\cdot\cos P$

Using the four consecutive parts formula from spherical trigonometry:

7. $$\tan(180° - A) = \frac{\sin P}{\dfrac{\sin(90° - \phi)}{\tan(90° - \delta)} - \cos(90° - \phi)\cdot\cos P}$$

which reduces to:

8. $\tan A = \sin P/(\cos\phi\cdot\tan\delta - \sin\phi\cdot\cos P)$

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
000	LBL	015	-	030	)
001	A	016	RCL	031	INV
002	1	017	01	032	SIN
003	STO	018	COS	033	PRT
004	04	019	x	034	STO
005	LBL	020	RCL	035	05
006	EE	021	02	036	RCL
007	(	022	COS	037	02
008	RCL	023	x	038	SIN
009	01	024	RCL	039	X⇄T
010	SIN	025	03	040	(
011	x	026	COS	041	RCL
012	RCL	027	x	042	01
013	03	028	RCL	043	TAN
014	SIN	029	04	044	x

Step	Key Entry
045	RCL
046	03
047	COS
048	+
049	RCL
050	02
051	COS
052	x
053	RCL
054	03
055	SIN
056	x
057	RCL
058	04
059	)
060	X≷T
061	INV
062	P/R
063	STO
064	06
065	IFF
066	01
067	Y^X
068	LBL
069	PAU
070	RCL
071	06
072	PRT
073	CP
074	INV
075	STF
076	01
077	R/S
078	LBL
079	A'
080	1
081	+/-
082	STO
083	04
084	STF
085	01
086	GTO
087	EE
088	LBL
089	Y^X
090	(
091	(
092	(
093	CE
094	+
095	1
096	8
097	0
098	)
099	+/-
100	÷
101	3
102	6
103	0
104	)
105	INV
106	INT
107	x
108	3
109	6
110	0
111	)
112	STO
113	06
114	RCL
115	02
116	GE
117	WRT
118	GTO
119	PAU
120	LBL
121	WRT
122	3
123	6
124	0
125	SUM
126	06
127	GTO
128	PAU
129	0
130	0
131	0
132	0
133	0

Operating Instructions

For azimuth-elevation to polar-declination:

Step	Instruction	Enter	Press
1	Store elevation in Memory 1	E	STO 01
2	Store azimuth in Memory 2	A	STO 02
3	Store latitude in Memory 3	ϕ	STO 03
4	Start program		A

With printer, the declination and the polar angle will be printed out in that order. Without printer, the polar angle will be left on display and stored in Memory 6. The declination will be stored in Memory 5.

For polar-declination to azimuth-elevation:

Step	Instruction	Enter	Press
1	Store declination in Memory 1	δ	STO 01
2	Store polar angle in Memory 2	P	STO 02
3	Store latitude in Memory 3	ϕ	STO 03
4	Start program		2nd A'

With printer, the elevation and the azimuth will be printed out in that order. Without printer, the azimuth will remain on display and stored in Memory 6. The elevation will be stored in Memory 5.

Limits

The angles, A and P, are measured from south (the solar noon position), negative to the east (before noon) and positive to the west (after noon). The angle E is measured from the horizontal plane. The declination, δ , is measured negative below the equator and positive above the equator. The angles, A, P, E, and δ have the following limits:

$$-180 \le A \le 180$$
$$-180 \le P \le 180$$
$$-90 \le E \le 90$$
$$-23.5 \le \delta \le 23.5 \text{ (approx.)}$$

Memory Listing

For azimuth-elevation to polar-declination:

Memory Register	Use
1	Elevation (input)
2	Azimuth (input)
3	Latitude (input)
4	+1
5	Declination (output)
6	Polar angle (output)

For polar-declination to azimuth-elevation:

Memory Register	Use
1	Declination (input)
2	Polar angle (input)
3	Latitude (input)
4	-1
5	Elevation (output)
6	Azimuth (output)

APPENDIX K

HP-67 Program for the Computation of
Collector Trough Tracking and Incidence Angles

Program Description

The geometry and nomenclature are shown in Figure K-1. Note that, for this program, the azimuth angle, A, is measured from due north toward the east. Given the sun's azimuth and elevation angles, this program computes the angle of incidence of the sun's rays on the collector aperture plane and the collector tracking angle for both E-W- and N-S-oriented collectors. The collector is a line-focusing, trough type with the focal line parallel to the horizontal plane. It is assumed that the collector is symmetric about a central plane, as is true for parabolic troughs in which the central plane is defined by the focal line and the apex line of the reflector surface (these two lines are parallel and hence define a plane). When the collector is "in focus," the extended central plane passes through the sun. In Figure K-1, the intersection of the central plane and the celestial sphere is shown.

Equations Used

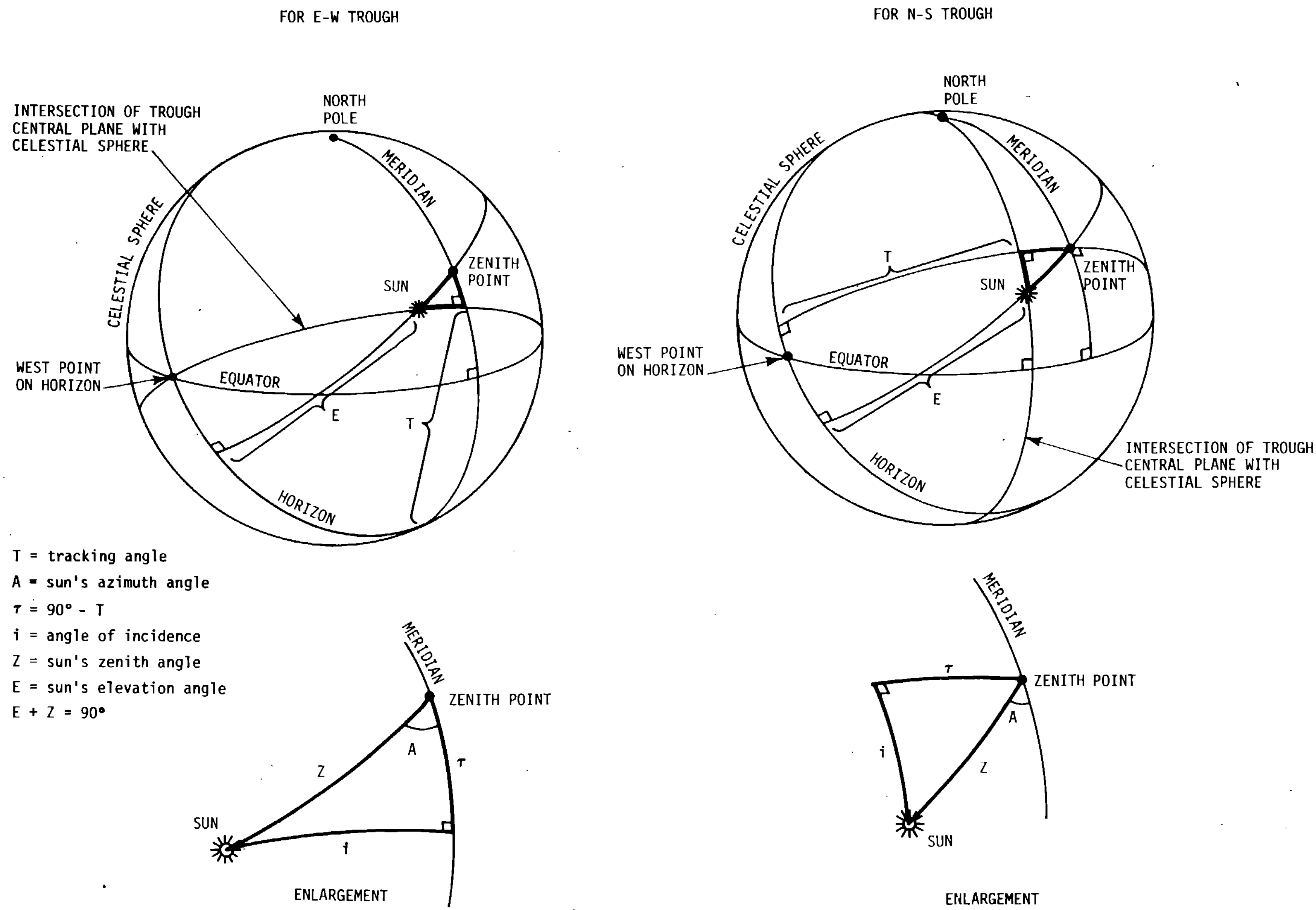
For E-W troughs:

1. $\sin i = \cos[90 - (90 - E)] \times \cos[90 - (A - 180)]$, which reduces to

$$\sin i = -\cos E \sin A$$

2. $\tan \tau = \dfrac{\sin[90 - (A - 180)]}{\tan[90 - (90 - E)]}$, which reduces to

$$\tan \tau = \frac{\cos A}{\tan E}$$



T = tracking angle
A = sun's azimuth angle
$\tau = 90° - T$
i = angle of incidence
Z = sun's zenith angle
E = sun's elevation angle
$E + Z = 90°$

Figure K-1. Geometry for Calculation of Tracking and Incidence Angles from the Sun's Azimuth-Elevation Coordinates

For N-S troughs:

3. $\sin i = \cos[90 - (90 - E)] \times \cos[90 - (270 - A)]$,
which reduces to

$$\sin i = -\cos E \sin A$$

4. $\tan \tau = \dfrac{\sin[90 - (A - 180)]}{\tan[90 - (90 - E)]}$, which reduces to

$$\tan \tau = -\frac{\sin A}{\tan E}$$

For both cases:

5. $T = 90 - \tau$

Program Listing

Step	Key Entry	Step	Key Entry
001	*LBLD	030	COS
002	RCLA	031	x
003	SIN	032	SIN
004	CHS	033	STO 06
005	RCLE	034	RCLA
006	COS	035	SIN
007	x	036	CHS
008	SIN^{-1}	037	RCLE
009	STO 06	038	TAN
010	RCLA	039	R►P
011	COS	040	R
012	CHS	041	9
013	RCLE	042	0
014	TAN	043	X≷Y
015	R►P	044	-
016	R▼	045	ST007
017	9	046	~x~
018	0	047	RCL06
019	X≷Y	048	RTN
020	-		
021	STO 07		
022	~x~		
023	RCL06		
024	RTN		
025	LBLE		
026	RCLA		
027	COS		
028	CHS		
029	RCLE		

Operating Instructions

Step	Instruction	Enter	Press
1	Enter azimuth angle, A, in decimal degrees and store in Memory A	A	STO A
2	Enter elevation angle, E, in decimal degrees and store in Memory E	E	STO E
3	Initiate program		D

Tracking angle is flashed then stored in 7. Incidence angle is left on display and is stored in 6.

Limits

$0 \le A \le 360$	A measured from north toward the east.
$-90 \le E \le 90$	E measured from the horizontal plane toward the zenith. A negative value of E is below the horizontal.
$0 \le T \le 180$	For E-W, T is measured from the south toward the zenith point, straight up is 90°, due north is 180°. For N-S, T is measured from the west toward the zenith point, straight up is 90°, due east is 180°.
$-90 \le i \le 90$	For E-W, a negative sign indicates that the sun is in the east quadrant, a positive sign indicates that the sun is in the west quadrant. For N-S, a negative sign indicates that the sun is in the north quadrant, a positive sign indicates that the sun is in the south quadrant.

Memory Listing

Memory Register	Use
A	Azimuth (input)
E	Elevation (input)
6	Incident angle (output)
7	Tracking angle (output)

APPENDIX L

TI-59 Program for the Computation of Collector Trough Tracking and Incidence Angles

Program Description

The geometry and nomenclature are shown in Figure L-1. Note that, for this program, the azimuth angle, A, is measured from due south toward the east. Given the sun's azimuth and elevation angles, this program computes the angle of incidence of the sun's rays on the collector aperture plane and the collector tracking angle for both E-W- and N-S-oriented collectors. The collector is a line-focusing, trough type with the focal line parallel to the horizontal plane. It is assumed that the collector is symmetric about a central plane, as is true for parabolic troughs in which the central plane is defined by the focal line and the apex line of the reflector surface (these two lines are parallel and hence define a plane). When the collector is "in focus," the extended central plane passes through the sun. In Figure L-1, the intersection of the central plane and the celestial sphere is shown.

Equations Used

For E-W troughs:

1. $\tan \tau = \cos A \cdot \tan(90 - E)$

2. $\tan i = \sin \tau \cdot \tan A$

For N-S troughs:

3. $\tan \tau = \cos(90 - A) \cdot \tan(90 - E)$

4. $\tan i = \sin \tau \cdot \tan(90 - A)$

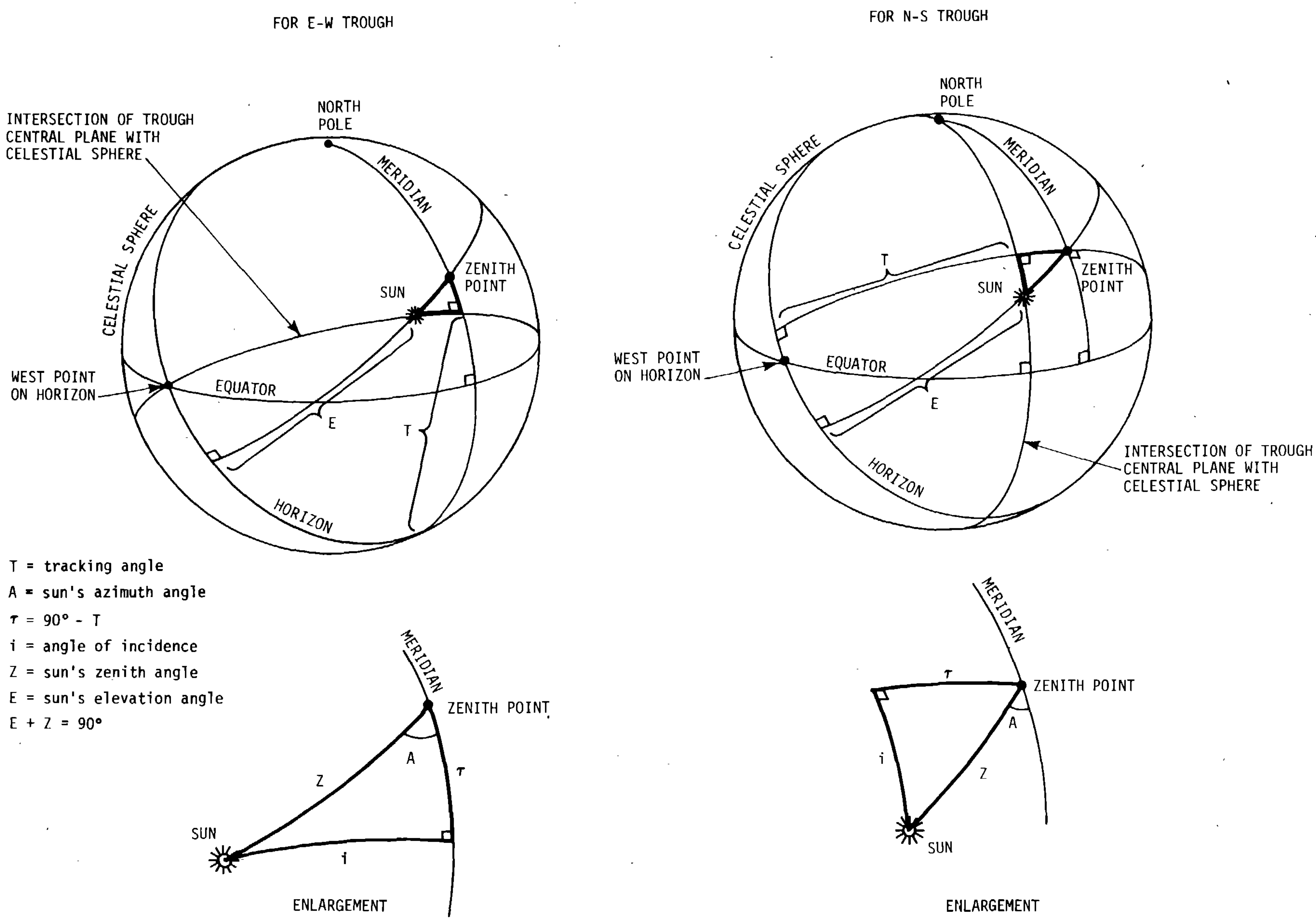


Figure L-1. Geometry for Calculation of Tracking and Incidence Angles from the Sun's Azimuth-Elevation Coordinates

For both cases:

5. $T = 90 - \tau$

Program Listing

Step	Key Entry	Step	Key Entry	Step	Key Entry
000	LBL	045	05	090	1
001	A	046	SIN	091	8
002	0	047	INV	092	0
003	X≷T	048	P/R	093	)
004	(	049	X≷T	094	GTO
005	RCL	050	1	095	RAD
006	01	051	8	096	LBL
007	+/-	052	0	097	SUM
008	+	053	X≷T	098	(
009	9	054	GE	099	CE
010	0	055	DEG	100	+/-
011	)	056	LBL	101	+
012	TAN	057	RAD	102	1
013	1/X	058	STO	103	8
014	X≷T	059	03	104	0
015	RCL	060	PRT	105	)
016	02	061	INV	106	GTO
017	IxI	062	STF	107	PRD
018	COS	063	01	108	0
019	INV	064	R/S	109	0
020	P/R	065	LBL	110	0
021	STO	066	B	111	0
022	05	067	0		
023	(	068	X≷T		
024	CE	069	(		
025	+/-	070	RCL		
026	+	071	02		
027	9	072	INV		
028	0	073	GE		
029	)	074	STF		
030	IFF	075	1		
031	01	076	IxI		
032	SUM	077	+/-		
033	LBL	078	+		
034	PRD	079	9		
035	PRT	080	0		
036	STO	081	)		
037	04	082	STO		
038	RCL	083	02		
039	02	084	A		
040	IxI	085	LBL		
041	TAN	086	DEG		
042	1/X	087	(		
043	X≷T	088	CE		
044	RCL	089	-		

Operating Instructions

Step	Instruction	Enter	Press
1	Enter elevation in decimal degrees	E	STO 01
2	Enter azimuth in decimal degrees	A	STO 02
3	Start Program for E-W orientation for N-S orientation		 A B

NOTE: If it is desired to calculate τ and i for both E-W and N-S orientations then E-W calculation must be done first.

Tracking angle is printed first and is stored in Memory 4. Incident angle is printed second and is stored in Memory 3. If printer is not available, omit print commands. Incident angle will be left on display and stored in Memory 3. Tracking angle will be stored in Memory 4.

Limits

$-90 \leq E \leq 90$	Horizontal is 0, vertical is 90.
$-180 \leq A \leq 180$	South is 0, positive toward the east.
$0 \leq i \leq 90$	i is the unsigned angle between the normal to the aperture plane and the incident ray.
$0 \leq T \leq 180$	For E-W troughs, T is measured from the south toward the zenith point, straight up is 90°, due north is 180°. For N-S troughs, T is measured from the east toward the zenith point, straight up is 90°, due west is 180°.

Memory Listing

Memory Register	Use
1	Elevation (input)
2	90-azimuth; for E-W case (input) Azimuth; for N-S case (input)
3	Incident angle (output)
4	Tracking angle (output)

APPENDIX M

Sample Output Data and Useful Additional Subroutines for the Sun-Pointing Programs

Introduction

This appendix provides data to assist programmers in verifying the operation of the sun-pointing programs. The various sun-pointing programs were executed using the following input data, which applies to the MSSTF at Albuquerque, NM:

Date:	21 March 1981
Latitude:	35°.05437
Longitude:	106°.54329
Altitude:	5,422 ft
Standard Atmospheric Pressure:	839.7 millibars
Average Temperature:	50°F

The hourly outputs of the various sun-pointing programs and some of the values of the program variables are listed below.

SUNAE Program Output

The SUNAE Program output, which is accurate to within ± 1 arc-second, is listed here for comparison with the other programs.

HR	MIN	SEC	ELANG	AZANG	Polar Azimuth	Declination
7	0	0.0	9.79619	96.47499	78.281062	.387026
8	0	0.0	21.80565	105.78188	63.312593	.380313
9	0	0.0	33.24655	116.74346	48.320466	.390181
10	0	0.0	43.47577	130.79749	33.323089	.403797
11	0	0.0	51.37777	149.75727	18.323815	.418914
12	0	0.0	55.24188	174.16328	3.323799	.434875
13	0	0.0	53.72326	200.00083	-11.676338	.451493
14	0	0.0	47.40443	221.55162	-26.676042	.468834
15	0	0.0	38.04706	237.59478	-41.674488	.487290
16	0	0.0	27.05666	249.74465	-56.669720	.508107
17	0	0.0	15.24969	259.66383	-71.654115	.536547
18	0	0.0	3.19462	268.53066	-86.541389	.633088

ECBDAT Program Output

NDAY = 80   Julian Day = -.5

HR	MIN	SEC	ELANG	AZANG
7	0	0.0	12.07333	98.97204
8	0	0.0	23.99108	108.57492
9	0	0.0	35.17897	120.10515
10	0	0.0	44.92846	135.07187
11	0	0.0	51.99919	155.14139
12	0	0.0	54.67598	179.99999
13	0	0.0	51.99919	204.85861
14	0	0.0	44.92846	224.92813
15	0	0.0	35.17897	239.89485
16	0	0.0	23.99108	251.42508
17	0	0.0	12.07333	261.02796

ECBDAT Program Variable Values

	8:00 a.m.	12:00 Noon	3:00 p.m.
PHIR	-1.58262299328	-1.58262299328	-1.58262299328
ALPHAR	-.00470631340531	-.00470631340531	-.00470631340531
THETAR	-1.0472	0	.7854
SD1	.4065943581677	.815895265845	.5761322990651
EAR	.4187232738606	.9542758737663	.6139887895501
X	.8335690541425	.3320910156443	.6664994757825
Y	-.2382351769665	-.4733185740069	-.3356098818006
Z	.2882493024066	0	-.3334906745224
AAR	1.246602850733	1.192092895508E-7	-1.045362334257
AZANGR	1.894989799267	3.141592520791	4.186954984257
ELANGR	.4187232738606	.9542758737663	.6139887895501

PLUTUS Program Output

TFLAG = 0   NDAY = 80   Julian Day = 2444684.5

HR	MIN	SEC	ELANG	AZANG
7	0	0.0	9.80721	96.76071
8	0	0.0	21.83339	106.10064
9	0	0.0	33.24716	117.11389
10	0	0.0	43.42028	131.23382
11	0	0.0	51.23389	150.23847
12	0	0.0	54.98968	174.57694
13	0	0.0	53.38723	200.21285
14	0	0.0	47.03173	221.57494
15	0	0.0	37.66358	237.51131
16	0	0.0	26.66600	249.60848
17	0	0.0	14.83769	259.49960
18	0	0.0	2.63858	268.34834

PLUTUS Program Variable Values

	8:00 a.m.	12:00 Noon	3:00 p.m.
XHANG	78.88	78.88	78.88
FLATO	35.054367944	35.054367944	35.054367944
FLONO	106.543293056	106.543293056	106.543293056
XNHR	8.	12.	15.
ZONE	7.	7.	7.
Q5	.002870997260816	.002870997260816	.002870997260816
Q6	296.8917655028	356.8917655028	401.8917655028
Q31	-1.62	-1.62	-1.62
Q32	.006618250947018	.006618250947018	.006618250947018
Q33	405.	465.	510.
Q34	1.745616453331	1.745616453331	1.745616453331
Q35	1.884652048157	1.884652048157	1.884652048157
Q36	-.9971060692325	-.9971060692325	-.9971060692325
Q37	1.784941441234	1.784941441234	1.784941441234
Q38	.002350219629255	.002350219629255	.002350219629255
POLAR2	.9282730527742	.5737263099438	.7916153651541
QE	1.564941441234	1.564941441234	1.564941441234
QA	-.2574336094929	-.5711583130838	-.4252028227085
QB	.8918625438991	.05422232120636	-.667725576797
QC	.371910449058	.8190521130572	.6110264775582

SUNAEP Program Output

NDAY = 80 Julian Day = 2444684.5

HR	MIN	SEC	ELANG	AZANG
7	0	0.0	9.79805	96.46896
8	0	0.0	21.80762	105.77544
9	0	0.0	33.24881	116.73629
10	0	0.0	43.47866	130.78934
11	0	0.0	51.38181	149.74848
12	0	0.0	55.24748	174.15566
13	0	0.0	53.73021	199.99651
14	0	0.0	47.41210	221.55031
15	0	0.0	38.05509	237.59510
16	0	0.0	27.06488	249.74571
17	0	0.0	15.25803	259.66518
18	0	0.0	3.20272	268.53209

SUNAEP Program Variable Values

	8:00 a.m.	12:00 noon	3:00 p.m.
A	105.7754404458	174.1556545987	237.5950982441
E	21.77438187618	55.23820258637	38.03801804477
LEAP	0	0	0
T	15.	19.	22.
TIME	444.625	444.7916666667	444.9166666667
DELYR	1.	1.	1.
THETA	7.648627909774	7.651494980493	7.653645283532
G	7.617155066475	7.620022061533	7.622172307827
EL	12.58241826742	12.5853059707	12.58747156933
EPS	.4091372367001	.4091372356643	.4091372348874
SEL	.01604696428997	.01893422482122	.02109938914217
RA	.01472335019516	.0173728436826	.01935982943284
DECL	.006383813340783	.007532445175136	.008393813664783
ST	3.124941635132	3.127808767335	3.129959116488
S	5.192401249241	6.242465961444	.7468291955964
H	-5.177677899046	-6.225093117761	-.7274693661635
ER	.3800346667789	.9640885345333	.6638886740747
E	21.77438187618	55.23820258637	38.03801804477
EC	21.80762232205	55.24748209103	38.05508440738
R	144.3591411396	40.2997399011	74.11709991797
RC	.03324044586974	.00927950465881	.01706636260368
RFAC	.8289437314906	.8289437314906	.8289437314906

SUNPOS Program Output

NDAY = 80   Julian Day = 2444684.5

HR	MIN	SEC	ELANG	AZANG
7	0	0.0	9.81319	96.47331
8	0	0.0	21.81360	105.78002
9	0	0.0	33.25176	116.74126
10	0	0.0	43.47970	130.79475
11	0	0.0	51.38126	149.75387
12	0	0.0	55.24567	174.15961
13	0	0.0	53.72794	199.99782
14	0	0.0	47.41030	221.54960
15	0	0.0	38.05443	237.59347
16	0	0.0	27.06626	249.74375
17	0	0.0	15.26421	259.66311
18	0	0.0	3.23929	268.53001

SUNPOS Program Variable Values

	8:00 a.m.	12:00 Noon	3:00 p.m.
NDATE	21	21	21
FMO	3.	3.	3.
IYR	1981	1981	1981
YRI	81.	81.	81.
XNHR	8.	12.	15.
MIN	0	0	0
XSEC	0.	0.	0.
TFLAG	0.	0.	0.
FLONO	106.543293056	106.543293056	106.543293056
FLATO	35.054367944	35.054367944	35.054367944
FJDI	2444685.	2444685.	2444685.
ZONE	7.	7.	7.
DELPSI	-13.6670759472	-13.6670759472	-13.6670759472
DELOBL	-5.057333132573	-5.057333132573	-5.057333132573
NDAY	80	80	80
T	.8121697467488	.8121697467488	.8121697467488
SEC	7041222.354507	7041222.354507	7041222.354507
GMSTOD	178.4264771106	178.4264771106	178.4264771106
TI	.8121868583162	.8121914214009	.8121948437143
SUNM	76.43084826716	76.59511497733	76.71831500984
SUNECC	.01671700747374	.01671700728207	.01671700713831
OOBLIQ	23.44031979141	23.44031973203	23.44031968749
SUNOMG	282.6174203971	282.6174282453	282.6174341313
TRUANS	78.30184607231	78.46728975664	78.59136228515
GMLON	.9192664694438	1.084718001894	1.208796416486
GTLON	.9154700594584	1.080921591908	1.2050000065
RSUN	.9963436952309	.9963906478948	.9964258805726
GALON	.909763081898	1.075214883276	1.199293499652
OOBLIQ	23.44031979141	23.44031973203	23.44031968749
GARA	.834695910885	.9865010134635	1.100347136131
DEC	.3618851563648	.427692496592	.4770419860496
UT	15.	19.	22.
GMSTI	404.0425067106	464.2067812706	509.3299871906
EOE	-.003483110948668	-.003483110950234	-.003483110951408
GASTI	404.0390235997	464.2032981597	509.3265040797
FLAST	297.4957305437	357.6600051037	42.78321102368
FLHA	296.6610346328	356.6735040902	41.68286388755
AZ	105.7800187425	174.1596148574	237.5934681492
EL	21.81360445328	55.24567278876	38.05443113368
REFC	.04008097616314	.01117726445133	.02056192730351
ELP	21.77352347711	55.23449552431	38.03386920637

RLAMB Program Output

NDAY = 80 Julian Day = 2444684.5

HR	MIN	SEC	POLAR AZ	Declination
7	0	0.0	78.449170	-.408006
8	0	0.0	63.449170	-.408006
9	0	0.0	48.449170	-.408006
10	0	0.0	33.449170	-.408006
11	0	0.0	18.449170	-.408006
12	0	0.0	3.449170	-.408006
13	0	0.0	-11.550830	-.408006
14	0	0.0	-26.550830	-.408006
15	0	0.0	-41.550830	-.408006
16	0	0.0	-56.550830	-.408006
17	0	0.0	-71.550830	-.408006
18	0	0.0	-86.550830	-.408006

RLAMB Program Variable Values

	8:00 a.m.	12:00 Noon	3:00 p.m.
POLAZ	63.44917015807	3.449170158069	-41.55082984193
RLMDC	-.4080063271615	-.4080063271615	-.4080063271615
NDFEB	28	28	28
X	1.3736	1.3736	1.3736
EQOFTM	-.1270584734712	-.1270584634712	-.1270584734712
SOLTIM	7.770055322795	11.7700553228	14.7700553228
XNHR	8.	12.	15.
SOLTIME	-4.229944677205	-.2299446772046	2.770055322795
TFLAG	0.	0.	0.
STIM	-.1028862037333	-.1028862037333	-.1028862037333

Useful Subroutines

Some functions and subroutines called for in some of the various sun-pointing programs are listed below:

```
******************
   FUNCTION QADATN(Y,X)
      TO DETERMINE THE CORRECT QUADRANT FOR AN ANGLE FOUND THROUGH THE
      ARC-TANGENT.
   PI = 3.141592653589793
   TWOPI=2.*PI
   DPR=180./PI
   IF(X.EQ.0.)  GO TO 9
   W=ATAN(Y/X)
   IF(X.GT.0.)  GO TO 7
   W=W+PI
   GO TO 14
```

```
 7 W=AMOD(W+TWOPI,TWOPI)
   GO TO 14
 9 W=0.
   IF(Y.EQ.0.)  GO TO 14
   W=PI/2.
   IF(Y.GT.0.)  GO TO 14
   W=3.*W
14 QADATN=DPR*W
   RETURN
   END
***********************************

      THIS FUNCTION FINDS THE ARCTANGENT AS A POSITIVE ANGLE BETWEEN
      ZERO AND 360 DEGREES.

   FUNCTION QADAT(Y,X)
   TWOPI=6.28318530717956
   DPR=180./3.141592653589793
   W=ATAN2(Y,X)
   IF(W.LT.0.0)W=W+TWOPI
   QADAT=W*DPR
   RETURN
   END
***********************************************
      THIS FUNCTIONS FINDS THE SINE OF AN ANGLE WHOSE ARGUMENT IS IN
      DEGREES.

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

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

   FUNCTION TAND(A)
   DPR=180./3.141592653589793
   R=A/DPR
   TAND=TAN(R)
   RETURN
   END
**************************************
```

```
**************************************
      THIS SUBROUTINE FINDS THE FIRST CIRCLE VALUE OF AN ANGLE, THAT
      IS IT REDUCES AN ANGLE TO A VALUE BETWEEN ZERO AND 360 DEGREES.

   SUBROUTINE FCV(A)
 1 IF(A.LT.360.) GO TO 2
   A=A-360.
   GO TO 1
 2 IF(A.GE.0.) GO TO 3
   A=A+360.
   GO TO 2
 3 RETURN
   END
**************************************
      SUBROUTINE NUTATE(FJDI,DELPSI,DELOBL)
          FINDS THE NUTATION IN LONGITUDE AND OBLIQUITY AS A FUNCTION
          OF A SPECIFIED JULIAN DATE.
             DATE OF LATEST REVISION  1977 MARCH 22

     DIMENSION Q(69),R(40)
     DAYS=FJDI-2415020.   $   DSMALL=DAYS
     DCAP=DSMALL/10000.   $   DSQ=DCAP*DCAP   $   DCUB = DSQ*DCAP
     FL=296.104608+13.0649924465*DSMALL+.0006890*DSQ+.000000295*DCUBE
     FLPRI=358.475833+.9856002669*DSMALL-.0000112*DSQ-.000000068*DCUBE
     F=11.250889+13.229350449*DSMALL-.0002407*DSQ-.000000007*DCUBE
     D=350.737486+12.1907491914*DSMALL-.0001076*DSQ+.000000039*DCUBE
     OMEGA=259.183275-.0529539222*DSMALL+.0001557*DSQ+.000000046*DCUBE
     T=DAYS/36525.
     Q(1)=(-17.2327-.01737*T)*SIND(OMEGA)
     Q(2)=(- 1.2729-.00013*T)*SIND(2.*(F-D+OMEGA))
     Q(3)=(   .2088+.00002*T)*SIND(2.*OMEGA)
     Q(4)=(  -.2037-.00002*T)*SIND(2.*(F+OMEGA))
     Q(5)=(   .1261-.00031*T)*SIND(FLPRI)
     Q(6)=(   .0675+.00001*T)*SIND(FL)
     Q(7)=(  -.0497+.00012*T)*SIND(FLPRI+2.*(F-D+OMEGA))
     Q(8)=(  -.0342-.00004*T)*SIND(2.*F+OMEGA)
     Q(9)= -.0261*SIND(FL+2.*(F+OMEGA))
     Q(10)=(.0214-.00005*T)*SIND(-FLPRI+2.*(F-D+OMEGA))
     Q(11)=-.0149*SIND(FL-2.*D)
     Q(12)=(.0124+.00001*T)*SIND(2.*(F-D)+OMEGA)
     Q(13)= .0114*SIND(-FL+2.*(F+OMEGA))
     Q(14)= .0060*SIND(2.*D)
     Q(15)= .0058*SIND(FL+OMEGA)
     Q(16)=-.0057*SIND(-FL+OMEGA)
     Q(17)=-.0052*SIND(-FL+2.*(F+D+OMEGA))
     Q(18)= .0045*SIND(-2.*FL+2.*F+OMEGA)
     Q(19)= .0045*SIND(2.*(FL-D))
     Q(20)=-.0044*SIND(FL+2.*F+OMEGA)
     Q(21)=-.0032*SIND(2.*(F+D+OMEGA))
     Q(22)= .0028*SIND(2.*FL)
     Q(23)= .0026*SIND(FL+2.*(F-D+OMEGA))
     Q(24)=-.0026*SIND(2.*(FL+F+OMEGA))
     Q(25)= .0025*SIND(2.*F)
     Q(26)=-.0021*SIND(2.*(F-D))
```

```
      Q(27)= .0019*SIND(-FL+2.*F+OMEGA)
      Q(28)=(.0016-.00001*T)*SIND(2.*FLPRI)
      Q(29)=-.0015*SIND(FLPRI+OMEGA)
      Q(30)=(-.0015+.00001*T)*SIND(2.*(FLPRI+F-D+OMEGA))
      Q(31)= .0014*SIND(-FLPRI+2.*D+OMEGA)
      Q(32)=-.0013*SIND(FL-2.*D+OMEGA)
      Q(33)= .0010*SIND(2.*(FL-F))
      Q(34)=-.0010*SIND(-FLPRI+OMEGA)
      Q(35)=-.0009*SIND(-FL+2.*(F+D)+OMEGA)
      Q(36)= .0007*SIND(FLPRI+2.*(F+OMEGA))
      Q(37)=-.0007*SIND(FL+FLPRI-2.*D)
      Q(38)=-.0006*SIND(-FLPRI+2.*(F+OMEGA))
      Q(39)=-.0006*SIND(FL+2.*(F+D+OMEGA))
      Q(40)= .0006*SIND(2.*(FL+F-D+OMEGA))
      Q(41)=-.0006*SIND(2.*D+OMEGA)
      Q(42)= .0006*SIND(FL+2.*D)
      Q(43)=-.0005*SIND(-2.*FL+2.*D+OMEGA)
      Q(44)=-.0005*SIND(-FLPRI+2.*(F-D)+OMEGA)
      Q(45)= .0005*SIND(FL+2.*(F-D)+OMEGA)
      Q(46)=-.0005*SIND(-2.*D+OMEGA)
      Q(47)=-.0005*SIND(2.*(F+D)+OMEGA)
      Q(48)=-.0004*SIND(2.*(-FLPRI+F-D)+OMEGA)
      Q(49)= .0004*SIND(2.*(FL-D)+OMEGA)
      Q(50)=-.0004*SIND(2.*(FL+F)+OMEGA)
      Q(51)= .0004*SIND(FL-FLPRI)
      Q(52)=-.0004*SIND(FLPRI-2.*D)
      Q(53)=-.0004*SIND(D)
      Q(54)= .0004*SIND(FL-2.*F)
      Q(55)= .0003*SIND(FLPRI+2.*(F-D)+OMEGA)
      Q(56)=-.0003*SIND(2.*(-FL+F+OMEGA))
      Q(57)= .0003*SIND(FL+2.*F)
      Q(58)=-.0003*SIND(FL+FLPRI)
      Q(59)=-.0003*SIND(FL-D)
      Q(60)=-.0003*SIND(FL-FLPRI+2.*(F+OMEGA))
      Q(61)=-.0002*SIND(FL-FLPRI-D)
      Q(62)=-.0002*SIND(-2.*FL+OMEGA)
      Q(63)=-.0002*SIND(-FL+2.*(F-D)+OMEGA)
      Q(64)= .0002*SIND(2.*FL+OMEGA)
      Q(65)=-.0002*SIND(-FL-FLPRI+2.*(F+D+OMEGA))
      Q(66)=-.0002*SIND(-FLPRI+2.*(F+D+OMEGA))
      Q(67)=-.0002*SIND(FL+2.*(F+OMEGA)
      Q(68)= .0002*SIND(FL+FLPRI+2.*(F+OMEGA))
      Q(69)=-.0002*SIND(3.*FL+2.*(F+OMEGA))
      DELPSI=0.
      DO 10  I-1.69
   10 DELPSI-DELPSI+Q(I)
      R(1)=(9.210+0.00091*T)*COSD(OMEGA)
      R(2)=( .5522-0.00029*T)*COSD(2.*(F-D+OMEGA))
      R(3)=(-.0904+0.00004*T)*COSD(2.*OMEGA)
      R(4)=( .0884-0.00005*T)*COSD(2.*(F+OMEGA))
      R(5)=( .0216-0.00006*T)*COSD(FLPRI+2.*(F-D+OMEGA))
      R(6)=( .0183+0.00000*T)*COSD(2.*F+OMEGA)
      R(7)=( .0113-0.00001*T)*COSD(FL+2.*(F+OMEGA))
      R(8)=(-.0093+0.00003*T)*COSD(-FLPRI+2.*(F-D+OMEGA))
```

```
      R(9)= -.0066*COSD(2.*(F-D)+OMEGA)
      R(10)=-.0050*COSD(-FL+2.*(F+OMEGA))
      R(11)=-.0031*COSD(FL+OMEGA)
      R(12)= .0030*COSD(-FL+OMEGA)
      R(13)= .0022*COSD(-FL+2.*(F+D+OMEGA))
      R(14)=-.0024*COSD(-2.*FL+2.*F+OMEGA)
      R(15)= .0023*COSD(FL+2.*F+OMEGA)
      R(16)= .0014*COSD(2.*(F+D+OMEGA))
      R(17)=-.0011*COSD(FL+2.*(F-D+OMEGA))
      R(18)= .0011*COSD(2.*(FL+F+OMEGA))
      R(19)=-.0010*COSD(-FL+2.*F+OMEGA)
      R(20)= .0008*COSD(FLPRI+OMEGA)
      R(21)= .0007*COSD(2.*(FLPRI+F-D+OMEGA))
      R(22)=-.0007*COSD(-FL+2.*D+OMEGA)
      R(23)= .0007*COSD(FL-2.*D+OMEGA)
      R(24)= .0005*COSD(-FLPRI+OMEGA)
      R(25)= .0005*COSD(-FL+2.*(F+D)+OMEGA)
      R(26)=-.0003*COSD(FLPRI+2.*(F+OMEGA))
      R(27)= .0003*COSD(-FLPRI+2.*(F+OMEGA))
      R(28)= .0003*COSD(FL+2.*(F+D+OMEGA))
      R(29)=-.0002*COSD(2.*(FL+F-D+OMEGA))
      R(30)= .0003*COSD(2.*D+OMEGA)
      R(31)= .0003*COSD(2.*(-FL+D)+OMEGA)
      R(32)= .0003*COSD(-FLPRI+2.*(F-D)+OMEGA)
      R(33)=-.0003*COSD(FL+2.*(F-D)+OMEGA)
      R(34)= .0003*COSD(-2.*D+OMEGA)
      R(35)= .0003*COSD(2.*(F+D)+OMEGA)
      R(36)= .0002*COSD(2.*(-FLPRI+F-D)+OMEGA)
      R(37)=-.0002*COSD(2.*(FL-D)+OMEGA)
      R(38)= .0002*COSD(2.*(FL+F)+OMEGA)
      R(39)=-.0002*COSD(FLPRI+2.*(F-D)+OMEGA)
      R(40)= .0002*COSD(2.*(-FL+F+OMEGA))
      DELOBL=0.
      DO 20   J=1,40
   20 DELOBL=DELOBL+R(J)
      RETURN
      END
```

Two subroutines for calculating the refraction correction of the earth's refraction correction of the earth's atmosphere are included below. REFRAC is the more correct, but REFRA may run faster and will cause errors only in the range of several arc-minutes.

```
***************************************
      SUBROUTINE REFRAC(A,R)
C      FINDS THE MEAN REFRACTION (R) IN ARC-SECONDS FOR A GIVEN
C      ELEVATION ANGLE (A) IN DEGREES.
C            DATE OF LATEST REVISION   1976 DECEMBER 6
```

```
      IF(A.LT.-0.575)  GO TO 20
      IF(A.LT.5.)      GO TO 10
      TANA=TAND(A)
      R=58.1/TANA-.070/TANA**3+.000086/TANA**5
      RETURN
   10 R=1735.+A*(-518.2+A*(103.4+A*(-12.79+A*0.711)))
      RETURN
   20 R=-20.774/TANA
      RETURN
      END


*************************************
      SUBROUTINE REFRA(A,B)
      DATA DPR/57.294577951/
      Q51=TAN(A/DPR)
      IF(A.LT.4.836)GO TO 10
      B=58./Q51-.058/(Q51**3)
      GO TO 100
   10 IF(A.LT.3.804)GO TO 20
      B=705.-(705.-590.)*(A-3.804)/(4.836-3.804)
      GO TO 100
   20 IF(A.LT.2.760)GO TO 30
      B=864.-(864.-705.)*(A-2.760)/(3.804-2.760)
      GO TO 100
   30 IF(A.LT.1.694)GO TO 40
      B=1100.-(1100.-864.)*(A-1.694)/(2.760-1.694)
      GO TO 100
   40 IF(A.LT.0.241)GO TO 50
      B=1458.-(1458.-1100.)*(A-0.241)/(1.694-0.241)
      GO TO 100
   50 B=2070.-(2070.-1458.)*(A-(-.575))/(0.241-(-0.575))
  100 B=B/3600.
      RETURN
      END
```

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