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THERMAL AND ORBITAL ANALYSIS OF EARTH MONITORING SUN-SYNCHRONOUS SPACE EXPERIMENTS

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INTRODUCTION

This report presents a method for generating all the orbital parameters needed for the thermal analysis of spacecraft in Earth monitoring Sun-synchronous orbits. The level of complexity is suitable for initial planning of missions. The mechanics of Sun-synchronous orbits and their impact on the thermal design of space experiments is discussed in detail. A Sun-synchronous Orbit Analysis Program (SOAP) was developed to calculate the orbital parameters necessary for a complete thermal analysis. An example case run with this program is discussed.

ANALYSIS OF SUN-SYNCHRONOUS ORBITS

An overview of Sun-synchronous orbits is presented here with particular emphasis on their application to Earth-monitoring missions. Additional analysis of Sun-synchronous orbits can be found in reference 1. A Sun-synchronous orbit is one whose right ascension of ascending node precesses at a rate which matches the average apparent rotation rate of the Sun about the Earth. This type of orbit is desirable for many types of Earth-monitoring missions because it allows for near-global coverage of the Earth's surface and atmosphere and repetitive latitude-longitude observations at near-constant conditions of solar illumination. Also of special significance for Earth observing satellites, are the times during which the Sun is rising or setting on the Earth's horizon, as viewed from the spacecraft. During sunset and sunrise it is possible to obtain vertical profiles of many different atmospheric constituents which attenuate the Sun's radiation. A spacecraft in Sun-synchronous orbit, with a typical low Beta angle[1] (angle between the solar vector and the orbit plane), will continue to experience a sunrise and sunset every revolution, for as long as the orbit is maintained. In the case of a purely Earth monitoring experiment, atmospheric data can be recorded over the same area under the same lighting conditions at a constant time increment.

Sun-synchronous orbits are retrograde, that is, the velocity component of the spacecraft in the equatorial plane opposes the rotational motion of the Earth. Thus, the orbit inclination (angle between the orbit plane and equatorial plane) will always be greater than 90 degrees. For circular orbits, the inclination is only a function of the orbit altitude. The variation of Sun-synchronous orbit inclination for circular orbits up to an altitude of 1600 kilometers is shown in Figure 1.

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[1]The Beta angle defined in this paper will always refer to the angle between the orbit plane and the Sun. Other publications often use the complement to this angle.

Another special characteristic of a Sun-synchronous orbit is that the orbit repetition factor (Q) is identical to the number of orbit revolutions in one day. Therefore, assuming a circular orbit, any Sun-synchronous orbit has the special property that its ground track will repeat precisely at intervals of a whole number of days. Table 1 shows the number of orbital revolutions per day as a function of orbit inclination or orbit altitude. This quantity Q is important for defining the longitude and latitude ground coverage of an Earth monitoring satellite. For example, an integer value for Q means that a particular ground track will be duplicated the next day. If Q includes a fraction, such as one-fifth, then the initial longitude coverage will be duplicated every five days. Therefore, long repeat cycles will allow for good longitude coverage, but poor repeat coverage. Similarly, short repeat cycles give good repetition, but poor longitude coverage (ref. 2).

It is necessary to note that, though a Sun-synchronous Earth monitoring orbit implies a fixed geometry with respect to the Sun, the solar radiation flux input is not necessarily fixed, but actually varies considerably. This is due to the satellite's path which crosses around the Earth and maintains a constant view of the Earth on one side. Though no single side of the satellite is fixed with respect to the Sun, there is often one side that receives a high average solar flux during an orbit. For example, if the satellite orbit plane is in line with the Sun, the satellite will receive direct solar radiation on its zenith side for the part of the orbit when the satellite is between the Earth and the Sun. As the satellite moves past the polar region it will go behind the Earth, thus being blocked from the Sun's radiation entirely. This type of orbit configuration can cause problems for optical experiments using nadir detectors with a horizon to horizon view. In this case, the nadir, or earth facing side of the experiment, will experience direct solar flux during sunrise and sunset as seen from the satellite as it passes around the Earth. The other extreme case occurs when the satellite orbit plane is perpendicular to the Sun. This will cause one side of the satellite to receive full solar flux. Similarly, the opposite side of the satellite would be facing deep space during the entire orbit.

As with any space experiment, the solar illumination or radiation flux input has a considerable impact on the thermal and mechanical design. Therefore, it is appropriate to discuss the orbital alignment with the Sun, specifically as it applies to an Earth monitoring Sun-synchronous experiment. In this case, the initial timing of the orbit is important, since it will determine the envelope of angles between the solar vector and the orbit plane. The initial timing of a Sun-synchronous orbit is often referred to as the "orbit time", which represents the longitudinal difference between the sun and the point where the spacecraft crosses the equator (15 degrees per hour). For example, if an orbit time of local clock noon is chosen, then the orbit plane would be closely in line with the Sun and the angle between the Sun and the orbit plane would be very small, even approaching zero at times. Each time the satellite passes the equator the local clock time at this crossing position on the Earth would be noon. Similarly, an orbit time six hours later would produce angles near 90 degrees and an envelope that generally includes larger angles. This type of orbit could create thermal problems since a particular side of the experiment would be facing the Sun at all times, providing the nadir side maintains a constant Earth view. In any event, the characteristics of a Sun-synchronous orbit have a direct effect on the design of a space experiment.

It is customary that the orbit time be expressed as either an ascending node or descending node. This describes the path of the satellite as it crosses the equator. In the case of an ascending node orbit, the satellite passes the equator traveling from South to North. Similarly, a descending node orbit crosses the equator traveling from North to South. Thus a 2:00 pm ascending node orbit is equivalent to a 2:00 am descending node orbit.

SUN-SYNCHRONOUS ORBIT ANALYSIS PROGRAM

A Sun-synchronous Orbit Analysis Program (SOAP), written in FORTRAN language, was created to calculate orbital parameters for an entire year for a fixed orbit altitude and orbit time. The source program has been written in the form of a subroutine, designed to be called from any other computer code.[2] The subroutine and a sample calling program are supplied in Appendix A and an example output is presented in Appendix B. The input and output calling arguments, for the SOAP subroutine, are shown in Appendix C and the governing equations used to calculate orbital parameters are presented in Appendix D.

The program is valid for Sun-synchronous orbits with launch dates after 1950 including leap years. Inputs for the program include the year of the launch, experiment altitude and Sun-synchronous orbit time. Output data includes orbit inclination angle, time in hours for a complete orbit or revolution time, a set of data for the maximum and minimum Beta angle, and orbital data for the entire year including solar declination, right ascension of the Sun, and longitude of the ascending node. The orbital parameters calculated by this program are extremely tedious to do by hand and require repetitive calculations for every day of the year. Thus, this program provides an efficient method for determining all of the orbital parameters needed for a thermal radiation analysis.

It was stated previously that a Sun-synchronous orbit allowed for a fixed inclination angle and a fixed revolution time. All of the other parameters are a function of orbital position and the day of the year. A typical set of output data will contain a maximum and minimum Beta angle for the year of interest. Though the year and altitude have a small effect on the Beta angles, the Sun-synchronous orbit time has the largest effect on these angles and their corresponding magnitudes. For example, a 6:00 orbit produces a large variation in the Beta angle with the average angles being high, even approaching 90 degrees in some cases. An orbit time of 12:00 would produce the smallest variation in Beta angle and the maximum and minimum angles would both be below 10 degrees. The yearly variation in Beta angle is due to seasonal variation of the Earth's position with respect to the Sun. In the case where the orbit plane is inclined at a high angle with respect to the Sun (orbit times near noon), the Earth's seasonal tilt will create large variations in Beta angle. Similarly, when the orbit plane is closely aligned with the Sun (orbit times near 6:00), the Earth's tilt has little effect on the Beta angle. Figure 2 shows the variation in Beta angle for different Sun-synchronous orbit times. These results, calculated by the SOAP computer program, are for a fixed altitude and year.

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[2]The source code can be acquired on either diskette or magnetic tape by contacting the author of this publication. Note, the author will not be responsible for any changes in the source code made by the user.

THERMAL ANALYSIS APPLICATION

A specific example case was chosen to illustrate the use of the Sun-synchronous Orbit Analysis Program (SOAP) in calculating the orbital fluxes incident on a Sun-synchronous space experiment. The example utilizes a radiation analysis program to predict heat fluxes on a cube for one complete orbit. Results from the orbital analysis program, described in the previous section, are used as input to this radiation program. An example orbit will be presented and the orbital heating data will be summarized.

The orbit chosen for this application was a 1:30 p.m. ascending node Sun-synchronous circular orbit with an altitude of 705 km and a launch date in 1998. Representative values for the solar constant, Earth infrared radiation and the Earth albedo were used. These values are commonly used by thermal analysts for spacecraft design. It was also assumed that the spacecraft surface was black, such that the emissivity and absorptivity were 1.0. This orbit data was used in the SOAP computer code to calculate pertinent orbit parameters required by the Thermal Radiation Analyzer System (TRASYS) program (ref.3). These parameters are summarized in Table 2. The TRASYS program was employed to define the incident infrared, solar and Earth albedo heat fluxes acting on a space experiment for one complete orbit. Thermal flux data were generated for one orbit on two distinct days of the year when the Sun's location, relative to the experiment, yields the highest and lowest Beta angles. These two days represent the highest and lowest average heat fluxes for the year. The ultraviolet (UV), which includes the solar and albedo fluxes, and the Earth infrared (IR) flux contributions are shown in Table 3. These heat fluxes can be used as the basis for further thermal analysis including sizing radiators or predicting instrument operating temperatures. Since these two sets of data contain the highest and lowest average heat fluxes for the year, the thermal analyst can be assured that all orbital heating fluxes will fall within these limits.

CONCLUSIONS

The fundamentals of an Earth monitoring Sun-synchronous orbit were presented. A Sun-synchronous Orbit Analysis Program (SOAP) was developed to calculate orbital parameters for an entire year. The output from this program provides the required input data for the TRASYS thermal radiation computer code, which in turn computes the infrared, solar and Earth albedo heat fluxes incident on a space experiment. Direct incident heat fluxes can be used as input to a generalized thermal analyzer program to size radiators and predict instrument operating temperatures. The SOAP computer code and the thermal analysis methodology presented in this paper should prove useful to the thermal engineer during the design phases of future Earth monitoring Sun-synchronous space experiments.
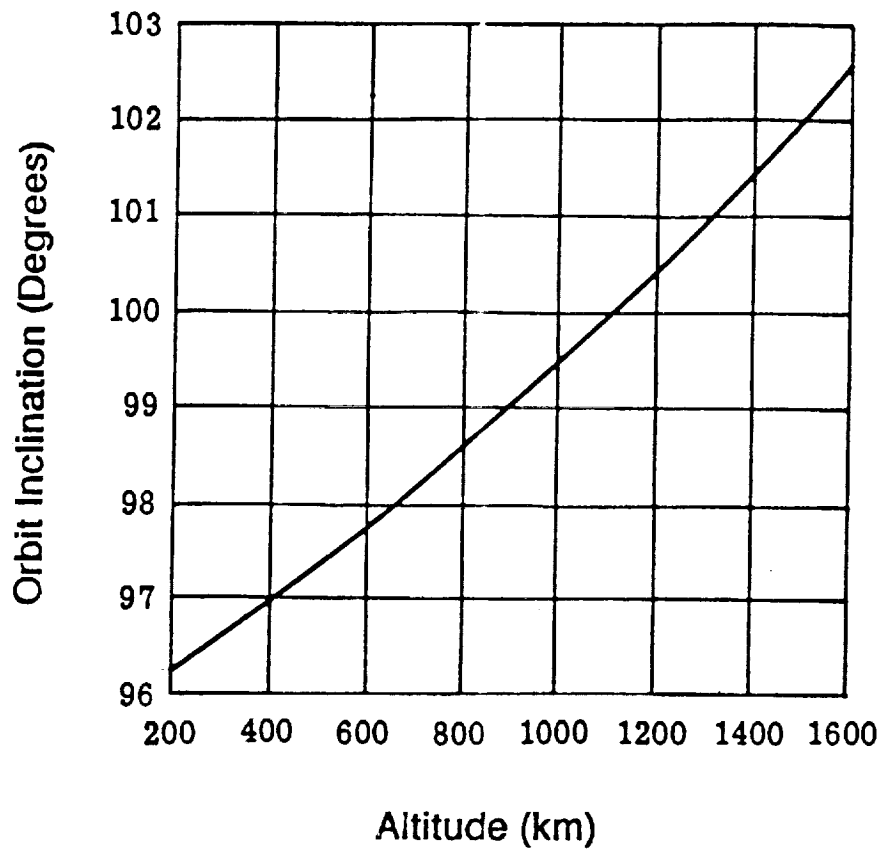
Figure 1. Sun-synchronous orbit inclination angle versus orbit altitude
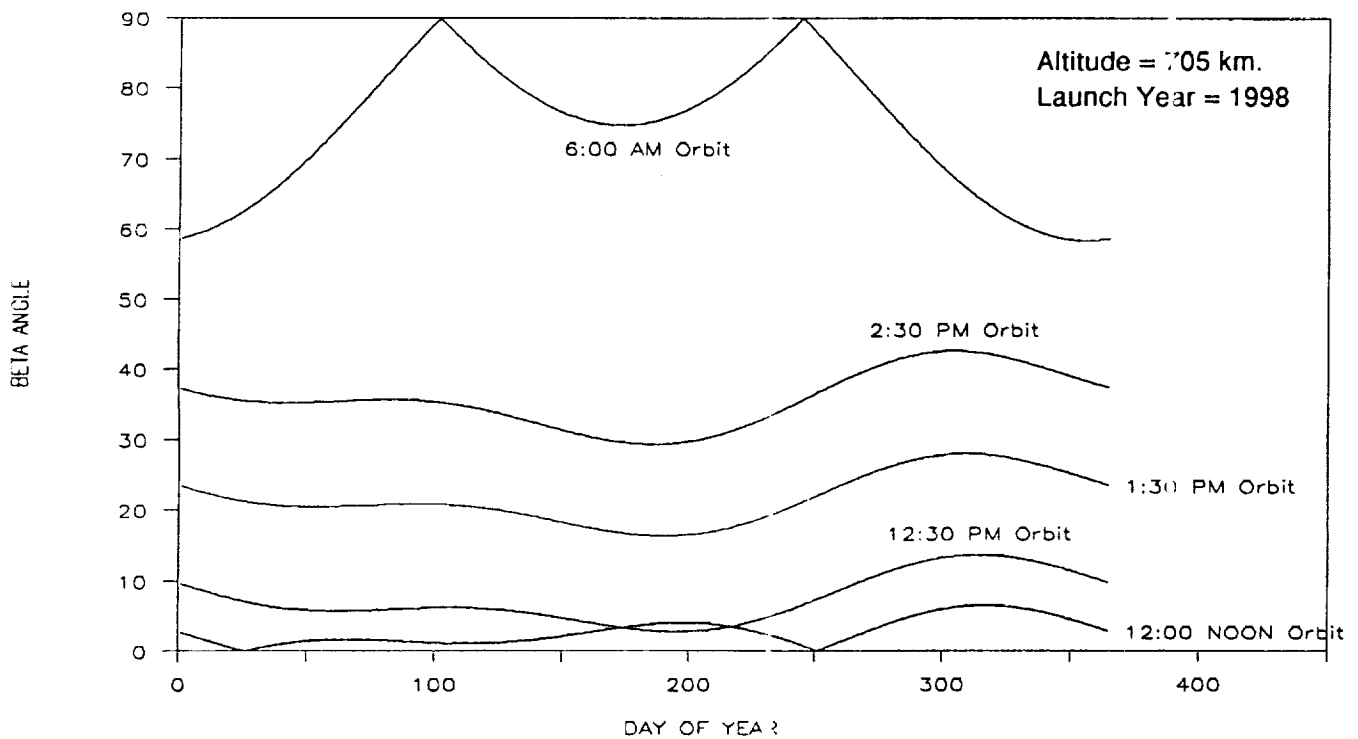
Figure 2. Beta angle versus day of the year for various sun-synchronous orbit times

REPETITION FACTOR (Q)	ALTITUDE (KM)	INCLINATION ANGLE (DEG)
12	1684.6	102.94
12 1/8	1629.1	102.63
12 1/4	1574.4	102.33
12 1/2	1467.9	101.75
13	1265.3	100.71
13 1/8	1216.6	100.47
13 1/4	1168.7	100.24
13 1/2	1075.2	99.79
14	896.5	98.99
14 1/8	853.4	98.80
14 1/4	811.0	98.62
14 1/2	728.1	98.28
15	569.1	97.64
15 1/8	530.8	97.49
15 1/4	492.9	97.35
15 1/2	418.8	97.07
16	276.3	96.57

Table 1. Circular Sun-Synchronous Orbit Parameters for Specific Repetition Factors

PARAMETER	DATE	
	July 9, 1998	November 5, 1998
Days After January 1	190	309
Longitude of Ascending Node	130.77	248.07
Right Ascension of the Sun	108.19	220.10
Solar Declination	22.39	−15.60

Orbital Constants:

Orbit Altitude = 705 km
Sun-synchronous Orbit Time = 1:30 pm Ascending Node
Revolution Time = 1.65 hours
Eccentricity = 0.0

Thermal Analysis Constants:

Solar Constant = 1352 W/m*m
Earth Infrared Radiation = 236.6 W/m*m
Earth Albedo = 0.30

Incident Flux Properties:

Absorptivity = 1.0
Emissivity = 1.0

Table 2. TRASYS Input Parameters

Surface Flux Data (W/m*m) – July 9, 1998 (Beta Angle = 17.28)							
Orbit Position (deg)	Flux Type	Velocity	Anti-Velocity	Sun	Anti-Sun	Nadir	Zenith
0	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
30	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
60	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
90	UV	1154	0	387	0	586	0
	IR	55	55	53	53	195	0
120	UV	1309	1	396	4	24	74
	IR	55	55	53	53	195	0
150	UV	1141	40	437	44	174	711
	IR	55	55	53	53	195	0
180	UV	667	75	466	73	283	1157
	IR	55	55	53	53	195	0
210	UV	89	164	475	82	317	1293
	IR	55	55	53	53	195	0
240	UV	69	791	461	68	265	1083
	IR	55	55	53	53	195	0
270	UV	30	1207	428	35	143	583
	IR	55	55	53	53	195	0
290	UV	3	1308	400	8	39	152
	IR	55	55	53	53	195	0
323	UV	0	1155	387	0	586	0
	IR	55	55	53	53	195	0
350	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
Surface Flux Data (W/m*m) – November 5, 1998 (Beta Angle = 29.04)							
0	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
20	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
47	UV	1031	0	648	0	587	0
	IR	55	55	53	53	195	0
80	UV	1199	1	659	3	21	63
	IR	55	55	53	53	195	0
120	UV	930	49	707	48	198	810
	IR	55	55	53	53	195	0
150	UV	428	75	729	69	278	1135
	IR	55	55	53	53	195	0
170	UV	81	145	732	73	290	1185
	IR	55	55	53	53	195	0
210	UV	53	876	711	52	212	867
	IR	55	55	53	53	195	0
250	UV	3	1198	664	6	38	144
	IR	55	55	53	53	195	0
287	UV	0	1031	648	0	587	0
	IR	55	55	53	53	195	0
310	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0
340	UV	0	0	0	0	0	0
	IR	55	55	53	53	195	0

Table 3. Experiment Heat Flux Data

```
.........................................................
.    Sun-Synchronous Orbit Analysis Program (SOAP)     .
.    Written in the form of a FORTRAN SUBROUTINE       .
.                                                      .
.    Written by:  Brian Killough - NASA Langley Research Center  .
.                              Mail Stop 431           .
.                              Hampton, VA 23665  (804) 864-7047  .
.                                                      .
.    This program calculates all of the necessary orbital parameters  .
.    for a sun-synchronous space experiment.  Input for the program   .
.    includes the year, experiment altitude, and sun-synchronous orbit .
.    time.  Output for the program includes the BETA Angle (Angle      .
.    between the sun and the experiment orbit plane) for each day of   .
.    the year, and the maximum and minimum BETA Angles for that year.  .
.    These maximum and minimum BETA Angles are used to calculate       .
.    orbital parameters such as: Julian Date, Days Relative to January .
.    1, Solar Declination, Orbit Inclination, Longitude of the Ascending .
.    Node, Right Ascension of the Sun, and the Orbit Time. These       .
.    parameters can be used to run any radiation analysis program that .
.    calculates radiation fluxes over one orbit, on a given day.       .
.........................................................

      PROGRAM MAIN

.   THIS IS AN EXAMPLE CALLING PROGRAM

      DIMENSION BETA(366),DECLI(366),LONGAS(366),RASSUN(366)
      DIMENSION MONTHS(2),DAYS(2),COUNTS(2)

      REAL BETA,DECLI,LONGAS,RASSUN
      REAL ALT,TLAUNCH,INCL,OTIME

      INTEGER LEAP,MONTHS,DAYS,COUNTS,YEAR


      CHARACTER*20 OUTFILE

    1 CONTINUE

      PRINT 10
   10 FORMAT (/,' Sun-Synchronous Orbit Analysis Program (SOAP)',/,
     > ' ..............................................',/)
      PRINT 20
   20 FORMAT(1X,'Enter an output file name in SINGLE quotes:')
      READ *,OUTFILE
      OPEN(UNIT=2,FILE=OUTFILE)
      PRINT 30
   30 FORMAT(1X,'Enter the Year:')
      READ *,YEAR
      PRINT 40
   40 FORMAT(1X,'Enter the Experiment Altitude (km):')
      READ *,ALT
      PRINT 50
   50 FORMAT(1X,'Enter the Sun-Synchronous Orbit Time:')
      PRINT 60
   60 FORMAT(1X,'Example >> 13.5 (= 1:30 pm Ascending Node)')
      READ *,TLAUNCH

      CALL SOAP(YEAR,ALT,TLAUNCH,LEAP,MONTHS,DAYS,COUNTS,INCL,OTIME,
     >      BETA,DECLI,LONGAS,RASSUN,IERROR)
      IF (IERROR .NE. 0 ) GO TO 1

      WRITE(2,70)
   70 FORMAT (1X,'................................................')
      WRITE(2,80)
   80 FORMAT (1X,' Sun-Synchronous Orbit Analysis Program (SOAP)')
      WRITE(2,90)
   90 FORMAT (1X,'................................................')
      WRITE(2,100) YEAR
  100 FORMAT (1X,' Year of Launch = ',I4)
      WRITE(2,120) ALT
  120 FORMAT (1X,' Altitude (km) = ',F5.1)
      WRITE(2,140) TLAUNCH
  140 FORMAT (1X,' Sun-Synchronous Orbit Time = ',F5.2)
      WRITE(2,150)
  150 FORMAT (1X,'................................................')
      WRITE(2,160) INCL
  160 FORMAT (1X,' Orbit Inclination Angle,deg. = ',F5.2)
      WRITE(2,170) OTIME
  170 FORMAT (1X,' Orbit Time (hours) = ',F4.2)
      WRITE(2,180)
  180 FORMAT (1X,'................................................')
      WRITE(2,190) BETA(COUNTS(1))
  190 FORMAT (1X,' Maximum Beta Angle,deg. = ',F6.2)
      WRITE(2,200) MONTHS(1),DAYS(1)
  200 FORMAT (1X,' Date of maximum Beta Angle = ',I2,'/',I2)
      WRITE(2,210) COUNTS(1)
  210 FORMAT (1X,' Days Relative to January 1 = ',I4)
      WRITE(2,220) DECLI(COUNTS(1))
  220 FORMAT (1X,' Solar Declination,deg. = ',F6.2)
      WRITE(2,230) LONGAS(COUNTS(1))
  230 FORMAT (1X,' Longitude of Ascending Node,deg. = ',F6.2)
      WRITE(2,240) RASSUN(COUNTS(1))
  240 FORMAT (1X,' Right Ascension of the Sun,deg. = ',F6.2)
      WRITE(2,250)
  250 FORMAT (1X,'................................................')
      WRITE(2,260) BETA(COUNTS(2))
  260 FORMAT (1X,' minimum Beta Angle,deg. = ',F6.2)
      WRITE(2,270) MONTHS(2),DAYS(2)
  270 FORMAT (1X,' Date of minimum Beta Angle = ',I2,'/',I2)
```

```
      WRITE(2,280) COUNTS(2)
  280 FORMAT (1X,' Days Relative to January 1 = ',I4)
      WRITE(2,290) DECLI(COUNTS(2))
  290 FORMAT (1X,' Solar Declination,deg. = ',F6.2)
      WRITE(2,300) LONGAS(COUNTS(2))
  300 FORMAT (1X,' Longitude of Ascending Node,deg. = ',F6.2)
      WRITE(2,310) RASSUN(COUNTS(2))
  310 FORMAT (1X,' Right Ascension of the Sun,deg. = ',F6.2)
      WRITE(2,320)
  320 FORMAT (1X,'................................................',/)
      WRITE(2,340)
  340 FORMAT (1X,'Day of Year',2X,'Beta Angle',2X,'Solar Declination',
     >2X,'Right Ascension',2X,' Longitude of',/,' ============',2X,
     >' ==========',2X,' ================',4X,'of the Sun',4X,
     >' Ascending Node',/,45X,'==============',1X,' ==============')
      DO 400 I=1,365+LEAP
      WRITE(2,350) I,BETA(I),DECLI(I),RASSUN(I),LONGAS(I)
  350 FORMAT (3X,I4,8X,F6.2,10X,F6.2,12X,F6.2,11X,F6.2)
  400 CONTINUE
      CLOSE(unit=2)
      STOP
      END
      SUBROUTINE SOAP(YEAR,ALT,TLAUNCH,LEAP,MONTHS,DAYS,COUNTS,INCL,
     >             OTIME,BETA,DECLI,LONGAS,RASSUN,IERROR)

.........................................................
.    Sun-Synchronous Orbit Analysis Program (SOAP)     .
.    Written in the form of a FORTRAN SUBROUTINE       .
.                                                      .
.    Written by:  Brian Killough - NASA Langley Research Center  .
.                              Mail Stop 431           .
.                              Hampton, VA 23665  (804) 864-7047  .
.                                                      .
.    This program calculates all of the necessary orbital parameters  .
.    for a sun-synchronous space experiment.  Input for the program   .
.    includes the year, experiment altitude, and sun-synchronous orbit .
.    time.  Output for the program includes the BETA Angle (Angle      .
.    between the sun and the experiment orbit plane) for each day of   .
.    the year, and the maximum and minimum BETA Angles for that year.  .
.    These maximum and minimum BETA Angles are used to calculate       .
.    orbital parameters such as: Julian Date, Days Relative to January .
.    1, Solar Declination, Orbit Inclination, Longitude of the Ascending .
.    Node, Right Ascension of the Sun, and the Orbit Time. These       .
.    parameters can be used to run any radiation analysis program that .
.    calculates radiation fluxes over one orbit, on a given day.       .
.........................................................


.........................................................
.    VARIABLE DEFINITION:                              .
.                                                      .
.    INPUT:                                            .
.    YEAR     = YEAR REQUEST >= 1950                   .
.    ALT      = Experiment Altitude                    .
.    TLAUNCH  = Sun-Synchronous Orbit Time (Hours past midnight)  .
.    OUTPUT:                                           .
.    LEAP     = 1, IF LEAP YEAR; 0, IF NOT LEAP YEAR   .
.    MONTHS   = MONTH INDICATOR FOR MAX, MIN BETA      .
.    DAYS     = DAY INDICATOR FOR MAX, MIN BETA        .
.    COUNTS   = INDEX INDICATOR FOR MAX, MIN IN ARRAYS .
.    INCL     = Inclination Angle                      .
.    OTIME    = Orbit time (hours)                     .
.    BETA     = BETA Angle (Angle between the Sun and the Orbit Plane) .
.    DECLI    = Solar Declination                      .
.    LONGAS   = Longitude of the Ascending Node        .
.    RASSUN   = Right Ascension of the Sun             .
.    IERROR   = 0, IF NO ERROR; 1, ERROR IF DATE < 1950  CAL. NOT VALID .
.........................................................
.    VARIABLES USED IN LOGIC:                          .
.    JLDATE = Julian Date                              .
.    MLONG    = Mean Longitude of the Sun              .
.    MANOM    = Mean Anomaly                           .
.    ECLONG   = Ecliptic Longitude                     .
.    OBLEC    = Obliquity of Ecliptic                  .
.    RAGREEN = Right Ascension of the Greenwich Meridian at midnight .
.    XNORM    = Vector Normal to the Experiment (RA-DECL Coord. System) .
.    SUN      = Solar Vector (RA-DECL Coord. System)   .
.........................................................
      DIMENSION BETA(366),DECLI(366),LONGAS(366),RASSUN(366)
      DIMENSION COUNTS(2),MONTHS(2),DAYS(2)

.   MAXIMUM THEN MINIMUM STORED IN ARRAYS

      INTEGER YEAR,LEAP,MONTHS,DAYS,COUNTS,IERROR

      REAL ALT,TLAUNCH,INCL,OTIME
      REAL BETA,DECLI,LONGAS,RASSUN

.........................................................

      REAL MLONG,MANOM,LESS,INC1,INC2,
     >   PI,RAD,ARG,ECLONG,JULDAT,JLDATE,NUMDAY,
     >   OBLEC,RAS1,RAS2,RAGREEN,ANG1,ANG2,XNORM1,XNORM2,XNORM3,
     >   XSUN,YSUN,ZSUN,XNSUN,BETAMAX,BETAMIN

      INTEGER COUNT,COUNT1,COUNT2,I,NFIRST,NLAST
      INTEGER DAYCNT(13)
```

8

```
      DATA DAYCNT/0,31,59,90,120,151,181,212,243,273,304,334,366/
*
*   DEFINE JULDAT = 12:00 NOON JAN. 1, 1950
*
      DATA JULDAT/2433282.5/
*
*....................................................................
*
      PRINT 2
*
2     FORMAT(/,1X,'********* PLEASE WAIT - PROCESSING *********',/)
*
      PI=3.14159265359
      LESS=0.
      LEAP=0
      RAD=180./PI
*.........................
*   CHECK YEAR REQUEST    *
*.........................
      IERROR = 0
      IF(YEAR.LT.1950) THEN
         PRINT *,' YEAR REQUEST LESS THAN 1950 ... CANNOT ',
     >           'CALCULATE'
         IERROR = 1
         GO TO 200
         ENDIF
*....................................................
*   CALCULATE INCLINATION ANGLE AND TIME           *
*....................................................
         INC1= RAD*ACOS(0.9856473*(6378.145+ALT)**3.5
     >        /(-2064.5874E+11))
         INC2= 1+(66058.33/((ALT+6378.145)**2))*(1-1.5*(SIN(INC1
     >        /RAD)**2))
         INCL= RAD*ACOS((COS(INC1/RAD))/INC2)
*
      OTIME=0.0
      IF ((INCL.LT.97.641).AND.(INCL.GE.96.566)) OTIME=
     >    24/((INCL-97.641)/(96.566-97.641)+15)
      IF ((INCL.LT.98.988).AND.(INCL.GE.97.641)) OTIME=
     >    24/((INCL-98.988)/(97.641-98.988)+14)
      IF ((INCL.LT.100.706).AND.(INCL.GE.98.988)) OTIME=
     >    24/((INCL-100.706)/(98.988-100.706)+13)
      IF ((INCL.LE.102.944).AND.(INCL.GE.100.706)) OTIME=
     >    24/((INCL-102.944)/(100.706-102.944)+12)
*
*.......................................................
*   CALCULATE JULIAN DATE FROM JAN 1 1950              *
*.......................................................
      NUMDAY = (YEAR-1950)*365. + JULDAT + INT(FLOAT(YEAR-1950.)/4.
     >        +0.49)
*
      IF (MOD((YEAR-1950),4).EQ.2) LEAP=1
*.......................................
*   ORBITAL PARAMETER CALCULATION      *
*.......................................
      DO 150 COUNT=1,365+LEAP
         JLDATE = COUNT + NUMDAY
         ARG= -4018.5 + COUNT
10       MLONG= 280.460+0.9856474*ARG+LESS*360.
         IF (MLONG.GT.0.0) GOTO 20
         LESS=LESS+1.
         GOTO 10
20       LESS=0.
30       MANOM= 357.528+0.9856003*ARG+LESS*360.
         IF (MANOM.GT.0.0) GOTO 40
         LESS=LESS+1.
         GOTO 30
40       LESS=0.
         ECLONG= MLONG+1.915*SIN(MANOM/RAD)+0.02*SIN(2*MANOM/RAD)
         OBLEC= 23.439-0.0000004*ARG
         DECL1(COUNT)= RAD*ASIN(SIN(ECLONG/RAD)*SIN(OBLEC/RAD))
         RAS1= (JLDATE-2415020.0)/36525*36000.7689
         RAS2= 0.00038708*((JLDATE-2415020.0)/36525)**2
50       RAGREEN= 99.6909833+RAS1+RAS2-LESS*360.
         IF (RAGREEN.LT.360.0) GOTO 60
         LESS=LESS+1.
         GOTO 50
60       LESS=0.
70       LONGAS(COUNT)= RAGREEN+TLAUNCH*60.*0.25068447-LESS*360.
         IF (LONGAS(COUNT).LT.360.0) GOTO 80
         LESS=LESS+1.
         GOTO 70
80       LESS=0.
         RASSUN(COUNT)= RAD*ATAN(COS(OBLEC/RAD)*TAN(ECLONG/RAD))
90       IF ((RASSUN(COUNT).GT.0.0).AND.(RASSUN(COUNT).LT.360.0))
     >        GOTO 130
         IF (RASSUN(COUNT).GT.360.0) GOTO 100
         IF (RASSUN(COUNT).LT.0.0) RASSUN(COUNT)=RASSUN(COUNT)+
     >                                           LESS*360.
         LESS=LESS+1.
         GOTO 90
100      LESS=1.
120      RASSUN(COUNT)=RASSUN(COUNT)-LESS*360.
         LESS=LESS+1.
         IF (RASSUN(COUNT).GT.360.0) GOTO 120
130      ANG1=ECLONG
         ANG2=RASSUN(COUNT)
         IF ((ANG1.GE.0.0).AND.(ANG1.LT.90.0)) THEN
            IF ((ANG2.GE.0.0).AND.(ANG2.LT.90.0)) GOTO 140
```

```
            IF ((ANG2.GE.90.0).AND.(ANG2.LT.180.0)) ANG2=ANG2-90.
            IF ((ANG2.GE.180.0).AND.(ANG2.LT.270.0)) ANG2=ANG2-180.
            ANG2=ANG2-270.
            ENDIF
         IF ((ANG1.GE.90.0).AND.(ANG1.LT.180.0)) THEN
            IF ((ANG2.GE.0.0).AND.(ANG2.LT.90.0)) ANG2=ANG2+90.
            IF ((ANG2.GE.90.0).AND.(ANG2.LT.180.)) GOTO 140
            IF ((ANG2.GE.180.0).AND.(ANG2.LT.270.)) ANG2=ANG2-90.
            ANG2=ANG2-180.
            ENDIF
         IF ((ANG1.GE.180.).AND.(ANG1.LT.270.)) THEN
            IF ((ANG2.GE.0.0).AND.(ANG2.LT.90.0)) ANG2=ANG2+180.
            IF ((ANG2.GE.90.0).AND.(ANG2.LT.180.0)) ANG2=ANG2+90.
            IF ((ANG2.GE.180.0).AND.(ANG2.LT.270.0)) GOTO 140
            ANG2=ANG2-90.
            ENDIF
         IF ((ANG1.GE.270.).AND.(ANG1.LT.360.)) THEN
            IF ((ANG2.GE.0.0).AND.(ANG2.LT.90.0)) ANG2=ANG2+270.
            IF ((ANG2.GE.90.0).AND.(ANG2.LT.180.0)) ANG2=ANG2+180.
            IF ((ANG2.GE.180.0).AND.(ANG2.LT.270.0)) ANG2=ANG2+90.
            ENDIF
140   RASSUN(COUNT)= ANG2
*
*..................................
*   BETA ANGLE CALCULATION        *
*..................................
*
      XNORM1=SIN(INCL/RAD)*SIN(LONGAS(COUNT)/RAD)
      XNORM2=-SIN(INCL/RAD)*COS(LONGAS(COUNT)/RAD)
      XNORM3=COS(INCL/RAD)
*
      XSUN=COS(ECLONG/RAD)
      YSUN=SIN(ECLONG/RAD)*COS(OBLEC/RAD)
      ZSUN=SIN(ECLONG/RAD)*SIN(OBLEC/RAD)
*
      XNSUN=RAD*ACOS(XNORM1*XSUN+XNORM2*YSUN+XNORM3*ZSUN)
      BETA(COUNT)=ABS(90-XNSUN)
150   CONTINUE
*
*...................................
*  MAXIMUM + MINIMUM BETA ANGLES   *
*...................................
      BETAMAX=BETA(1)
      BETAMIN=BETA(1)
*
      DO 160 I=2,365+LEAP
         IF (BETAMIN.GT.BETA(I)) THEN
            COUNT2=I
            BETAMIN=BETA(I)
            ENDIF
         IF (BETAMAX.LT.BETA(I)) THEN
            COUNT1=I
            BETAMAX=BETA(I)
            ENDIF
160   CONTINUE
*
*................................
*   FIND DATE OF MAX AND MIN    *
*................................
      NFIRST = DAYCNT(1)
      DO 170 I=1,12
      NLAST = DAYCNT(I+1)
      IF(I.GT.1) THEN
         NLAST = NLAST + LEAP
         ENDIF
*
      IF(COUNT1.GT.NFIRST .AND. COUNT1.LE.NLAST) THEN
         COUNTS(1) = COUNT1
         DAYS(1) = COUNT1 - NFIRST
         MONTHS(1) = I
         ENDIF
      IF(COUNT2.GT.NFIRST .AND. COUNT2.LE.NLAST) THEN
         COUNTS(2) = COUNT2
         DAYS(2) = COUNT2 - NFIRST
         MONTHS(2) = I
         ENDIF
*
      NFIRST = NLAST
170   CONTINUE
*
200   CONTINUE
      RETURN
      END
```

Appendix B

SOAP Example Output

```
******************************************************
** Sun-Synchronous Orbit Analysis Program (SOAP) **
******************************************************
             Year of Launch - 1998
             Altitude (km) - 705.0
          Sun-Synchronous Orbit Time - 13.50
******************************************************
          Orbit Inclination Angle,deg. - 98.21
               Orbit Time (hours) - 1.65
******************************************************
          Maximum Beta Angle,deg. -  29.04
          Date of Maximum Beta Angle -  11/5
          Days Relative to January 1 -  309
          Solar Declination,deg. -  -15.60
     Longitude of Ascending Node,deg. -  248.07
     Right Ascension of the Sun,deg. -  220.10
******************************************************
          Minimum Beta Angle,deg. -  17.28
          Date of Minimum Beta Angle -   7/9
          Days Relative to January 1 -  190
          Solar Declination,deg. -  22.39
     Longitude of Ascending Node,deg. -  130.77
     Right Ascension of the Sun,deg. -  108.19
******************************************************
```

Day of Year	Beta Angle	Solar Declination	Right Ascension of the Sun	Longitude of Ascending Node
1	24.33	-23.02	281.47	304.48
2	24.22	-22.94	282.58	305.47
3	24.12	-22.84	283.68	306.46
4	24.01	-22.75	284.78	307.44
5	23.91	-22.64	285.88	308.43
6	23.81	-22.52	286.98	309.41
7	23.71	-22.40	288.07	310.40
8	23.61	-22.27	289.16	311.39
9	23.52	-22.14	290.25	312.37
10	23.42	-21.99	291.34	313.36
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
358	25.24	-23.42	272.34	296.36
359	25.13	-23.40	273.45	297.35
360	25.02	-23.37	274.56	298.33
361	24.91	-23.34	275.67	299.32
362	24.79	-23.29	276.78	300.30
363	24.68	-23.24	277.89	301.29
364	24.57	-23.18	279.00	302.28
365	24.46	-23.12	280.10	303.26

APPENDIX C

Input and Output Calling Arguments for the SOAP Subroutine

SOAP has been written in FORTRAN in the form of a subroutine, designed to be called from any other computer code. The input and output calling arguments are described below in detail.

USE: CALL SOAP (YEAR,ALT,TLAUNCH,LEAP,MONTHS,DAYS,COUNTS,
             INCL,OTIME,BETA,DECLI,LONGAS,RASSUN,IERROR)

INPUT: YEAR   An input integer, designating the year, must be >= 1950.

ALT   An input real variable, experiment altitude, km.

TLAUNCH An input real variable, Sun-synchronous Orbit time (hours past midnight). i.e. 13.5 (= 1:30 pm ascending node)

OUTPUT: LEAP   Output integer variable, = 0, YEAR is not a leap year; = 1, YEAR is a leap year.

MONTHS Output integer array, dimensioned 2, containing the month indicator for maximum followed by the minimum BETA occurrence.

DAYS   Output integer array, dimensioned 2, containing the day indicator of the value MONTHS for the maximum followed by the minimum BETA occurrence.

COUNTS Output integer array, dimensioned 2, containing the index pointers in the BETA, DECLI, LONGAS, RASSUN arrays for the maximum followed by the minimum BETA occurrence.

INCL   Output real variable, the inclination angle, deg.

OTIME   Output real variable, Orbit time, hours.

BETA   Output real array, dimensioned 366, angle between the Sun and the Orbit Plane,deg.

DECLI   Output real array, dimensioned 366, solar declination angle, deg.

LONGAS Output real array, dimensioned 366, longitude of the ascending node, deg.

RASSUN Output real array, dimensioned 366, right Ascension of the Sun, deg.

IERROR Output integer, = 0, if no error; = 1, error if YEAR < 1950.

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APPENDIX D

Governing Equations for the Calculation of Orbital Parameters

Assuming a fictitious spherical Earth and a nearly circular orbit, the altitude of the spacecraft can be expressed as

$$a = h + 6378.145 \tag{D1}$$

where a is the altitude above the center of the Earth and h is the nominal altitude of the satellite above the Earth's surface in kilometers. Using an iterative approach, the orbit inclination can be found from the following equations (ref. 4)

$$c1 = \cos^{-1} (0.9856473 \ a^{3.5} / -2.0645874 \times 10^{14}) \tag{D2}$$

$$c2 = 1 + 66058.33 (1 - 1.5 \sin^2 (c1)) / a2 \tag{D3}$$

$$i = \cos^{-1} (\cos (c1) / c2) \tag{D4}$$

where i is the orbit inclination in degrees. Equations (D1) and (D2) are iterative steps used to calculate the orbit inclination.

The following equations used to calculate orbital parameters give the apparent coordinates of the Sun to a precision of 0.01 degrees and time to a precision of 0.1 minutes. Similar equations can be found in references 3 and 6. As expected, the location of the Sun is dependent on the day of the year. Thus a time argument is used to calculate the Sun's location in a right ascension - declination coordinate system. The time argument is expressed as (ref. 5)

$$n = -4018.5 + d \tag{D5}$$

where d is the day of the year. The time argument is used to calculate several orbital angles

$$L = 280.460 + 0.9856474 \ n \tag{D6}$$

$$g = 357.528 + 0.9856003 \ n \tag{D7}$$

$$\lambda = L + 1.915 \sin g + 0.02 \sin 2g \tag{D8}$$

$$\epsilon = 23.439 - 0.0000004 \ n \tag{D9}$$

where L is the mean longitude of the Sun, g is the mean anomaly, λ is the ecliptic longitude, and ϵ is the obliquity of the Earth's equator to the ecliptic, in degrees. These equations are used to calculate the right ascension of the Sun (D10), and the solar declination (D11).

$$\alpha = \tan^{-1} (\cos \epsilon \tan \lambda) \tag{D10}$$

$$\delta = \sin^{-1} (\sin \epsilon \sin \lambda) \tag{D11}$$

In equations (D6) through (D11), and other equations involving angular results in degrees, the results often produce angles not within the customary range of

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0 to 360 degrees. Therefore, all angles should be converted to values within this range. Using the results from equations (D8) and (D9) the Sun's position, normalized with respect to the distance from the Sun to the Earth, can be expressed as a vector with rectangular coordinates.

$$X_s = \cos \lambda \tag{D12}$$

$$Y_s = \cos \epsilon \ \sin \lambda \tag{D13}$$

$$Z_s = \sin \epsilon \ \sin \lambda \tag{D14}$$

The solar vector in the right ascension - declination coordinate system is

$$\hat{S} = X_s \ \hat{i} + Y_s \ \hat{j} + Z_s \ \hat{k} \tag{D15}$$

The spacecraft position can be expressed in a similar manner using equations dependent on the day of the year, sun-synchronous orbit time, and the inclination angle. The time argument for these equations is (ref. 4)

$$T = (J - 2415020) / 36525 \tag{D16}$$

where T is the time in Julian centuries from the date January 0.5, 1900 and J is the Julian date. The right ascension of the Greenwich meridian at midnight can be expressed as

$$r = 99.6909833 + 36000.7689 \ T + 0.00038708 \ T^2 \tag{D17}$$

with the result falling between 0 and 360 degrees. The equation for longitude of ascending node is

$$\Omega = r + 15.0410682 \ t \tag{D18}$$

where t is the sun-synchronous orbit time in hours past midnight. Equations (D4) and (D18) can be used to calculate the spacecraft position in rectangular coordinates for a right ascension - declination coordinate system. These coordinates are

$$X_n = \sin i \ \sin \Omega \tag{D19}$$

$$Y_n = - \sin i \ \cos \Omega \tag{D20}$$

$$Z_n = \cos i \tag{D21}$$

and the corresponding vector equation

$$\hat{N} = X_n \ \hat{i} + Y_n \ \hat{j} + Z_n \ \hat{k} \tag{D22}$$

The angle between the orbit plane of the spacecraft and the solar vector can be found by taking the dot product of the two vectors in equations (D15) and (D22). This result yields the "Beta Angle", in degrees, which is one of the most important parameters for spacecraft thermal analysis.

$$\beta = 90 - \cos^{-1} (\hat{S} \cdot \hat{N}) \tag{D23}$$

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16. Abstract

The fundamentals of an Earth monitoring Sun-synchronous orbit are presented. A Sun-synchronous Orbit Analysis Program (SOAP) has been developed to calculate orbital parameters for an entire year. The output from this program provides the required input data for the TRASYS thermal radiation computer code, which in turn computes the infrared, solar and Earth albedo heat fluxes incident on a space experiment. Direct incident heat fluxes can be used as input to a generalized thermal analyzer program to size radiators and predict instrument operating temperatures. The SOAP computer code and its application to the thermal analysis methodology presented in this paper, should prove useful to the thermal engineer during the design phases of Earth monitoring Sun-synchronous space experiments.

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