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HIGH ALTITUDE SATELLITE COMMUNICATIONS, WITH CROSSLINKS.(U)  
JAN 77 P F CHRISTOPHER, E R EDELMAN

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SATELLITE COMMUNICATIONS,  
WITH CROSSLINKS

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JANUARY 1977

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ELECTRONIC SYSTEMS DIVISION  
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UNITED STATES AIR FORCE  
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	<b>Analysis and FORTRAN programs that quantitatively describe the uplink, crosslinks, and downlinks for a 10 satellite, two ground-station satellite communications system are described. The existence of each link (accounting for earth obstruction for crosslinks and coverage for up/downlinks), angles, ranges, and Dopplers are given as outputs of the programs listed in less than one minute central processing unit (CPU)</b>	

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20. Abstract (Continued)

time on a 370/158 computer. General Keplerian orbits are allowed ( $0 \leq$  eccentricity  $\leq 0.99$ ). A new analysis is presented, which results in simple estimates of orbital stability as a function of lunar perturbations. Thus, very general satellite communication orbits (altitude range 3000 to 250,000 nautical miles) can be analyzed with little additional CPU time.

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Several individuals have contributed to the work presented herein. W. T. Brandon and A. L. Cohn have recognized many interesting features of crosslinks which served as a valuable background. H. B. Gershman provided the impetus for a convenient local satellite coordinate system which appears in program SATLUNAE (App. 6). He later used this coordinate system to study the effects of satellite obstructions on crosslink antenna pointing. E. E. Crampton's continuing interest in the development of the programs (App. 1-9) resulted in a short, efficient subroutine for the solution of Kepler's equation for high eccentricity. He also developed an alternate solution to ground station azimuth angle which is a valuable check for the program AZ1 (App. 8).

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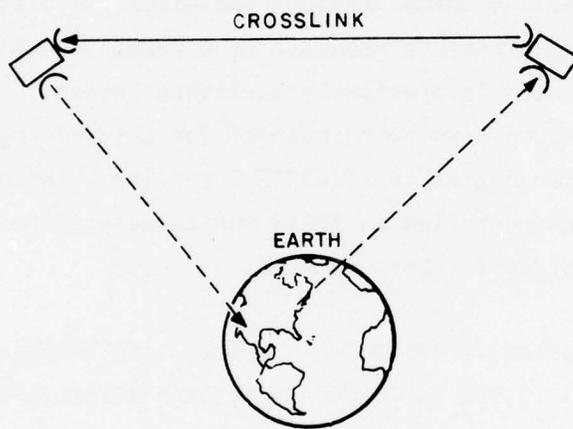
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## INTRODUCTION AND SUMMARY

This report gives a quantitative description of the uplinks, crosslinks, and downlinks of a general high altitude satellite system. The analysis was performed at intervals during 1973 and 1974, in support of the Electronic Systems Division (ESD) responsibility to define a high altitude, crosslinked system of satellites for the Air Force Satellite Communications (AFSATCOM) II program. Specific quantitative results provided as a result of this effort have been incorporated in previously published reports. The computer programs have also been employed for determining test sites having low elevation angles in AFSATCOM I testing. The present report documents the detailed analysis and associated computer programs, and provides further examples.

Efforts to define an AFSATCOM II system have required analysis of medium altitude (3,000 to 20,000 nmi), high altitude (20,000 to 250,000 nmi), and highly eccentric (eccentricity  $>0.7$ ) orbits. Various system concepts also employed satellite to satellite links or crosslinks as shown in Figure 1. While there were some computer programs available for problems in each class of orbit, there were severe limitations on their utility in context of the AFSATCOM system problem. Close analysis of such a general satellite communication system (uplinks, crosslinks, and downlinks) has been going on only for the past few years.

Principal, significant results of the work described in this report are:



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Figure 1 A GENERAL SATELLITE COMMUNICATIONS LINK INCLUDING CROSSLINK

- Analytic solution for high altitude lunar perturbations, which has allowed study of a wide range of orbit parameters because of the resulting programs are less costly to run than previously used numerical integration programs.

This led to a conclusion in a particular case that 12-day retrograde orbits have stability comparable to 10-day posigrade orbits.

- Computer programs, which offer the following extensions in comparison to other programs known to us:
  1. Unified uplink, crosslink, downlink analysis in a single program.
  2. Programs which handle high eccentricity orbits efficiently.
  3. Allowance for incorporation of vector antenna radiation patterns for precise received power at the ground terminals.
  4. Low central processing unit (CPU) time requirements to run the programs. For example, less than 30 seconds CPU time (IBM 370/158) is required for uplinks, crosslinks, and downlinks for two ground stations and 10 satellites.
- Coverage of multiple satellites.

Part I of the report includes a simple two-body analysis (satellite, earth), which is a good basis for the communications engineer in designing orbital links of 3000 to 20,000 nautical miles (nmi) altitude. General Keplerian orbits are analyzed with the aid of a notably efficient iterative solution to Kepler's equation.

Part II considers orbital altitudes between 20,000 to 250,000 nmi. Analysis of higher eccentricity orbits was achieved through use of a Taylor series expansion of eccentric anomaly, which allows both analysis of a higher eccentricity and lower CPU time than standard methods.

Analysis of high altitude orbits had been previously carried out using a numerical integration program.<sup>[1]</sup> For altitudes greater than approximately 20,000 nmi, lunar and solar perturbations significantly disturb the satellite orbit.\* Results had shown that retrograde equatorial satellite orbits are more stable than posigrade orbits. A new approach was adopted of combining perturbed orbital elements to provide an analytic solution to orbit perturbation and resulting stability.

Derivation of the rate of change of semi-major axis has provided physical insight into the mechanism which causes satellites moving retrograde with respect to the moon's motion to be more stable than those moving posigrade. This result had been inexplicable previously. As noted above, the low running cost of the program has allowed more extensive analysis of orbits for stability. As in Part I, the uplink, crosslink, and downlink analysis is reduced to a program.

Examples of the use of Part I and II programs are given in Part III. Computer programs are listed and described in Appendices 1 through 9. The table of contents identifies the author of each program. A portion of the above programs was used to generate a succinct program for coverage in a multiple satellite system (Example 3 in Part III and Appendix 9).

The programs are intended for actual communications link analysis. The positions of all stations and satellites are retained in vector form in the programs so that antenna gain patterns can be added later for specific link calculations. It is expected that these programs will be useful in high altitude satellite communications planning. In addition, the low CPU time of the attached programs may allow a spacecraft with limited processing capability to autonomously calculate its own available communications links.

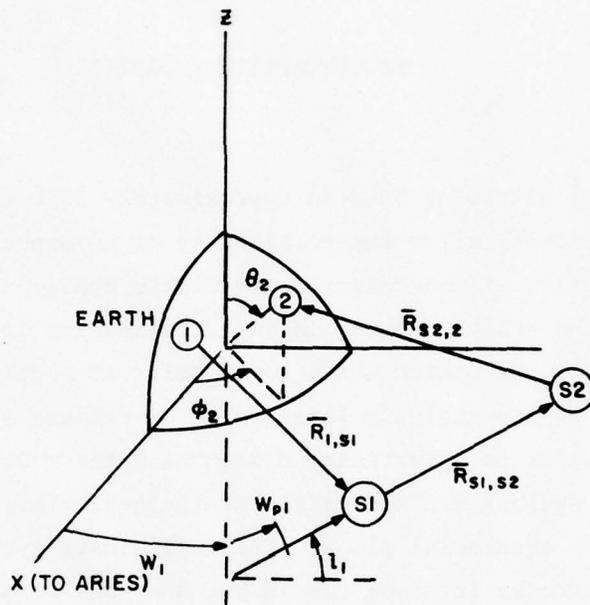
## PART I

### MEDIUM ALTITUDE ORBITS

Orbital altitudes between approximately 3000 to 20,000 nmi (medium altitude) allow the possibility of an especially simple orbit analysis. A non-rotating coordinate system is chosen as a basis for the analysis to avoid any acceleration problems inherent in the coordinate system which would arise if Doppler rates were added to the analysis later. The coordinate system is shown in Figure 2; it is a Cartesian system with the x axis pointing to the vernal equinox and the origin at the geocenter. The x - y plane is the equatorial plane. This coordinate system translates with the earth as it moves around the sun, but does not rotate. Aries (the direction of the x-axis and the vernal equinox) is so far away that movements of the earth around the sun cause insignificant changes in direction of the axes.

In Figure 2, note that all four sites are moving. The ground stations are rotating with the earth at  $15^\circ/\text{hr}$ , and the motion of the satellites is determined by Kepler's laws.

A convenient starting point for an orbital analysis (time =  $T = 0$  hrs) can occur when earth coordinates equal celestial coordinates. This occurs at 12 noon Greenwich mean time (GMT) on March 21. Immediately after, the inertial longitude of an earth station will be greater than the earth coordinates.



ONE WAY TO LINK GROUND STATIONS 1 AND 2 IS SHOWN. THE COORDINATE SYSTEM IS STATIONARY, BUT ALL FOUR SITES ARE MOVING. THE ORBIT OF SATELLITE S1 CAN BE COMPLETELY DESCRIBED FOR KEPLERIAN ORBITS BY

- $w_1$  = RIGHT ASCENSION, DEGREES
- $i_1$  = INCLINATION WITH RESPECT TO THE EQUATORIAL PLANE, DEGREES
- $w_{p1}$  = ARGUMENT OF PERIGEE, DEGREES
- $T_{p1}$  = TIME OF PERIGEE, HOURS
- $a$  = SEMIMAJOR AXIS, NAUTICAL MILES (OR, IN KM BY MULTIPLYING THE SEMIMAJOR AXIS BY 1.852)
- $e$  = ECCENTRICITY, WHERE  $0 \leq e < 1$ . AT  $e = 0$ , THE ORBIT IS CIRCULAR

IA-45,619

Figure 2 GEOMETRY OF A TWO SATELLITE, TWO GROUND STATION SYSTEM

## 1.1 MOTION OF THE SATELLITE

Only elliptical orbits are considered here, because a circular orbit can be considered a degenerate ellipse. Kepler's laws of planetary motion can be abbreviated as:<sup>[2]</sup>

1. The orbit of a satellite is an ellipse, with the earth's center (geocenter) at one of the foci:

$$R = \frac{P}{1+e} \cos \theta \quad (1-1)$$

The parameters are shown in Figure 3.

2. In the coordinate system of Figure 4 (called the prime system in the remainder of the discussion), the radius vector of each satellite sweeps through equal areas in equal times:

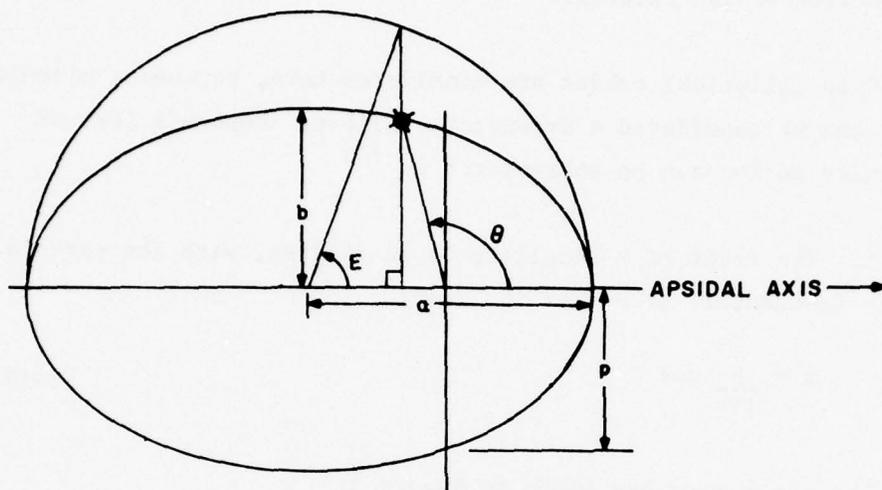
$$R^2 \dot{\theta} = \text{constant} = \sqrt{\mu p} \quad \text{where } \mu = Gm_e \quad (1-2)$$

= earth's gravitational constant.

3. The squares of the periods of the satellites are to each other as the cubes of the semi-major axes of their respective orbits:

$$\frac{\tau_1^2}{a_1^3} = \frac{\tau_2^2}{a_2^3} \quad (1-3)$$

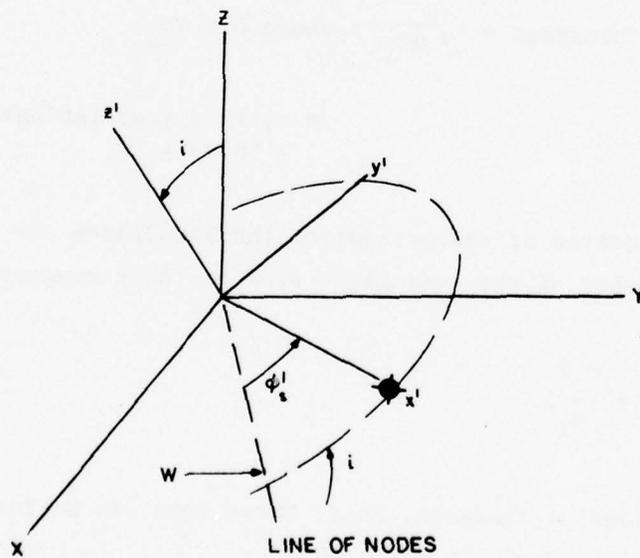
After extensive analysis, these three laws can be interpreted as a single equation (Kepler's equation):



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THE COORDINATE SYSTEM IS AT ONE FOCUS (GEOCENTER) OF THE ELLIPTICAL ORBIT

Figure 3 RELATION OF TRUE ANOMALY  $\theta$  TO ECCENTRIC ANOMALY  $E$



IA-45,622

Figure 4 ROTATIONS THROUGH THREE EULER ANGLES AND THEIR RELATION TO THE SATELLITE ON THE  $x'$  AXIS

$$M = E - e \sin E \quad (1-4)$$

where  $M$  = mean eccentric anomaly =  $n(t-t_p)$   
 $n$  = mean angular rate  
 $t$  = time, hrs  
 $t_p$  = time at perigee  
 $e$  = eccentricity  
and  $E$  = eccentric anomaly.

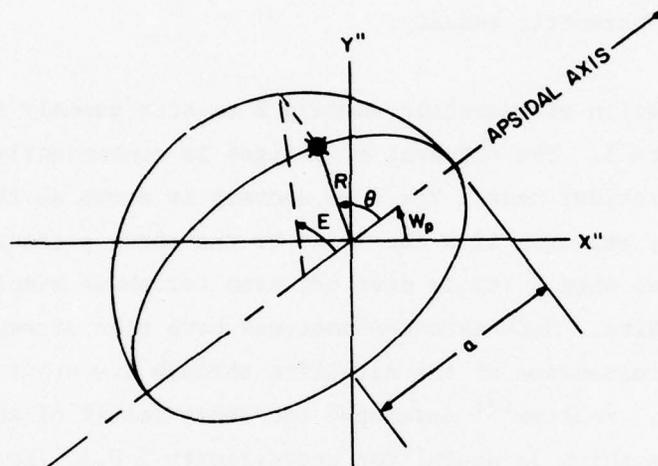
The relation of eccentric anomaly  $E$  to true anomaly  $\theta$  can be seen in Figure 5. The argument of perigee is conveniently located here on the apsidal axis. The true anomaly is shown as the angle from perigee, measured from the focus at the earth's center. Serious problems arise when  $\theta(t)$  is desired, even for these simple Keplerian orbits. Many extended analyses have been attempted to describe the progression of the satellite through its orbit as a function of time. Moulton<sup>[3]</sup> developed one short result of an important analysis which is useful for eccentricity  $\lesssim 0.5$ . Eccentricities greater than 0.5 were desired for this analysis and for most of these programs, however.

A direct attack on Kepler's equation (Equation (1-4)) has been employed. Although the Kepler equation is transcendental, an initial guess at eccentric anomaly

$$E_1 \doteq M + e \sin M \quad (1-5)$$

enables one to take a second, much more accurate estimate,

$$E_2 \doteq \frac{M + e (\sin E_1 - (e \cos E_1) E_1)}{1 - e \cos (E_1)} \quad (1-6)$$



IA-45,623 THE DOUBLE PRIME COORDINATE SYSTEM IS STATIONARY, WITH THE  $x''$  AXIS ON THE LINE OF NODES (EQUATORIAL PLANE AND ORBITAL PLANE)  
 $\theta$  = TRUE ANOMALY  
 $R$  = GEOCENTRIC DISTANCE OF SATELLITE  
 $w_p$  = ARGUMENT OF PERIGEE  
 $E$  = ECCENTRIC ANOMALY  
 $\phi'_s = w + \theta$

Figure 5 MOTION IN THE ORBITAL PLANE

This estimate for  $E_2$  is the result of linearizing Kepler's equation by means of a Taylor series expansion. All terms beyond the first power in  $E_1$  are neglected. More estimates for eccentric anomaly can be similarly made (e.g.,  $E_3$  as a function of  $E_2$ ). When differences of successive approximations are adequately small,  $E_3$  can be accepted as the solution for  $E$ . The true anomaly  $\theta$  is related<sup>[2]</sup> to the eccentric anomaly by

$$\theta = \cos^{-1} \left( \frac{\cos E - e}{1 - e \cos E} \right) \quad (1-7)$$

This true anomaly will be needed to accurately determine the time-varying position of the satellite on its prescribed ellipse. The range from the geocenter is given as

$$R = \frac{a(1 - e^2)}{1 + e \cos \theta} \quad (1-8)$$

These relations (Equations (1-5) to (1-8)) are implemented in subroutine ELLIP of the computer programs. The iterations for  $E$  are surprisingly fast; representatively, they are as fast as Moulton's esoteric development, which was meant expressly to free the early twentieth century analyst from laborious computations. The advantage over Moulton's development is that the programs can handle eccentricity from 0 to 0.99. The subroutine ELLIP can be forced into seven iterations at  $e = 0.99$ . This iterative technique requires less CPU time than a standard procedure.<sup>[4]</sup> In the subroutine,  $M$  becomes

$$z = \frac{2\pi(t - t_p)}{\tau} = \text{mean angular rate, radians.}$$

Also,  $\phi'_s = Wp + \theta$  since  $\theta$  is measured from the argument of perigee, but  $\phi'_s$  is measured from the line of nodes where the orbital plane intersects the equatorial plane.

## 1.2 COORDINATE TRANSFORMATIONS

In the previous section, it was found convenient to describe angular motion (true anomaly  $\theta$ ) in the plane of the satellite. However, after a position (or a velocity) in the satellite plane has been found, it should be converted back into an inertial coordinate system, which is required for correct interstation vectors.

Fortunately, a coordinate transformation that compares directly to the needs here has been extensively analyzed.<sup>[5]</sup> This transformation makes use of the Euler angles. The first Euler angle occurs with a rotation about the z axis. See Figure 6, where the nomenclature of Goldstein is used. This first rotation through W will correspond to right ascension for this analysis.

The second rotation occurs about  $\xi$ ; again, this rotation is counterclockwise. This rotation is an angle  $i$ , where  $i$  here corresponds to orbital inclination. Finally, a rotation ( $\phi'_s$ ) in the orbital plane can occur which is measured from the line of nodes. See Figure 4.

The three rotations define a new (PRIME) coordinate system ( $x', y', z'$ ). For the purpose of this analysis, the  $x'$  axis is a radius vector from the geocenter to the satellite.

The transformation of a vector  $\underline{x}'$  in the prime coordinate system to the inertial system can be expressed in matrix form as

$$\underline{x}' = \underline{A} \underline{x}$$

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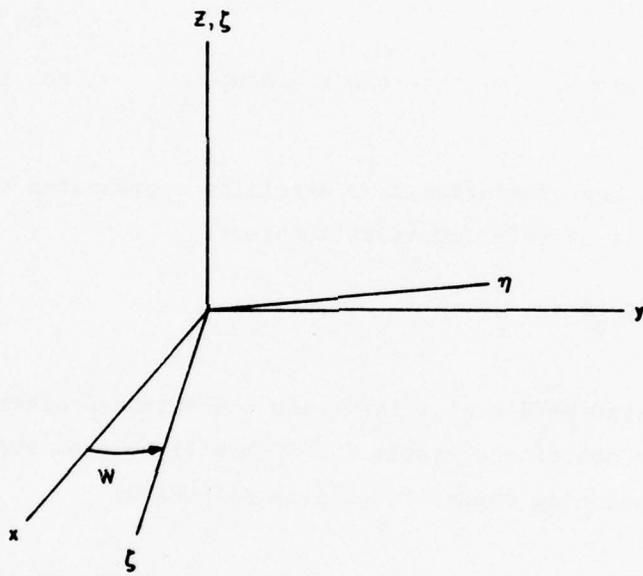


Figure 6 THE FIRST ROTATION OF EULER ANGLE W ABOUT THE Z AXIS

and A is the product of three separate matrices, B, C, and D. Omit Goldstein's intermediate steps,

$$\begin{aligned} & \cos \phi'_s \cos W - \cos i \sin W \sin \phi'_s, \quad \cos \phi'_s \sin W + \cos i \cos W \sin \phi'_s, \\ & \hspace{20em} + \sin W \sin i \\ \underline{A} = & \begin{matrix} -\sin \phi'_s \cos W - \cos i \sin W \cos \phi'_s & -\sin \phi'_s \sin W + \cos i \cos W \cos \phi'_s, \\ & \cos \phi'_s \sin i \\ \sin i \sin W, & -\sin i \cos W, & \cos i \end{matrix} \quad (1-9) \end{aligned}$$

and the inverse transformation from satellite coordinates to the inertial frame is of more immediate interest:

$$\underline{x} = \underline{A}^{-1} \underline{x}^1$$

(A subroutine UNPRIM will later use the matrix A directly for a local satellite coordinate system. UNPRIM will be used specifically for crosslink pointing angles in program SATLUNAE.)

A<sup>-1</sup> is found from the transpose of A because the magnitude of A is unity. The elements of A<sup>-1</sup> are then

$$a_{11} = \cos \phi'_s \cos W - \cos i \sin W \sin \phi'_s$$

$$a_{12} = -\sin \phi'_s \cos W - \cos i \sin W \cos \phi'_s$$

$$a_{13} = \sin i \sin W$$

$$a_{21} = \cos \phi'_s \sin W + \cos i \cos W \sin \phi'_s$$

$$a_{22} = -\sin \phi'_s \sin W + \cos i \cos W \cos \phi'_s$$

$$a_{23} = -\sin i \cos W$$

$$a_{31} = \sin i \sin \phi'_s$$

$$a_{32} = \sin i \cos \phi'_s$$

$$a_{33} = \cos i \tag{1-10}$$

The subscripts refer to row and column.

All of these elements except  $a_{13}$ ,  $a_{23}$  and  $a_{33}$  are inserted into the attached subroutine PRIME. They are omitted because there is no z component for satellite coordinate.

An example of the calling of subroutine PRIME can be useful. If the position of Satellite #8 in its own coordinate system is specified by  $x' = R8$ ,  $y' = 0.$ ,  $z' = 0.$ , this information must be sent to PRIME along with the three angles specifying the coordinate transformation. The angle of the satellite from the line of nodes is FSP, the right ascension is W8, and the inclination is x18 for the purpose of this example. The attached programs call PRIME in the following way.

```
CALL PRIME (FSP, W8, x18, R8, 0., xs, ys, zs).  
           input variables  output variables
```

The output variables xs, ys, and zs represent position in inertial space. The position will be useful in getting crosslink and downlink vectors.

A slightly different form of coordinate conversion will be required for range rate. When it is discussed later, it should not be confused with the prime coordinate system in which the  $x'$  axis is pointed through the satellite. It will use a stationary  $x''$  axis pointed along the line of nodes.

### 1.3 DOPPLER ANALYSIS

In a central force field such as that assumed for Keplerian orbits, the velocity of a satellite is dependent only on the magnitude of its radius vector once its initial conditions have been determined. Similarly, it is also determined by  $\theta$  (its angle measured from perigee) since  $R(\theta)$  is determined by the Keplerian ellipse. Expressions directly related to velocity<sup>[2]</sup> are

$$\dot{R} = \frac{(2\pi A e)}{\tau \sqrt{1-e^2}} \sin \theta \quad (1-11)$$

and

$$\dot{\theta} = \frac{2\pi (1 + e \cos \theta)^2}{\tau (1-e^2)^{3/2}} \quad (1-12)$$

The geometry is given by Figure 6,

where  $\phi'_s = \theta + W_p$ ,  $W_p$  = argument of perigee

and  $(\dot{\phi}'_s) = \dot{\theta}$ .

The  $x''$  axis is stationary and lies in the equatorial plane.

Further, the derivatives of the position vector (with the  $x''$  axis now lying along the line of nodes and the  $y''$  axis  $90^\circ$  ahead in the orbit plane) can give the  $x''$  component of velocity and the  $y''$  component of velocity. The symbol  $\phi'_s$  is later changed to FSP so it can be more directly related to the FORTRAN programs.

$$x'' \text{ component} = \left(\frac{1}{3600}\right) (\dot{R} \cos(\phi'_s) - R \dot{\theta} \sin(\phi'_s)) \text{ nmi/sec} \quad (1-13)$$

and

$$y'' \text{ component} = \left(\frac{1}{3600}\right) (\dot{R} \sin(\phi'_s) + R \dot{\theta} \cos(\phi'_s)) \text{ nmi/sec} \quad (1-14)$$

To convert these velocity components to components in the inertial system, the general coordinate conversion (PRIME) can be called, but with  $\phi'_s = 0$ , because the  $x''$  axis does not rotate with the satellite in this case. Velocity components are found in the subroutine DOPE of the attached programs. This stationary  $x''$  axis was not required for range rate but will be desirable if  $\ddot{R}$  is analyzed.

The velocities of the earth stations are straightforward.

$$\dot{x}_1 = \frac{-\omega}{3600} R_e \sin \theta_1 \sin \phi_1$$

$$\dot{y}_1 = \frac{\omega}{3600} R_e \sin \theta_1 \cos \phi_1$$

where

$$\omega = \frac{15^\circ/\text{hr}}{57.296} \text{ earth rotation rate, rad/hr} *$$

---

\*Note that the distinction between solar hours and sidereal hours is not retained here because only three place accuracy is desired in the answers.

$\dot{z}_1 = 0$  because rotation is about the z axis.

The background for velocities of satellites and earth stations is now concluded. The relation of velocities to uplink and crosslink Doppler shift is of more interest to the communications engineer than velocities per se.

The relation of a Doppler shifted frequency to the transmitted frequency is shown by Jackson<sup>[6]</sup> to be

$$F' = \frac{F}{\sqrt{1 - \frac{v_R^2}{c^2}}} \left(1 - \frac{v_R}{c} \cos \theta_j\right) \quad (1-15a)$$

Where  $v_R$  is relative velocity between transmitter and receiver and  $\theta_j$  is the angle between the relative velocity vector and the pointing vector between transmitter and receiver.

This expression includes the (relativistic) transverse Doppler shift which may be of interest for crosslink Doppler. For  $v_R \ll c$ , Equation (1-15a) becomes

$$F' = F \left(1 + \frac{1}{2} \frac{v_R^2}{c^2}\right) \left(1 - \frac{v_R}{c} \cos \theta_j\right) \quad (1-15b)$$

or

$$\Delta F = \text{Doppler shift} = F \left(\frac{1}{2} \frac{v_R^2}{c^2}\right) - \frac{F}{c} (v_R \cos \theta_j) \quad (1-15c)$$

The two components are called transverse Doppler shift and ordinary Doppler shift, respectively. At synchronous altitude, the transverse Doppler shift can be of the order of (first term of Equation (1-15c))

$$(35 \times 10^9 \text{ Hz}) \left( \frac{1}{2} \left( \frac{1.655 \text{ nmi/sec}}{1.6198 \times 10^5 \text{ nmi/sec}} \right)^2 \right) = 1.82 \text{ Hz at K band.}$$

This is so small, even with a millimeter wave carrier, that transverse Doppler is dropped for the remainder of the discussion and in the computer programs (Appendices 1-9).

The ordinary Doppler shift is

$$F = -\frac{F}{C} (v_R \cos \theta_j)$$

In order to get  $(\cos \theta_j)$ , the relative velocity vector  $\bar{v}$  is found by taking differences of velocity components in the inertial frame:

$$\bar{v}_R = (\dot{x}_2 - \dot{x}_1) \bar{i} + (\dot{y}_2 - \dot{y}_1) \bar{j} + (\dot{z}_2 - \dot{z}_1) \bar{k}$$

By vector analysis,

$$v_R (\cos \theta_j) = \bar{v}_R \cdot \bar{P}_{12}$$

where

$$\bar{P}_{12} = \text{unit vector which points from transmitter to receiver.}$$

$$= \frac{(x_2 - x_1) \bar{i} + (y_2 - y_1) \bar{j} + (z_2 - z_1) \bar{k}}{R_{12}}$$

so,

$$V_R (\cos \theta_j) = \bar{v}_R \cdot \bar{P}_{12} = \frac{(\dot{x}_2 - \dot{x}_1)(x_2 - x_1) + (\dot{y}_2 - \dot{y}_1)(y_2 - y_1) + (\dot{z}_2 - \dot{z}_1)(z_2 - z_1)}{R_{12}}$$

(1-16)

and the one-way Doppler shift can be found by substituting this result, Equation (1-16), into

$$\Delta F = \frac{F}{C} (v_R \cos \theta_j).$$

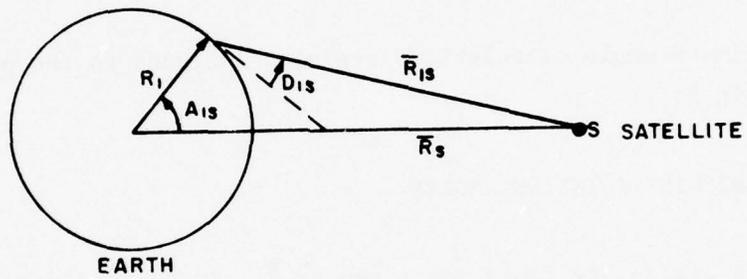
This calculation is done in the attached programs after the sub-routine DOPE is called.

#### 1.4 ELEVATION ANGLE

The elevation angle for the ground station antenna is important to the communications engineer in many ways: (1) it serves as a check for satellite visibility; (2) it can give an estimate of mean atmospheric attenuation of signal strength and (3) its derivative is useful in an estimate of antenna slewing rate. Only the elevation angle is treated here, and not its derivative.

Elevation angle is found by noticing the following geometry, which is in the plane of the ground station position vector and the satellite position vector (Figure 7).

The geocentric angle  $A_{13}$  can be found by taking the dot product  $\bar{R}_1, \bar{R}_{1S}$ :



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Figure 7 ELEVATION ANGLE  $D_{1s}$

$$A_{1S} = \cos^{-1} \left( \frac{(x_1 x_s + y_1 y_s + z_1 z_s)}{R_e R_s} \right) \quad (1-17)$$

with the aid of the law of sines, the elevation angle

$$D_{1S} = \sin^{-1} \left( (\sin A_{1S}) \frac{R_s}{R_{1S}} - \pi/2 \right) \quad (1-18)$$

is found. A sign check for  $D_{1S}$  is still necessary because the obtuse angle  $(D_{1S} + \pi/2)$  in Figure 7 is read as  $(\pi/2 - D_1)$  by the computer. It cannot distinguish between sines of the first and second quadrants.

Azimuth angle calculations are also included in the program AZ1 (Appendix 8).

#### 1.5 CROSSLINK POINTING ANGLES

The angles are found for a vector  $\bar{R}_{89}$  in a coordinate system centered at Satellite #8. The coordinate system has axes parallel to the inertial coordinate system. This kind of coordinate system makes sense only if the satellite has to know the directions of the inertial axes anyway. Otherwise, the coordinate system is a local satellite coordinate system (shown as angles TU12 and FU12 of the program SATLUNAE in Appendix 6).

The angles are found in terms of local longitude and colatitude.

$$\text{Colatitude } \theta_{S1,S2} = \cos^{-1} \left( \frac{z_{S2} - z_{S1}}{R_{S1, S2}} \right) \quad (1-19)$$

$$\text{Longitude } \phi_{S1,S2} = \tan^{-1} \left( \frac{y_{S2} - y_{S1}}{x_{S2} - x_{S1}} \right) \quad (1-20)$$

These angles are found near the end of the main part of the programs. Again, some sign tests must occur because the computer has trouble with correct quadrants. Another problem, which is merely inconvenient, remains: Longitudes less than  $-360^\circ$  sometimes occur. If this is too inconvenient for the user, a two-line logical check can be done as on lines 662 and 664 of the program AZ1 (Appendix 8).

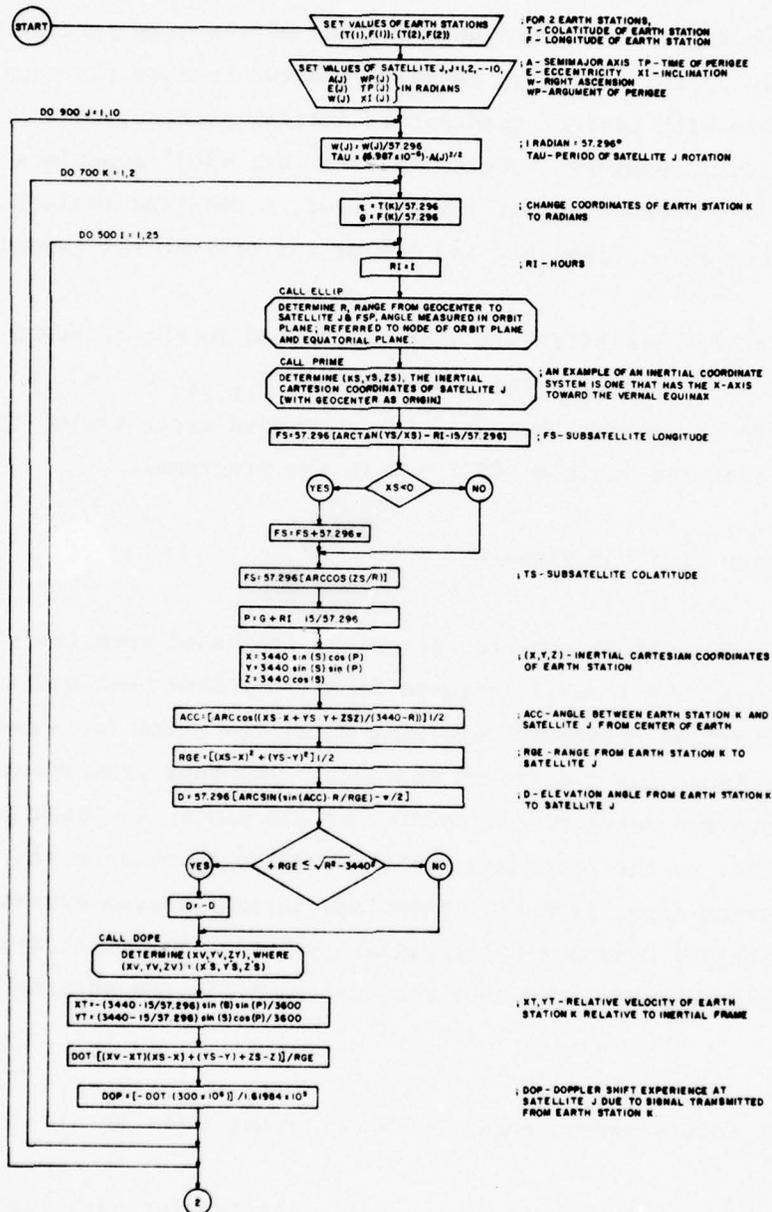
Crosslink visibility is also calculated in the attached programs. It is found by checking the angle between  $\bar{R}_{1S,2S}$  and  $(-\bar{R}_{1S})$ ; if this angle is greater than half the subtended earth angle, the crosslink is declared visible (CVIS = 1 in the programs).

#### 1.6 MEDIUM ALTITUDE PROGRAMS

Four FORTRAN IV computer programs, all based upon the flowchart listed on Blocks 1 and 2 (Figures 8a and 8b) have been written to examine various relations regarding satellite links for a maximum of ten satellites and two ground stations. The four programs may be divided into two categories according to the manner in which input data is supplied to the program: those for which input data are supplied by answering input prompting questions during program execution at a Time Sharing Option (TSO) terminal and those for which input data are supplied by changing the data statements within the program before execution.

All four programs require the following input data:

1. The semi-major axis in nautical miles for each satellite.
2. The eccentricity for each satellite.
3. The right ascension in degrees for each satellite.
4. The argument of perigee in degrees for each satellite.
5. The time of perigee in hours for each satellite.



[C-45.726]

Figure 8a FLOWCHART, BLOCK I

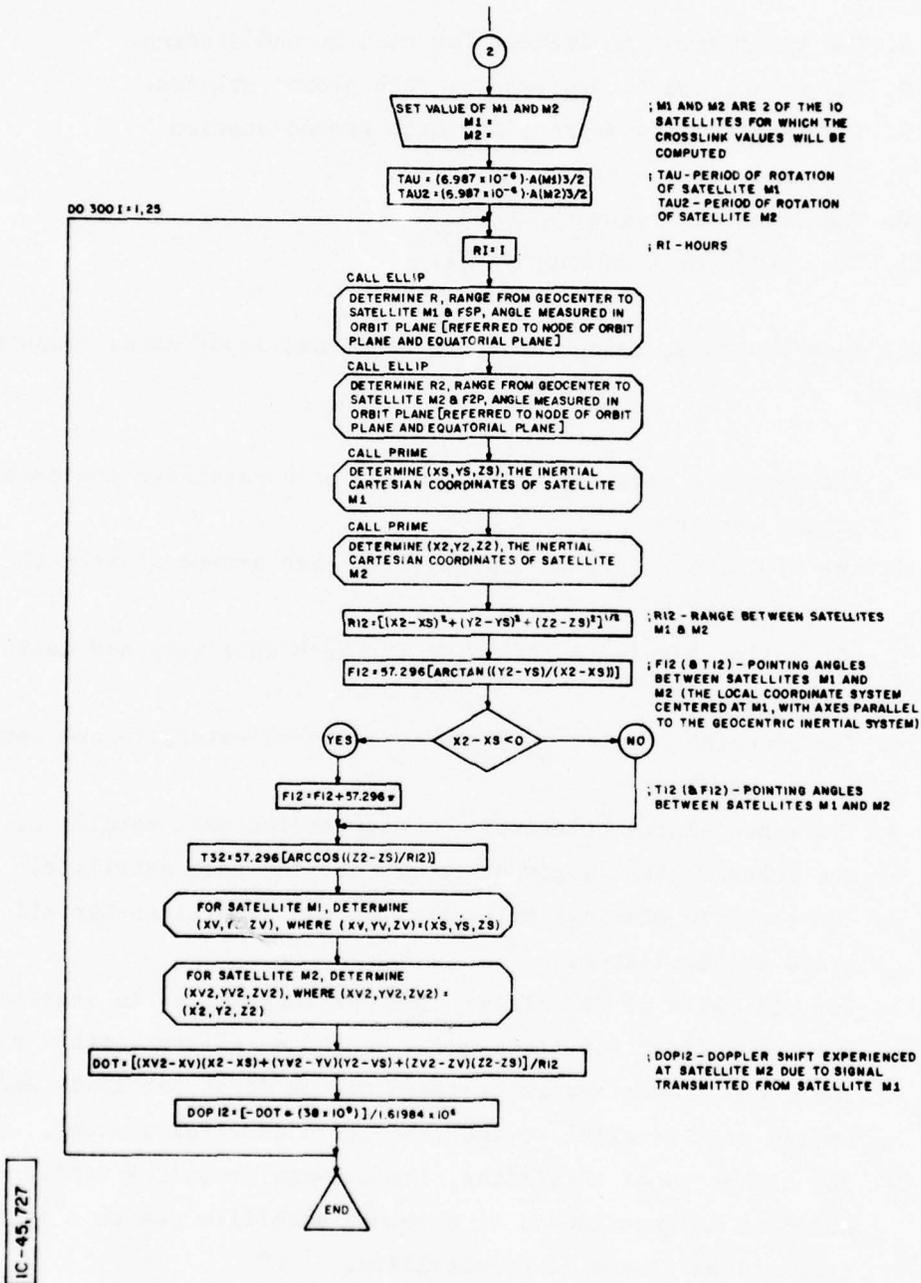


Figure 8b FLOWCHART, BLOCK 2

6. The inclination in degrees for each ground station.
7. The colatitude in degrees for each ground station.
8. The longitude in degrees for each ground station.
9. The uplink frequency in Hz.
10. The downlink frequency in Hz.
11. The crosslink frequency in Hz.

All four programs, using the above-mentioned input data, compute the following:

1. The range in nautical miles between each satellite and each ground station.
2. The elevation angle in degrees from each ground station to each satellite.
3. The uplink Doppler shift in Hz for each satellite and each ground station.
4. The downlink Doppler shift in Hz for each satellite and each ground station.
5. The subsatellite colatitude in degrees for each satellite.
6. The subsatellite longitude in degrees for each satellite.
7. The range in nautical miles between two satellites for all pairs of satellites.
8. For all pairs of satellites, the pointing angles in degrees between a first satellite and a second satellite (with the local coordinate system centered at the first satellite and having axes parallel to the geocentric inertial system).
9. For all pairs of satellites, the one-way crosslink Doppler shift in Hz experienced at a second satellite due to a signal transmitted from a first satellite.
10. The crosslink visibility between two satellites for all pairs of satellites.

#### 1.6.1 SATE (Appendix 1)

The first program listed has been entered on TSO, and may be executed either in the foreground\* with the output printed at the terminal or in the background with the output printed on the high speed printer. Input data is entered in this program by changing the data statements within the program before execution.

#### 1.6.2 SATD (Appendix 2)

The second program listed is simply the double precision version of SATE; that is to say, SATD has the same attributes as SATE except for the fact that it has a precision of approximately 16 decimal digits as opposed to the precision of approximately seven decimal digits of SATE. Because of this increased accuracy, SATD has a running time longer than that of SATE.

#### 1.6.3 SATVIZE (Appendix 3)

The third program listed has also been entered on TSO but, unlike the two above-mentioned programs, is on-line foreground executable only with output being printed at the terminal. Also, the necessary input data in this program are entered during program execution merely by answering the input prompting questions supplied by the program. For the casual user, default values and points for stopping various parts of program execution have been incorporated within the program.

---

\*To run this program in the foreground, lines 10 to 40 inclusive must be deleted first.

1.6.4 SATVIZD (Appendix 4)

The fourth program listed is merely the double precision version of SATVIZE. Because of its increased precision, SATVIZD, like SATD, has a running time longer than that of its single precision counterpart.

## PART II

### HIGH ALTITUDE SATELLITES WITH LUNAR PERTURBATIONS

Conventional three-body (earth-moon-satellite) perturbation analysis can consume great amounts of computer time with concomitant expense. For example, the carefully planned and very extensive Lincoln Laboratory Planetary Ephemeris Program (PEP) can perform numerical integrations of satellite motion, including the perturbations of the satellite orbit by many non-terrestrial bodies. The implicit penalty of this program is its expense. The disadvantages of numerical integration become even more marked for a multiple satellite communications system. For these reasons, and to account for long term lunar perturbations, programs incorporate existing short analytic (i.e., closed-form) results. Dr. M. Ash's elegant and useful analytic results<sup>[1]</sup> for variation of right ascension, argument of perigee, and eccentricity are combined with a short approximate result for the time rate of change of a semi-major axis which we developed. A changing semi-major axis can account for the difference in stability of posigrade and retrograde orbits.

The programs discussed and listed in this section (Appendices 5-7) are the only ones known to us that can be used to estimate orbital stability with modest computation time, while noting the difference between posigrade and retrograde orbits.

#### 2.1 ANALYSIS

One way to avoid extensive computations for the position of a satellite in a non-Keplerian orbit is to describe the fundamental

motion at any time as Keplerian with defined orbital elements. However, these orbital elements can be allowed to change as a function of the perturbing forces. When the Keplerian motion is elliptical, the corresponding orbital elements for perturbed motion are called "osculating" elliptic orbital elements.

With a few changes to the nomenclature of Ash,

$$\begin{aligned}
 a &= \text{semi-major axis} \\
 e &= \text{eccentricity} \\
 I &= \text{inclination with respect to lunar plane} \\
 \Omega &= \text{right ascension of ascending node on lunar plane} \\
 W_p &= \text{argument of perigee} \\
 M &= \text{mean anomaly} \\
 \mu_m &= \text{gravitational constant times lunar mass} \\
 \mu &= \text{gravitational constant times mass of earth} \\
 n &= \mu^{1/2} a^{-3/2} = \text{mean motion, rad/hr} \\
 \theta &= \text{true anomaly} \\
 p &= \text{semi-latus rectum} \\
 r &= \frac{p}{1 + e \cos \psi} = \text{radius from geocenter} \\
 \rho &= \text{lunar radius} \\
 \eta &= \theta + W_p
 \end{aligned}$$

Further, if  $\tilde{R}$ ,  $\tilde{S}$ , and  $\tilde{W}$  are the three orthogonal perturbation force components ( $\tilde{R}$  along radius vector from geocenter,  $\tilde{S}$  close to the velocity vector, and  $\tilde{W}$  completing the right handed coordinate system) for a lunar mass spread into a torus at lunar altitude, Ash derived the relations for  $\tilde{R}$ ,  $\tilde{S}$ ,  $\tilde{W}$  given by Equations (2-1), (2-2) and (2-3).

$$\tilde{R} = \frac{\mu_m}{\rho^2} \sum_{\ell=1}^{\infty} 2\ell \left(\frac{r}{\rho}\right)^{2\ell-1} \sum_{k=0}^{\ell} (-1)^{k+\ell} \frac{1 \cdot 3 \cdot 5 \cdots (2k+2\ell-1)}{(\ell-k)! 2^{\ell+k} k!}$$

$$\cdot \sum_{m=0}^k \frac{(\cos I)^{2k-2m}}{m! (k-m)!} (\cos \eta)^{2m} (\sin \eta)^{2k-2m} \quad (2-1)$$

$$\tilde{S} = \frac{\mu_m}{\rho^2} \sum_{\ell=1}^{\infty} \left(\frac{r}{\rho}\right)^{2\ell-1} \sum_{k=1}^{\ell} (-1)^{k+\ell} \frac{1 \cdot 3 \cdot 5 \cdots (2k+2\ell-1)}{(\ell-k)! 2^{\ell+k} k!}$$

$$\cdot \sum_{m=0}^k \frac{(\cos I)^{2k-2m}}{m! (k-m)!} [(2k-2m) (\cos \eta)^{2m+1} (\sin \eta)^{2k-2m-1}$$

$$-2m(\cos \eta)^{2m-1} (\sin \eta)^{2k-2m+1}] \quad (2-2)$$

$$\tilde{W} = \frac{-\mu_m \sin I}{\rho^2} \sum_{\ell=1}^{\infty} \left(\frac{r}{\rho}\right)^{2\ell-1} \sum_{k=1}^{\ell} (-1)^{k+\ell} \frac{1 \cdot 3 \cdot 5 \cdots (2k+2\ell-1)}{(\ell-k)! 2^{\ell+k} k!}$$

$$\cdot \sum_{m=0}^{k-1} \frac{(2k-2m)}{m! (k-m)!} (\cos I)^{2k-2m-1} (\cos \eta)^{2m} (\sin \eta)^{2k-2m-1} \quad (2-3)$$

When Equations (2-1), (2-2), and (2-3) are substituted into Gauss' form of the equation of the osculating elements and extensive operations are performed, Ash finds the change of right ascension, eccentricity, and argument of perigee. Change in semi-major axis and inclination were deemed negligible.

The changes in right ascension, eccentricity, and argument of perigee per orbit were found to be:

$$\begin{aligned} \Delta W = & 2\pi \left(\frac{\mu_m}{\mu}\right) \left(\frac{a}{\rho}\right)^3 \cos I \left\{ \frac{3}{4} + \left(\frac{a}{\rho}\right)^2 \left[ -\frac{135}{128} + \frac{315}{128} \cos^2 I \right] \right. \\ & \left. + \left(\frac{a}{\rho}\right)^4 \left[ \frac{2625}{2048} - \frac{7875}{1024} \cos^2 I + \frac{17325}{2048} \cos^4 I \right] + \dots \right\} \quad (2-4) \end{aligned}$$

$$\begin{aligned} \Delta e = & -\pi \left(\frac{\mu_m}{\mu}\right) \left(\frac{a}{\rho}\right)^3 e \sin(2W_p) \left\{ -\frac{15}{4} \sin^2 I \right. \\ & \left. + \left(\frac{a}{\rho}\right)^2 \left[ \frac{315}{128} - \frac{315}{16} \cos^2 I + \frac{2205}{128} \cos^4 I \right] + \dots \right\} \quad (2-5) \end{aligned}$$

$$\begin{aligned} \Delta W_p = & \pi \left(\frac{\mu_m}{\mu}\right) \left(\frac{a}{\rho}\right)^3 \left\{ 3 - \frac{15}{2} \sin^2 W_p \sin^2 I \right. \\ & + \left(\frac{a}{\rho}\right)^2 \left[ -\frac{45}{32} + \frac{315}{64} \sin^2 W_p + \left(\frac{225}{32} - \frac{315}{8} \sin^2 W_p\right) \cos^2 I \right. \\ & \left. \left. + \frac{2205}{64} \sin^2 W_p \cos^4 I \right] + \dots \right\} \quad (2-6) \end{aligned}$$

The changes represented by Equations (2-4), (2-5) and (2-6) can be very useful for long term (secular) changes in orbits as a function of lunar perturbations. The computational order which should be followed is:

1.  $\Delta W_p$  should be computed from Equation (2-6) from an initial value of argument of perigee  $W_o$ . A new value of  $W_p$  is then found from  $(W_o + W_p)$ . Sometimes, however,  $\Delta W_p$  is identically zero and a stable argument of perigee exists; this can happen at high inclination angle (XI) and large semi-major axis (a). Program PERTP, Appendix 5, calculates the stability of argument of perigee in a subroutine ARGPER.
2.  $W_p$  is then substituted into Equation (2-5) to find  $\Delta e$  per orbit. This is done in PERTP on line 630 (App. 5).
3. The change of right ascension is calculated from Equation (2-4). This is done in PERTP on line 620 (App. 5).

PERTP is also more comprehensive; this will be shown in the following estimates of change in semi-major axis.

## 2.2 ESTIMATED CHANGE IN SEMI-MAJOR AXIS

A surprising difference in long term stability of posigrade compared to retrograde orbits was identified by Ash<sup>[2]</sup>. For example, 12-day retrograde orbits appear approximately as stable as 10-day posigrade orbits over a two-year interval. This difference in stability does not appear in Equations (2-1), (2-5), and (2-6) after the development of perturbations due to a torus of lunar matter.

Clearly, at least one major physical concern has been deleted from the development for Equations (2-4), (2-5), and (2-6). This is the interaction time between the satellite and the moon, which would show a difference between posigrade and retrograde orbits. Figure 9 gives a planar diagram of lunar perturbation.

If the satellite is in a circular orbit about the earth, it becomes convenient to consider the tangential impulse and the radial impulse imparted to the satellite from the moon. By symmetry, it can be seen that the satellite loses about as much tangential impulse as it passes the moon as when it approaches. However, the impulse along the radial direction is always positive.

$$\begin{array}{l} \text{Radial force} \\ \text{per unit mass} \end{array} = F_r = \frac{GM_m}{r_{ij}^2} (\cos \theta_m) \quad (2-7a)$$

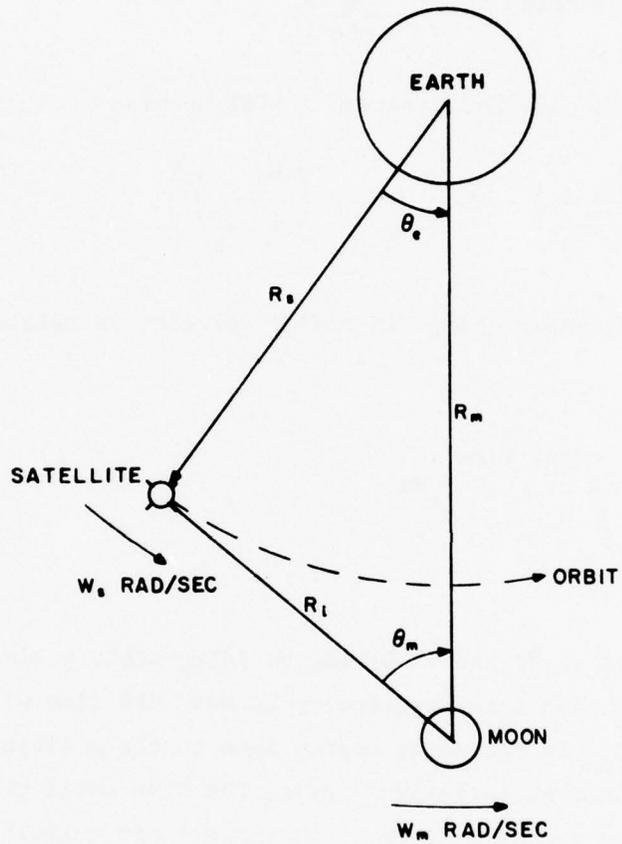
where

$r_{ij}$  = distance between satellite and lunacenter

G = gravitational constant

$$\theta_m = \theta_e \cdot \frac{R_s}{(R_m - R_s)} \quad \text{for } \theta_e \approx 0.15 \text{ rad} \quad (2-7b)$$

$M_m$  = lunar mass



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Figure 9 GEOMETRY FOR LUNAR PERTURBATIONS

Further,

$$r_{ij} \text{ can be noted to be } \frac{R_m - R_s}{\cos \theta_m}$$

for  $\theta_e \approx 0.15 \text{ rad}$ , and Equation (2-7a) becomes

$$F_r \approx \frac{GM_m}{(R_m - R_s)^2} \cos^3 \left( \theta_e \cdot \left( \frac{R_s}{R_m - R_s} \right) \right) \quad (2-8)$$

The first order change in radial velocity is related to radial impulse by

$$\Delta V_r = \int_0^{\text{total time}} F_r dt \quad (2-9)$$

Equations (2-8) and (2-9) can be integrated, yielding a closed form solution, and this opportunity to save CPU time will be adopted. If an angle  $\theta_{e0}$  is chosen as appropriate to the position at which noticeable lunar perturbations begin, the time until the earth, satellite, and moon are lined up (maximum lunar perturbation force) is  $\theta_{e0}(\omega_s - \omega_m)$ . Using the small angle approximation, Equation (2-7b), and substituting Equation (2-8) into Equation (2-9) yields:

$$\Delta V_r = \frac{1}{\omega_{rel}} \cdot \frac{2 GM_m}{(R_m - R_s)} R_s \left[ \frac{1}{3} \sin \left( \theta_{e0} \cdot \frac{R_s}{R_m - R_s} \right) \cdot \left\{ \cos^2 \left( \theta_{e0} \cdot \frac{R_s}{R_m - R_s} \right) + 2 \right\} \right] \quad (2-10)$$

where  $\omega_{rel}$  = relative angular velocity of satellite and moon. This is shown explicitly later in Equation (2-16).

Equation (2-10) has been implemented in subroutine MOON of PERTP (Appendix 5). The limit of integration,  $\theta_{eo}$ , is entered as TE = 0.3 radians on line 1210. This is felt to give an underestimate of lunar perturbations, because a tidal displacement actually occurs during the radial impulse. The radial velocity of Equation (2-10) must be related to orbital energy, and hence to semi-major axis (a) as soon as the satellite leaves the influence of the moon.

The vis viva integral is the relation between orbital energy and semi-major axis for a simple central force field and has the form

$$\frac{V^2}{\mu} - \frac{2}{R} = -\frac{1}{a} \text{ for elliptic motion} \quad (2-11)$$

where

V = total velocity

$\mu = Gm_e$

$m_e$  = mass of earth

R = geocentric distance.

When Equation (2-11) is rewritten

$$\frac{V^2}{2} - \frac{\mu}{r} = \frac{\mu}{2} \left( -\frac{1}{a} \right) ,$$

the left side is recognized as total orbital energy, or

$$-\frac{2}{\mu} (\text{total energy}) = \frac{1}{a}$$

After rearranging Equation (2-13) and differentiating the expression of (a), a function of (total energy), one finds

$$da = \left( \frac{\mu}{2} \right) \frac{d(\text{total energy})}{(\text{total energy})} \quad (2-14)$$

Changing Equation (2-14) to an incremental form and substituting  $\frac{\Delta V_r^2}{2}$  for change in total energy gives

$$\Delta a = \frac{(\Delta V_r)^2 a^2}{Gm_e} \quad (2-15)$$

Since  $\Delta V_r$  is proportional to interaction time, the square of  $\Delta V_r$  in Equation (2-15) implies that the instability of the semi-major axis increases in a nonlinear way with the lunar interaction time. The actual interaction time depends on a vector difference of angular velocities,  $(\omega_s - \omega_m)$ . The relative angular velocity can be approximated by

$$\omega_{rel} = (\omega_s \cos I - \omega_m)^2 + (\omega_s \sin I)^2 \quad (2-16)$$

where again  $I$  is the inclination angle of the satellite with respect to the lunar plane.

The remaining considerations which have gone into the subroutine MOON are:

1. The total region of possible interaction of the satellite with the moon is approximately limited (to ANG) if the inclination angle is large and,
2. Change of (a) per year is proportional to the number of times per year in which interaction happens, or  $\Delta a /_{yr}$   
 $\alpha \omega_{rel}$ .

Even with the second item included for completeness, however, a distinct difference between the stabilities of posigrade and retrograde orbits is seen in only a few seconds of CPU time. When the effects of subroutine MOON are included in PERTP and a variable to represent instability

$$V_5 = a(1 + e) / a_0(1 + e_0) \quad (2-17)$$

is generated to represent normalized apogee distance, a 10-day orbit at inclination  $0^\circ$  has approximately the same value for  $V_5$  (1.003) as a 12-day orbit at inclination  $180^\circ$ .

It appears that the gross secular results for orbital instability<sup>[1]</sup> have been qualitatively reproduced with very modest CPU requirements.

The reader will notice that a running change in units has occurred in these programs. At the time these lunar perturbation programs were generated, a new Federal interest was expressed in metric units. Semi-major axis (a) is expressed in the program of Example 2 and Appendices 5-7 in kilometers. The relation between nautical miles and kilometers is:

$$1.852 \times (\text{length in nautical miles}) = \text{length in kilometers}.$$

### 2.3 PROGRAM PERTP (Appendix 5)

Program PERTP calculates a new semi-major axis ( $a$ , km), eccentricity ( $E$ ), right ascension ( $W$ ), and normalized apogee distance  $V_5$ . It does this from estimated lunar secular perturbations. Iterations in orbital elements are performed every 10 days for a total of 400 days.

CALCOMP plots are generated (e.g.,  $V_5$  vs time in days).

This program gives an estimate of orbital stability implicit in the variable  $V_5$ . When  $V_5$  increases to approximately 1.01 in 400 days, the orbit's stability is very questionable. This stability has qualitative agreement with Ash's numerical results.

### 2.4 PROGRAM SATLUNAE (Appendix 6)

Program SATLUNAE combines a variation of SATE and a subroutine LUNA. To save CPU time for orbits which are to be perturbed by the moon for a long time (say,  $T > 3$  years), integrated versions of Equations (2-4), (2-5), and (2-6) were prepared for subroutine LUNA. The equation for argument of perigee offered two choices: either (1) it kept rotating, or (2) it was assigned a stationary value immediately as in the ARGPER subroutine of PERTP. If it kept rotating, an average value of angular velocity was assigned by using  $\sin_2 \omega = 1/2$ .

The order of calculations in LUNA was as follows:

1. A linear estimate of growth in semi-major axis ( $a$ ) was done, so that  $\bar{A}$  (AB in the program) could be used for later calculations.
2. Argument of perigee was estimated as either stationary or rotating, which gave the possibility of two integrals for the eccentricity calculation.
3. If a stationary  $\omega_p$  existed, a simple exponential growth in eccentricity resulted. This is similar to the result of the 1974 Ash report<sup>[2]</sup>. A less simple result occurred (on line 3020) if  $\omega_p$  kept rotating. Lines 3020 and 3030 are deceptive in their simplicity, and to see the complexity one should substitute the various  $c$ 's. Many of the  $c$ 's are not constants, but are functions of the orbital elements.

Right ascension and normalized apogee distance are finally estimated. The results show a satisfying but not exact comparison to an iterated (not integrated) change in orbital elements. A program which iterates the orbital elements appears as SCOREE (Appendix 7).

## PART III

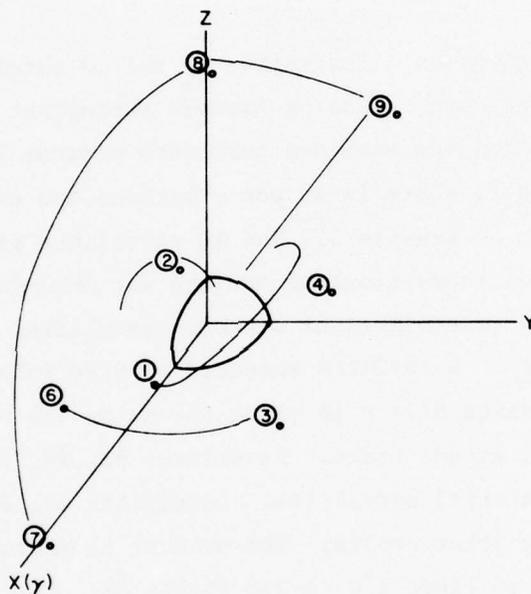
### EXAMPLES

#### 3.1 EXAMPLE 1

Figure 10 gives an illustration of the 10 satellites chosen for this example; they are a running example throughout this section. These 10 satellites are examined here with program SATE. They appear again in Example 2, where lunar perturbations are examined, and in a coverage problem of Example 3. The 10 satellites give an idea of the capability of these programs and are not intended as a specifically useful satellite communications system. Satellites #1 and #2 are Aerospace Type A<sup>[7]</sup> satellites selected to give polar coverage. These 12-hour orbits differ in right ascension (W) by  $90^\circ$  in order to give the same ground trace. Satellites #3, #4, #5, and #6 are synchronous equatorial satellites. Satellites #7, #8, #9, and #10 are in 4-day polar orbits. The orbital elements are entered in program SATE on lines 160 to 240 (Table 1). The ground station coordinates are entered on line 250; Lexington, Massachusetts and San Diego, California, are entered as ground stations 1 and 2.

Lines 160 and 170 list the semi-major axes of the satellites in nautical miles, in order of increasing altitude. Line 180 gives the respective eccentricities. Lines 190 and 200 give the right ascensions in degrees. Line 210 gives arguments of perigee in degrees. Lines 220 and 230 give the time at perigee in hours, and line 240 gives orbital inclination in degrees. Line 250 gives colatitudes of Lexington, Massachusetts, and San Diego, California; then, the longitudes of the same sites.

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IA-45,725

Figure 10 ARRAY OF SATELLITES AT T = 0 HRS FOR THREE EXAMPLES.  
TEN SATELLITES TOTAL. (NOT TO SCALE; 5 AND 10 NOT SHOWN)

TABLE 1

## ORBITAL ELEMENTS ENTERED IN SATE

00150	Dimension A(10), E(10), W(10), WP(10), TP(10), XI(10), B(4)
00160	Data A/14342., 14342., 22767., 22767., 22767., 22767.,
00170	3 57369.2, 57369.2, 57369.2, 56369.2/
00180	Data E/.725, .725, 0., 0., 0., 0., 0., 0., 0., 0./
00190	Data W/0., 270., 0., 0., 0., 0.,
00200	4 0., 0., 0., 0./
00210	Data WP/-90., -90., 0., 0., 0., 0., 0., 0., 0., 0./
00220	Data TP/0., -6., -3., -9., -15., -21.,
00230	1 0., -24., -48., -72./
00240	Data xI/63.435, 63.435, 0., 0., 0., 0., 90., 90., 90., 90./
00250	Data B/47.54, 57.23, 288.73, 242.8/

As an important aside, it should be noted that the communications designer does not really care as much about orbital elements as he does about the subsatellite traces which he will require in order to get adequate satellite visibility. The designer can tell that Satellite #1 was at  $-90^\circ$  longitude ( $90^\circ$  West longitude) at  $T = 0$  hrs because  $TP = 0$ ,  $WP = -90^\circ$ , and  $W = 0$ . The subsatellite "starting point" of a satellite with  $TP \neq 0$  requires some calculation. Satellite #2, with  $TP = -6$  hrs, was at perigee 6 hours before the computation began. It is therefore halfway through its 12-hour orbit at  $T = 0$  hrs, and is at apogee. Since the right ascension is  $270^\circ$  and the argument of perigee is  $-90^\circ$  for Satellite #2, the perigee occurred at  $180^\circ$  longitude in celestial coordinates. However, perigee occurred 6 hours previously for Satellite #2; the earth advanced 1/4 revolution in that period, or perigee

occurred over 270° East longitude on the earth. Since this is involved, a simple check for the communications engineer is available on the computer output which gives the subsatellite trace.

The computer output of SATE gives the time history of all combinations of links. It is not a graphical output, but a compensatory feature is its 28-second CPU time on a 370/158 for 25 hours of data. A sample link from Satellite #1 to Lexington, Massachusetts, is shown on Table 2. From left to right, the columns are satellite number, time in hours, range in nautical miles, elevation angle in degrees, uplink Doppler shift (Hz) for a 300 MHz signal, downlink Doppler shift (Hz) for a 245 MHz signal, subsatellite longitude, subsatellite colatitude, and ground station number. It is seen that range increases until a maximum is reached at 6 hours for the first apogee.

No earth harmonics for the potential field have been introduced for Table 2, so this near earth orbit should not be examined beyond two orbits or 24 hours.

The 55 possible crosslinks are also listed in the computer output. A crosslink from Satellite #1 to Satellite #3 is examined in Table 3. This represents a highly eccentric Aerospace Type A orbit crosslinking to a synchronous satellite. From left to right, time is given in hours, range in nautical miles, L12 and C12 are the longitude and colatitude of the crosslink pointing vector (in the inertial coordinate system), crosslink Doppler (Hz) is given for the 60 GHz crosslink<sup>[8]</sup>, and CVIS gives a visibility check on the crosslink. CVIS = 1 means the crosslink exists; CVIS = 0 if the earth blocks the crosslink. The first maximum for crosslink range is seen to occur at 6 hours and 27822

TABLE 2  
 AN ECCENTRIC SATELLITE LINK TO LEXINGTON, MASSACHUSETTS  
 (Range in nautical miles, Angle = elevation angle, Up and Down Doppler in Hz.)

SAT	HRS	RANGE	ANGLE	UPDOPPLER	DNDOPPLER	SUBL	SUBC	STATION
1	1.0	9260.367	12.721	-2913.700	-2379.520	-0.850	63.945	1
1	2.0	14332.676	29.205	-2244.127	-1832.704	1.094	44.073	1
1	3.0	18017.570	35.326	-1568.874	-1281.247	0.369	35.092	1
1	4.0	20501.965	37.995	-1000.994	-817.478	-0.347	30.087	1
1	5.0	21946.953	38.956	-492.098	-401.880	-0.431	27.416	1
1	6.0	22429.563	39.012	-5.500	-4.573	0.000	26.565	1
1	7.0	21965.715	39.540	486.038	396.931	0.421	27.415	1
1	8.0	20519.180	37.624	1009.954	824.795	-0.337	30.085	1
1	9.0	17998.438	35.788	1595.607	1303.079	-0.378	35.087	1
1	10.0	14262.535	30.786	2259.376	1845.157	-1.104	44.065	1
1	11.0	9336.133	11.419	2637.558	2154.005	0.836	63.923	1
1	12.0	7227.129	-77.318	-1064.329	-869.202	89.594	153.434	1
1	13.0	10861.879	-14.168	-2537.382	-2072.195	-180.864	63.967	1
1	14.0	15488.333	7.132	-2120.911	-1732.076	-178.915	44.081	1
1	15.0	19018.594	15.295	-1508.299	-1231.777	-179.640	35.096	1
1	16.0	21405.051	19.402	-958.151	-782.490	-180.356	30.090	1
1	17.0	22778.605	21.613	-461.964	-377.271	-180.441	27.417	1
1	18.0	23219.723	22.477	5.412	4.420	-180.000	26.565	1
1	19.0	22762.797	21.947	466.511	380.984	-179.588	27.413	1
1	20.0	21393.457	19.693	948.133	774.308	-179.673	30.082	1
1	21.0	19043.566	14.962	1481.625	1209.994	-180.388	35.083	1
1	22.0	15573.766	5.998	2106.593	1720.383	-181.114	44.057	1
1	23.0	10810.207	-13.120	2770.763	2262.790	-179.178	63.901	1
1	24.0	5944.375	-50.624	1303.522	1064.543	-90.810	153.433	1
1	25.0	9252.035	12.697	-2914.108	-2379.854	-0.877	63.988	1

TABLE 3  
 CROSSLINK BETWEEN AN ECCENTRIC SATELLITE AND A SYNCHRONOUS SATELLITE  
 (Range in nautical miles, Crosslink Doppler in Hz (60 GHz crosslink))[2]

HRS	RANGE	L12	C12	CRDOPPLER	CVIS	SAT1	SAT2
1.0	18135.488	82.850	104.826	-3149.510	1	1	3
2.0	20296.223	103.276	125.216	-327932.750	1	1	3
3.0	23453.848	119.355	134.814	-299587.875	1	1	3
4.0	25918.691	133.851	139.511	-203648.563	1	1	3
5.0	27382.699	148.046	141.850	-97484.000	1	1	3
6.0	27822.402	162.619	142.687	6063.633	1	1	3
7.0	27285.309	177.877	142.114	103529.188	1	1	3
8.0	25834.590	193.715	139.736	193547.375	1	1	3
9.0	23550.559	209.504	134.566	272253.875	1	1	3
10.0	20638.660	223.687	124.561	318659.688	1	1	3
11.0	17834.590	232.492	105.057	180939.813	1	1	3
12.0	21833.891	221.684	80.702	-1390808.000	1	1	3
13.0	30509.875	226.932	98.738	-489000.813	1	1	3
14.0	33991.332	240.728	110.134	-268575.625	1	1	3
15.0	36094.801	255.249	117.252	-173069.813	1	1	3
16.0	37454.848	-89.800	121.752	-109688.313	1	1	3
17.0	38259.199	-74.595	124.251	-56613.570	1	1	3
18.0	38558.977	-59.365	125.021	-4373.715	1	1	3
19.0	39330.488	-44.338	124.182	52297.195	1	1	3
20.0	37515.762	-29.592	121.703	116766.875	1	1	3
21.0	36030.969	-14.988	117.318	190206.625	1	1	3
22.0	33790.941	0.044	110.279	272366.438	1	1	3
23.0	30666.230	17.363	98.725	382652.000	1	1	3
24.0	24319.582	47.896	81.660	1249408.000	1	1	3
25.0	18133.688	82.804	104.791	-2092.753	1	1	3

nautical miles. Crosslink Doppler peaks at 1.39 MHz at 12 hours. A more convenient and intuitive crosslink pointing system will be given later in program SATLUNAE.

These results were given in single precision. Because elevation angle was required only within  $0.3^\circ$  and earth harmonic terms were omitted, greater accuracy was not felt to be justified here. Single precision can lead to a strange result for crosslink Doppler between two coplanar satellites in circular orbit; the required zero Doppler shift is calculated to be a fraction of a Hz because it is the result of a subtraction of two large numbers. Another embarrassment for single precision can occur in crosslink pointing angles. The tangent of angles near  $90^\circ$  may be read as  $\tan(90^\circ)$ . If these inconveniences are to be avoided, the double precision program SATD (Appendix 2) can be used.

### 3.2 EXAMPLE 2

The orbital configuration of Figure 10 is used again in Example 2, but this time the stability of the orbits relative to lunar perturbations is to be checked. The orbital elements of Figure 10 are entered into program SATLUNAE (Appendix 6), but unlike the previous example the semi-major axis is entered in km. The initial semi-major axes are 26561 km, 42164 km, and 106247 km respectively for the 12-hr, 24-hr, and 4-day orbits.

The first part of the output of SATLUNAE is an estimate of new orbital elements after a long period of lunar perturbation. Although SATLUNAE is meant for very long periods, like five years, 365 days is the period used for this example. The estimate for the new orbital elements after one year is shown in Table 4a.

The semi-major axis for the 12-hour satellites is seen to be the same as the initial value, but the eccentricity has increased from 0.725 to 0.745. This jump in eccentricity is due to the entry of the fourth column, WPS. WPS is a stationary argument of perigee which was set immediately in the computer program SATLUNAE. This stationary argument of perigee allows the eccentricity from the program to start growing immediately, although real satellite eccentricity does not immediately grow. Therefore the new eccentricity  $E_1$  should be considered an upper bound. The new right ascension  $W$  is only slightly changed from the original  $0^\circ$  for Satellite #1. The normalized apogee distance  $V_5$  has increased 1.2% in one year.

TABLE 4a

FUTURE SEMI-MAJOR AXIS, ECCENTRICITY, RIGHT ASCENSION,  
 ARGUMENT OF PERIGEE, AND NORMALIZED APOGEE DISTANCE  $V_5$

ABIG	E1	W	WPS	$V_5$
26561.0	0.745798409	-0.360600	44.963928	1.0120573
26561.0	0.745798409	269.639160	44.963928	1.0120573
42164.2	0.0	-1.655902	0.0	1.0000038
42164.2	0.0	-1.655902	0.0	1.0000038
42164.2	0.0	-1.655902	0.0	1.0000038
42164.2	0.0	-1.655902	0.0	1.0000038
106249.1	0.0	-0.000002	39.585815	1.0000191
106249.1	0.0	-0.000002	39.585815	1.0000191
106249.1	0.0	-0.000002	39.585815	1.0000191
106249.1	0.0	-0.000002	39.585815	1.0000191

Surprising stability appears in the  $V_5$  column for Satellites #3 through #10. This is because the initial eccentricity was 0. A more reasonable estimate of stability can be found if a non-zero value for initial eccentricity is used. Table 4b lets the initial eccentricity value be 0.05.

The synchronous Satellites #3 through #6 are still stable since  $V_5$  retains a value close to unity. However, it is seen that the 4-day polar satellites show a 1.4% increase in normalized apogee distance. Questionable stability is indicated.

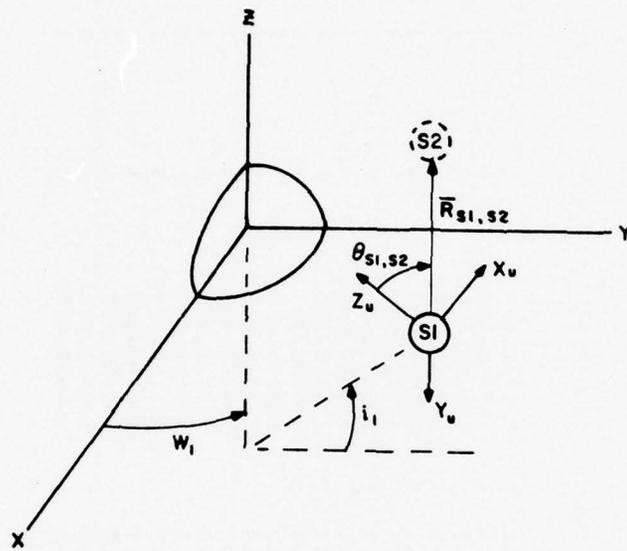
TABLE 4b

SATELLITES #3 THROUGH #10, INITIAL ECCENTRICITY = 0.05

ABIG	E1	W	WPS	V <sub>5</sub>
26561.0	0.745798409	-0.360600	44.963928	1.0120573
26561.0	0.745798409	269.639160	44.963928	1.0120573
42164.2	0.050000001	-1.655902	0.0	1.0000038
42164.2	0.050000001	-1.655902	0.0	1.0000038
42164.2	0.050000001	-1.655902	0.0	1.0000038
42164.2	0.050000001	-1.655902	0.0	1.0000038
106249.1	0.065072298	-0.000002	39.585815	1.0143747
106249.1	0.065072298	-0.000002	39.585815	1.0143747
106249.1	0.065072298	-0.000002	39.585815	1.0143747
106249.1	0.065072298	-0.000002	39.585815	1.0143747

SATLUNAE then goes through link calculations with the new orbital elements. These are largely omitted here, since they are reminiscent of the output from SATE. One other crosslink calculation does occur here, however, which makes it worthwhile to include one crosslink. Crosslink angle in a local satellite coordinate system is shown in Figure 11 and it is included as TU12 and FU12 in Table 5; this table is part of one output table of SATLUNAE.

Except for the columns FU12 and TU12, Table 5 was discussed in Example 1. TU12 and FU12 are discussed in Figure 11. Again, TU12 is a local co-elevation angle and FU12 is a local azimuth angle.



THE LOCAL ZENITH ANGLE  $\theta_{s1,s2}$  IS COMPUTED IN SUBROUTINE UNPRIM  
AND PRINTED OUT AS  $TU_{12}$  IN PROGRAM SATLUNAE. THE LOCAL AZIMUTH  
ANGLE (PROJECTION IN THE  $X_u Y_u$  PLANE, MEASURED FROM THE  $X_u$  AXIS)  
IS PRINTED AS  $FU_{12}$

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Figure II LOCAL COORDINATE SYSTEM FOR SATELLITE CROSSLINK

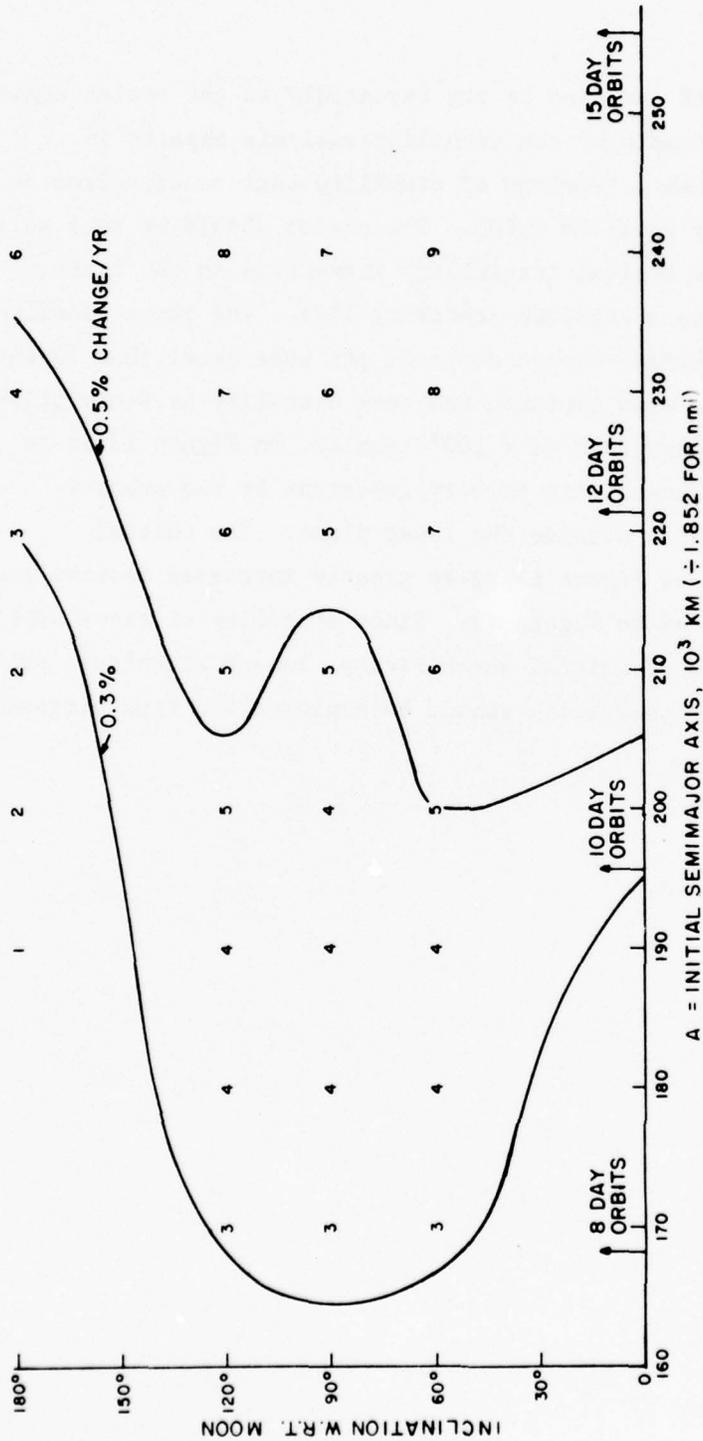
TABLE 5  
CROSSLINK RELATIONS FROM PROGRAM SAILUNAE

(FU12 and TU12 are local satellite crosslink pointing angles)

HRS	RANGE	L12	C12	FU12	TU12	CRODPLER	CVIS	SAT1	SAT2
3.0	66205.875	67.6	65.4	105.0	36.1	-125757.425	1	1	3
6.0	67722.688	111.1	53.5	139.0	37.8	43986.353	1	1	3
9.0	62309.625	160.3	56.2	179.0	41.3	160184.250	1	1	3
12.0	45815.824	224.8	97.9	-43.0	55.5	1145508.000	0	1	3
15.0	44591.199	-54.7	51.3	-75.0	61.1	-365203.750	1	1	3
18.0	56475.742	-15.7	44.5	-41.0	47.3	-52756.477	1	1	3
21.0	49892.930	23.8	48.9	-1.1	55.5	295039.813	1	1	3
24.0	39484.520	41.3	99.2	136.2	107.1	-1323487.000	1	1	3
27.0	56208.438	67.6	65.4	105.0	30.1	-126798.250	1	1	3
30.0	67727.313	111.1	53.5	139.0	37.8	44000.723	1	1	3
33.0	62314.855	160.3	58.2	178.9	41.3	160175.688	1	1	3
36.0	45827.313	224.8	97.9	-43.8	55.4	1145065.000	0	1	3
39.0	44583.375	-54.7	51.8	-75.1	61.1	-365948.563	1	1	3
42.0	56469.711	-15.7	44.5	-41.0	47.3	-52733.488	1	1	3
45.0	49891.406	23.7	48.9	-1.1	55.5	295005.250	1	1	3
48.0	39475.130	41.3	99.2	136.2	107.2	-1323150.000	1	1	3
51.0	66211.438	67.6	65.4	104.9	36.1	-125840.125	1	1	3
54.0	67732.000	111.1	53.5	139.0	37.8	44015.590	1	1	3
57.0	62319.609	160.3	58.2	178.9	41.3	160163.063	1	1	3
60.0	45835.004	224.7	97.9	-43.6	55.3	1144835.000	0	1	3

Program SATLUNAE can also be run repeatedly to get entire regions of stability. An example of the stability analysis appears in Figure 12, which gives a topology of stability that results from an initial eccentricity equal to 0.005. The curves should be read as a contour map with the orbital instability increasing to the right. Each curve represents a constant stability line. The curve labelled 0.3% change in normalized apogee distance per year shows that 10-day posigrade ( $I = 0^\circ$ ) orbits approach the same stability as 8-day polar orbits and 12-day retrograde ( $I = 180^\circ$ ) orbits. On Figure 13 it is seen that initial eccentricity is very important to the orbital stability of satellites outside the lunar plane. The initial eccentricity (0.05) of Figure 13 gives greatly increased instability at  $I = 90^\circ$  as compared to Figure 12. Since stability of these orbits is a strong function of initial eccentricity, launch techniques producing low initial eccentricity should be employed for high altitude orbits.

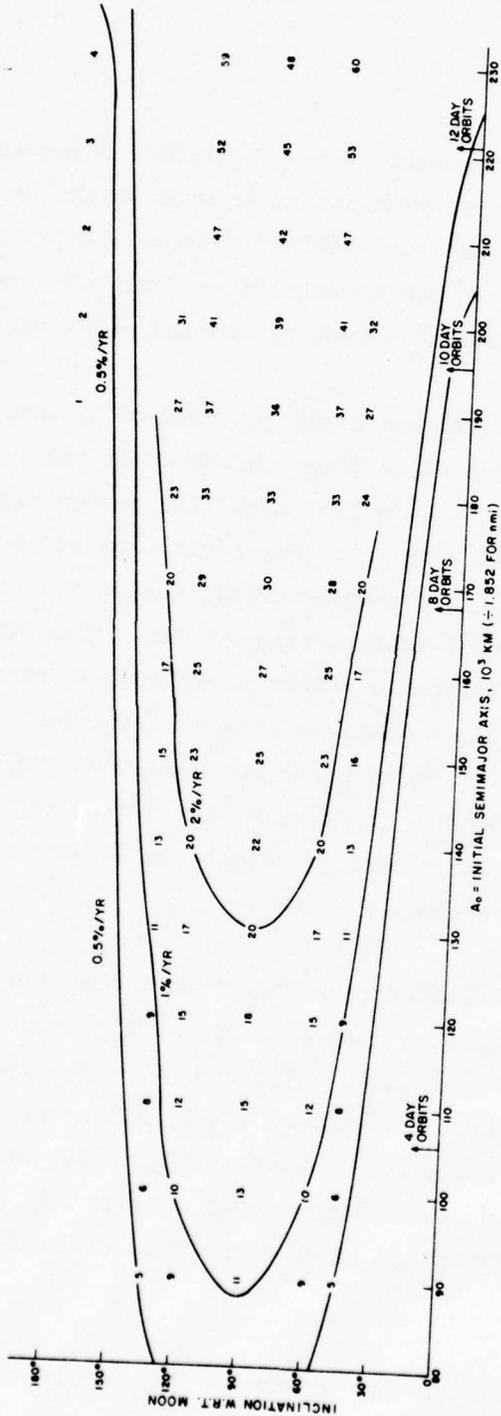
IA-45,478



PROGRAM SATLUNAE

(REGIONS TO THE LEFT OF THE CURVES ARE "STABLE")

Figure 12 ESTIMATED AVERAGE CHANGE IN NORMALIZED APOGEE DISTANCE  $\left[ \frac{a(1+e)}{e_0(1+e_0)} \right]$  PER YEAR (AVERAGED OVER 5 YEARS) AS A FUNCTION OF LUNAR PERTURBATIONS  $e_0 = .005$



(REGIONS TO THE LEFT OF THE CURVES ARE CALLED STABLE)

FROM PROGRAM SATLUMAE

Figure 13 ESTIMATED AVERAGE CHANGE IN NORMALIZED APOGEE DISTANCE  $\left[ \frac{\sigma(i+\epsilon_0)}{\epsilon_0(i+\epsilon_0)} \right]$  PER YEAR (AVERAGED OVER 5 YEARS) AS A FUNCTION OF LUNAR PERTURBATIONS.  $\epsilon_0 = 0.5$

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### 3.3 EXAMPLE 3

Two of the initial problems which face a satellite communications designer are: (1) Given a set of satellites, at what points on the earth can an observer see a satellite? (2) If many satellites are involved, at what spots on earth are no satellites visible? Preferably, the designer should see a graphical output of covered/uncovered areas.

In seeking an answer to (1), one might get swamped by information from the  $180^\circ \times 260^\circ$  projection which forms the Mercator projection. The really interesting locations in a good satellite system might be those which can see no satellite at all. Identification of these uncovered locations yields a fast, comprehensible output. It is with this idea of limited output that program NOLINKE (Appendix 9) was generated. With 10 satellites in Keplerian orbits, it examines a  $12 \times 24$  grid of possible ground stations (covering the  $180^\circ \times 360^\circ$  Mercator projection in  $15^\circ$  increments) for elevation angle to all ten satellites. It performs a printout at a given coordinate only if elevation angle to each of the 10 satellites is less than some minimum acceptable elevation angle (EM).

The lines 10 to 70 of NOLINKE (Appendix 9) represent the orbital elements of 10 satellites. The four DO LOOPS, progressing from outside to inside, are time (RI), colatitude (T), longitude (F), and satellite number (L). So, at each (T, F) all satellites are considered. Elevation angle (D) to each satellite is generated at each location. A print statement is allowed only if all satellites have been considered and if no satellite is visible (SATNO = 0).

This limited output can be very helpful to the designer of a many satellite system.

The program NOLINKE runs in the foreground on TSO. The limited output allows this to be done conveniently. For example, the orbital elements implied by Figure 10 can be typed into lines 20 to 70, a minimum elevation angle =  $35^\circ$  typed into line 210, and the resultant output (at T = 0 hrs, 1 hr) is shown on Table 6. T1 and F1 are ground station colatitude and longitude at which no satellite is observed. No. is the number of satellites observed at these locations. T is time in hours.

TABLE 6

AN OUTPUT OF NOLINKE

T1	F1	NO.	T
60.000	90.000	0.0	0.0
60.000	270.000	0.0	0.0
120.000	90.000	0.0	0.0
120.000	270.000	0.0	0.0
60.000	90.000	0.0	1.000
60.000	270.000	0.0	1.000
120.000	90.000	0.0	1.000
120.000	270.000	0.0	1.000

Although only four locations appear at each hour,  $12 \times 24 = 288$  calculations were done worldwide to see if elevation angle requirements were met. The locations and times of Table 6 were the only places which did not meet the required  $35^\circ$  elevation angle.

No output occurs for NOLINKE for a 6-hour period if a 25° elevation angle is required. Therefore, this 10-satellite system meets a 25° minimum elevation angle requirement.

## CONCLUSIONS AND RECOMMENDATIONS

An analysis has been presented which gives fast, convenient computations for range, Doppler, crosslink data, and pointing angles for a two ground-station, 10-satellite system. With the programs listed, data on all ways to link one ground station with the other via the satellite are given on one computer output. The writers are not aware of the existence of other complete link solutions on one output. Three place accuracy is representatively given. Completely general Keplerian orbits are allowable with  $0 \leq \text{eccentricity} \leq 0.99$ .

The coverage of a 10-satellite system is quickly found in a program with very limited output.

In continuing the emphasis on low computation time, analytic results for orbital stability as a function of lunar perturbations were used to generate a very efficient program. It can be used as a first economical estimate of high altitude orbital parameters after many years of lunar perturbations. Figures 12 and 13 were also included to indicate stability regions.

None of the listed FORTRAN programs requires more than one minute CPU time on an IBM 370/158 computer.

In the future, it is recommended that real signal propagation be interposed between the stations. This could include ideal antenna gain patterns and regions of ionospheric disturbance to yield estimates of the received signal/noise ratio. A "point ahead" capability should also be added to the crosslinks; this can be done conveniently with the existing velocity calculations.

NOTATION

<u>Symbol</u>	<u>Definition</u>	<u>Comment</u>
a	semi-major axis; invariant for Keplerian orbits	Nautical miles, except in programs for lunar perturbations, where a is entered in km.  1 nmi = 1.852 km  Subscript 1 is used to denote satellite 1, etc.
$\bar{a}$	average semi-major axis	Average taken over a period of lunar perturbation.
$a_0$	initial semi-major axis (before lunar perturbations)	
$a_{11}^{-a_{33}}$	elements of Euler rotation matrix	
ABIG	future semi-major axis, subject to lunar perturbations	
$\underline{A}$	Euler rotation matrix	
$\underline{A}^{-1}$	inverse of $\underline{A}$	
$A_{1S}$	geocentric angle between sub-satellite point and ground station 1	
AZ1	FORTTRAN program which includes azimuth calculations (App. 8)	
b	semi-minor axis	Not used here.
c	velocity of light = $1.6187 \times 10^5$ nmi/sec	

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$D_{1S}$	elevation angle from ground station to satellite, degrees	
$\Delta$	denotes small changes in orbital elements (e.g. $\Delta e$ =small change in eccentricity)	
$e$	eccentricity; for the elliptical Keplerian orbits considered here $0 \leq e < 1$ .	The programs with the iterative subroutine ELLIP work for $0 \leq e \leq 0.99$
$e_1$	future eccentricity, subject to lunar perturbations	
$E$	eccentric anomaly	$E_1, E_2, \dots$ used for successive approximations to eccentric anomaly.
$F$	carrier frequency, Hz	
$F'$	Doppler shifted carrier frequency, Hz	
$F_r$	lunar radial force/unit mass of satellite (scalar)	
FSP	angle measured from the line of nodes in the satellite plane	
$\phi'_s$	same as FSP	$\phi'_s = W_p + \theta$
$G$	gravitational constant = $6.6732 \times 10^{-11}$ newton meter $2/kg^2$	
$i$	orbital inclination angle with respect to equatorial plane	Becomes XI in FORTRAN programs. Numbered subscripts refer to satellite number.
$\bar{i}, \bar{j}, \bar{k}$	unit vectors in x, y, and z directions, respectively	
$I$	orbital inclination with respect to lunar plane	

$M$	mean anomaly	
$M_e$	mass of earth	
$M_m$	mass of moon	
$\mu$	$GM_e$	
$\mu_m$	$GM_m$	
nautical mile (nmi)	1.852 km (exact)	
$n$	mean angular rate, rad/hr	$M = n(t-t_p)$
NOLINKE	a coverage program of very limited output for ten satel- lites (App. 9)	
	angle in satellite plane measured from line of nodes in the lunar plane	
$p$	semi-latus rectum	
PERTP	FORTTRAN program which cal- culates effects of lunar per- turbations on orbital elements (App. 5)	
$\bar{P}_{12}$	unit vector from transmitter to receiver	
$R$	geocentric distance of satel- lite at a given instant of time (nmi for programs without lunar perturbations, km for those with)	
$\dot{R}$	$\frac{d}{dt}(R)$	
$R_e$	earth radius = 3440 nmi	
$R_{12}$	distance from transmitter to receiver	

$R_{1S}$	distance from ground transmitter 1 to satellite	
$R_{S1, S2}$	distance from Satellite #1 to Satellite #2	
RI	time index (hrs) in programs (T in analysis)	Note that solar hours are not distinguished from sidereal hours because only three-place accuracy is desired in results.
$\tilde{R}, \tilde{S}, \tilde{W}$	lunar perturbation components in Ash analysis	
SATD	FORTTRAN program which calculates ground-satellite relations ( $e \leq 0.5$ ) in double precision (App. 2)	
SATE	FORTTRAN program which calculates ground-satellite relations ( $0 \leq e \leq 0.99$ ) in single precision (App. 1)	
SATLUNAE	like SATE, but includes long term estimates ( $\geq 5$ years) of lunar perturbations (App. 6)	
SATVIZD	like SATD, but interactive with the user (App. 4)	
SATVIZE	like SATE, but interactive with the user (App. 3)	
SCOREE	like SATE, but includes effects of lunar perturbations on orbital elements for periods up to a few years (App. 7)	
T	time in hours	RI in programs
TP	time at perigee, hours	

$\tau$	period for Keplerian orbit (subscripts are added for particular satellites)	
TU12, FU12	crosslink angles in a local satellite coordinate system	
$\theta$	true anomaly	
$\dot{\theta}$	$\frac{d}{dt} ( )$	
$\theta_j$	angle between relative velocity vector and pointing vector	
$\theta_1, \phi_2$	spherical coordinates associated with ground station 1	
$\theta_{S1, S2};$ $\phi_{S1, S2}$	inertial spherical coordinates associated with crosslink vec- tor (called L12, C12 in com- puter output)	TU12, FU12 are usually more con- venient than $\theta_{S1, S2}; \phi_{S1, S2}$ .
$\theta_e$	angle of satellite with respect to earth-moon vector	
$\theta_{eo}$	bounding angle for lunar pertur- bations (representatively, 0.3 radians)	
$\theta_m$	angle of satellite with respect to moon-earth vector	
$V_R$	relative velocity between trans- mitter and receiver	
$V_r$	satellite radial velocity	
$V$	potential energy in <u>vis viva</u> integral	
$V_5$	normalized apogee distance = final apogee/initial apogee	

<u>vis viva</u> integral	gives relation between potential and kinetic energy for Keplerian orbits	
W	right ascension for Keplerian orbit, degrees	Subscripts are used for particular satellites.
$W_p$	argument of perigee for Keplerian orbit, degrees	
WPS	stationary argument of perigee, subject to lunar perturbations	
$\omega$	earth rotation rate - $15^\circ/\text{solar hour} = 15.04^\circ/\text{sidereal hour}$	
$\omega_s$	angular rotation rate of satellite about earth, rad/hr	
$\omega_m$	angular rotation rate of moon about earth, rad/hr	
$\omega_{rel}$	vector difference of $\omega_s, \omega_m$	$\omega_{rel}$ determines the time of interaction of satellite and moon.
$\tilde{W}$	one of three lunar perturbation components used by Ash (others, $\tilde{R}, \tilde{S}$ )	
X,Y,Z,	inertial Cartesian coordinate system, with x pointed toward Aries (X,Y,Z, associated with ground station 1)	
X',Y',Z',	a moving coordinate system in the satellite plane	

$X'', Y'', Z''$ ,

a stationary coordinate system  
in the satellite plane

The double prime  
system will be con-  
venient if Doppler  
rates are later added  
to the programs.

$X_S, Y_S, Z_S$

coordinates of satellite in  
inertial space axis of a re-  
lated coordinate system which  
lies along Z axis

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1. M. Ash, "Doubly Averaged Effect of the Moon and Sun on a High Altitude Earth Satellite Orbit", TN 1974-5, Lincoln Laboratory, 1 March 1974

2. J. Jensen, et al., Design Guide to Orbital Flight, McGraw-Hill Book Co. Inc., N.Y. 1962

The title of this book suggests a very straightforward handbook presentation; this is deceptive, however, and the book is replete with subtle and extensive derivations.

3. F. R. Moulton, An Introduction to Celestial Mechanics, MacMillan Co., N.Y. 1914

This book has been important for insight; the purpose of many derivations is to minimize computational tedium.

4. P. R. Escobal, Methods of Orbit Determination, John Wiley & Sons, N.Y., 1965

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6. J. D. Jackson, Classical Electrodynamics, J. Wiley, N.Y., 1962
7. J. L. LeMay, et al., "HANS High Altitude Navigation Study", Aerospace Report No. TR-0073(3491)-1, Air Force Report No. SAMSO-TR-74-10, 29 June 1973
8. J. W. Dees, J. C. Wiltse, "An Overview of Millimeter Wave Systems", Microwave Journal 12, No. 11, November 1969, pp 42-49.

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S. Chandrasekhar, Principles of Stellar Dynamics, Dover,  
N.Y. 1942

Chandrasekhar developed the concept of "dynamical friction". An important part of dynamical friction is the integration time of the perturbations. This concept led to the integration here of the radial perturbation during a dynamic interaction of the satellite and moon. Differences between posigrade and retrograde orbits were seen in the results which are not present in static analyses.

P. Michaels, J. Crocco, "Behavior of Selected Satellite Orbits Near a Lunar Libration Point", USAFESD Working Paper 1974-75,  
1 May 1974

APPENDIX 1

PROGRAM SATE

This background version of SATVIZE is usually more valuable than SATVIZE for more than two satellites or two ground stations. The high speed printer allows the extensive output to be more quickly and neatly finished than the terminal output of SATVIZE.

Orbital elements are entered on lines 160-240. The ground station latitudes are entered consecutively for the ground stations, then the longitudes (East). For example, the locations of Lincoln, Massachusetts ( $47.54^\circ$  colatitude,  $288.73^\circ$  E. Long.) and San Diego, California ( $57.34^\circ$  colatitude,  $242.8^\circ$  E. Long.) are entered as:

DATA B/47.54, 57.23, 288.73, 242.8/

240

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//TS0420A JOB (6360,D91,DESK),'CHRISTOPHER P',NOTIFY=TS0420, 00000010
// TIME=1 00000020
// EXEC FORTGCG 00000030
//FORT.SYSIN DD * 00000040
C THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR A MAXIMUM OF 00000050
C TEN SATELLITES AND TWO GROUND STATIONS. 00000060
C THE ARRAYS CONTAIN THE FOLLOWING INFORMATION FOR EACH SATELLITE: 00000070
C A--SEMI-MAJOR AXIS IN NAUTICAL MILES 00000080
C E--ECCENTRICITY 00000090
C W--RIGHT ASCENSION IN DEGREES 00000100
C WP--ARGUMENT OF PERIGEE IN DEGREES 00000110
C TP--TIME OF PERIGEE IN HOURS 00000120
C XI--INCLINATION IN DEGREES 00000130
C ARRAY B CONTAINS THE COLATITUDE AND LONGITUDE FOR EACH GROUND STATION. 00000140
      DIMENSION A(10),P(10),W(10),WP(10),TP(10),XI(10),B(4) 00000150
      DATA A/14342.,14342.,22767.,22767.,22767.,22767., 00000160
      3 57369.2,57369.2,57369.2,57369.2/ 00000170
      DATA E/.725,.725,0.,0.,0.,0.,0.,0.,0.,0./ 00000180
      DATA W/C.,270.,243.733,243.733,0.,0., 00000190
      4 0.,0.,0.,0./ 00000200
      DATA WP/-90.,-90.,0.,0.,0.,0.,0.,0.,0.,0./ 00000210
      DATA TP/0.,-6.,0.,-6.,-15.,-21., 00000220
      1 0.,-24.,-48.,-72./ 00000230
      DATA XI/63.435,63.435,23.4,23.4,0.,0.,90.,90.,90.,90./ 00000240
      DATA B/153.435,26.565,270.,0./ 00000250
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED. 00000260
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED. 00000270
      NUMS=4 00000280
      NUMG=2 00000290
      P=3.1415926 00000300
      PE=3440. 00000310
      RTD=57.29577951 00000320
      WRAD=15.0/RTD 00000330
C CL IS THE VELOCITY OF LIGHT IN NAUTICAL MILES PER SECOND. 00000340
      CL=1.61984*10.**5 00000350
C FR IS THE UPLINK FREQUENCY IN HZ. 00000360
C FPI IS THE DOWNLINK FREQUENCY IN HZ. 00000370
      FR=300.0*10.**6 00000380
      FPI=245.0*10.**6 00000390
      CON=5.987*10.**(-6) 00000400
      DO 900 J=1,NUMS 00000410
      W(J)=W(J)/RTD 00000420
      WP(J)=WP(J)/RTD 00000430
      XI(J)=XI(J)/RTD 00000440
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J. 00000450
      TAU=CON*A(J)**1.5 00000460
      DO 700 K=1,NUMG 00000470
      WRITE(5,10) 00000480
10  FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLE',9X,'UPDOPPLER'00000490
      1',8X,'DNDOPPLER',9X,'SUPL',9X,'SUBC',6X,'STATION',//) 00000500
      T=B(K)/RTD 00000510
      G=B(K+2)/RTD 00000520
C I IS THE HOUR. 00000530
      DO 500 I=1,25 00000540
      RI=I 00000550
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND 00000560
C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE 00000570
C AND EQUATORIAL PLANE. 00000580
      CALL ELLIP(RI,E(J),WP(J),TP(J),A(J),TAU,FSP,R) 00000590
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE 00000600
C SATELLITE J (WITH GEOCENTER AS THE ORIGIN). 00000610

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```

CALL PRIME(FSP,W(J),XI(J),R,0.,XS,YS,ZS) 00000620
C PS IS THE SUBSATELLITE LONGITUDE IN DEGREES. 00000630
PS=(ATAN(YS/XS)-WRAD*RI)*RTD 00000640
IF(XS.LT.0.)PS=PS+P*PTD 00000650
11 IF(PS.LT.-360.)PS=PS+360. 00000652
IF(PS.LT.-360.)GO TO 11 00000654
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES. 00000660
TS=RTD*APCOS(ZS/R) 00000670
F=G+WRAD*RI 00000680
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K. 00000690
X=RE*SIN(T)*COS(F) 00000700
Y=RE*SIN(T)*SIN(F) 00000710
Z=RE*COS(T) 00000720
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE 00000730
C CENTER OF THE EARTH. 00000740
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL 00000750
C MILFS. 00000760
ACC=APCOS((X*XS+Y*YS+Z*ZS)/(RE*R)) 00000770
RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5 00000780
ARG=SIN(ACC)*R/RGE 00000790
IF(ARG.GT.1.0000000)ARG=1.0000000 00000800
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO 00000810
C SATELLITE J. 00000820
D=(ARSIN(ARG)-P/2.)*RTD 00000830
RT=SQRT(R*R-RE*RE) 00000840
IF(RGE.LE.RT)D=-D 00000850
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY. 00000860
CALL DOPE(R,F(J),A(J),TAU,FSP,WP(J),W(J),XI(J),XV,YV,ZV) 00000870
C (XT,YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND 00000880
C STATION K. 00000890
XT=-WRAD*RE*SIN(T)*SIN(F)/3600. 00000900
YT=WRAD*RE*SIN(T)*COS(F)/3600. 00000910
DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z) 00000920
DOT=-DOT/RGE 00000930
C UPDOP IS THE UPLINK DOPPLER SHIFT IN HZ. 00000940
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ. 00000950
UPDOP=DOT*FP/CL 00000960
DNDOP=DOT*FP1/CL 00000970
WRITE(6,20)J,RI,RGF,D,UPDOP,DNDOP,PS,TS,K 00000980
20 FORMAT(1H ,I3,F8.1,P17.3,P14.3,P17.3,P17.3,P13.3,P13.3,I10) 00000990
500 CONTINUE 00010000
WRITE(6,25) 00010010
25 FORMAT(1H ,//) 00010020
700 CONTINUE 00010030
900 CONTINUE 00010040
WRITE(6,30) 00010050
30 FORMAT(1H ,/////) 00010060
L=NUMS-1 00010070
IF(L.F0.0)GO TO 350 00010080
C FP IS THE CROSSLINK FREQUENCY IN HZ. 00010090
FP=60.*10.**9 00011000
C M1 IS THE FIRST SATELLITE. 00011110
C M2 IS THE SECOND SATELLITE. 00011120
DO 350 M1=1,L 00011130
TAU=CON*A(M1)**1.5 00011140
N=M1+1 00011150
DO 250 M2=N,NUMS 00011160
WRITE(6,40) 00011170
40 FORMAT(1H ,2X,'HFS',12X,'RANGE',11X,'L12',12X,'C12',11X, 00011180
,'CDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//) 00011190
TAU2=CON*A(M2)**1.5 00011200

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```

DC 300 I=1,25
RI=1
C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE C MFANS NO VISIBILITY
C AND 1 MFANS VISIBILITY.
NOVIZ=1
CALL ELLIP (PI, F (M1), WP (M1), TP (M1), A (M1), TAU, FSP, R)
CALL ELLIP (RI, F (M2), WP (M2), TP (M2), A (M2), TAU2, F2P, R2)
CALL PRIME (FSP, W (M1), XT (M1), R, 0., XS, YS, ZS)
CALL PRIME (F2P, W (M2), XI (M2), R2, 0., X2, Y2, Z2)
TC1=X2-XS
TC2=Y2-YS
TC3=Z2-ZS
C R12 IS THE RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES.
C F12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES.
R12=(TC1**2+TC2**2+TC3**2)**.5
F12=RTD*ATAN (TC2/TC1)
IF (TC1.LT.0.) F12=F12+P*RTD
VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)
IF (VIZ.GT..99999999)VIZ=.99999999
DELM=ARCOS (VIZ)
DELM=ABSIN (DELM/R)
IF (DELM.LT.0.) NOVIZ=C
T12=ARCOS (TC3/R12)*RTD
CALL DOPE (F, F (M1), A (M1), TAU, FSP, WP (M1), W (M1), XI (M1), XV, YV, ZV)
CALL DOPE (R2, F (M2), A (M2), TAU2, F2P, WP (M2), W (M2), XI (M2), S2, U2, V2)
DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3
DOT=DOT/R12
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ.
DOP12=-DOT*PP/CL
WRITE (6, 50) RI, P12, F12, T12, DOP12, NOVIZ, M1, M2
50  FORMAT (1H , F5.1, F17.3, F14.3, F15.3, F20.3, I9, I10, I10)
300  CONTINUE
WRITE (6, 60)
60  FORMAT (1H , //)
250  CONTINUE
350  CONTINUE
END
SUBROUTINE PRIME (FSP, WS, XIS, XPS, YPS, XS, YS, ZS)
A11=COS (FSP)*COS (WS)-COS (XIS)*SIN (WS)*SIN (FSP)
A12=-SIN (FSP)*COS (WS)-COS (XIS)*SIN (WS)*COS (FSP)
A21=COS (FSP)*SIN (WS)+COS (XIS)*COS (WS)*SIN (FSP)
A22=-SIN (FSP)*SIN (WS)+COS (XIS)*COS (WS)*COS (FSP)
A31=SIN (XIS)*SIN (FSP)
A32=SIN (XIS)*COS (FSP)
XS=A11*XPS+A12*YPS
YS=A21*XPS+A22*YPS
ZS=A31*XPS+A32*YPS
RETURN
END
SUBROUTINE ELLIP (T, E, WP, TP, A, TAU, FSP, P)
P=3.1415926
Z=2.*P*(T-TP)/TAU
P2=2.*P
IF (Z.GT.P2) Z=Z-P2
IF (Z.GT.P2) GO TO 2
E1=Z+E*SIN (Z)
E2=(Z+E*(SIN (E1))-(E*COS (E1))*P1)/(1.-E*COS (E1))
Q=0.
4  E3=(Z+E*(SIN (E2))-(E*COS (E2))*P2)/(1.-E*COS (E2))
Q=Q+1.
DE=E3-E2
0001210
0001220
0001230
0001240
0001250
0001260
0001270
0001280
0001290
0001300
0001310
0001320
0001330
0001340
0001350
0001360
0001370
0001380
0001390
0001400
0001410
0001420
0001430
0001440
0001450
0001460
0001470
0001480
0001490
0001500
0001510
0001520
0001530
0001540
0001550
0001560
0001570
0001580
0001590
0001600
0001610
0001620
0001630
0001640
0001650
0001660
0001670
0001680
0001690
0001700
0001710
0001720
0001730
0001740
0001750
0001760
0001770
0001780
0001790
0001800
0001810

```

```

DE2=DE**2                                00001820
E2=E3                                     00001830
IF (DE2.GT..00000001) GO TO 4            00001840
TH=ARCOS ( (COS (E2) -E) / (1.-E*COS (E2)) ) 00001850
IF (Z.GT.P) TH=2.*P-TH                   00001860
FSP=WP+TH                                 00001870
R=(A*(1.-E**2))/(1.+P*COS (FSP-WP))      00001880
RETURN                                     00001890
END                                        00001900
SUBROUTINE DOPE (R,E,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD) 00001910
P=3.1415926                               00001920
T=FSP-WP                                   00001930
RD=(A*E*2.*P/(TAU*(1.-E**2)**.5))*SIN(T) 00001940
TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*COS(T))**2 00001950
XPC=RD*COS (FSP) -P*TD*SIN (FSP)         00001960
XPC=XPC/3600.                              00001970
YPC=RD*SIN (FSP) +P*TD*COS (FSP)         00001980
YPC=YPC/3600.                              00001990
CALL PRIME (0.,WS,XIS,XPC,YPC,XD,YD,ZD) 00002000
RETURN                                     00002010
END                                        00002020

```

\*\*\*\*\*

APPENDIX 2

PROGRAM SATD

Unlike SATE, SATD runs in double precision. It is rarely used except to check crosslink Doppler for low-eccentricity satellites within a given constellation. Differences of large velocities can be found accurately with SATD, and accurate crosslink Dopplers result.

```

//TS0420A JOB (6360,D91,DESK),CHRISTOPHER P,NOTIFY=TS0420,      00000010
// TIME=3                                                             00000020
// EXEC FORTGCG                                                       00000030
//PORT.SYSIN DD *                                                    00000040
C THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR A MAXIMUM OF    00000050
C TEN SATELLITES AND TWO GROUND STATIONS.                          00000060
C THE ARRAYS CONTAIN THE FOLLOWING INFORMATION FOR EACH SATELLITE: 00000070
C A--SEMI-MAJOR AXIS IN NAUTICAL MILES                             00000080
C E--ECCENTRICITY                                                 00000090
C W--RIGHT ASCENSION IN DEGREES                                  00000100
C WP--ARGUMENT OF PERIGEE IN DEGREES                             00000110
C TP--TIME OF PERIGEE IN HOURS                                    00000120
C XI--INCLINATION IN DEGREES                                     00000130
C ARRAY B CONTAINS THE COLATITUDE AND LONGITUDE FOR EACH GROUND 00000140
C STATION.
  IMPLICIT REAL*8(A-H,O-Z)                                           00000145
  DIMENSION A(10),E(10),W(10),WP(10),TP(10),XI(10),B(4)           00000150
  DATA A/22767.,22767.,22767.,22767.,36140.36,36140.36,          00000160
  3 36140.36,36140.36,14342.3,14342.3/                               00000170
  DATA E/.1,.1,.1,.1,.1,.1,.1,.1,.1,.1,.65,.65/                00000180
  DATA W/243.733,243.733,243.733,243.733,243.733,243.733,      00000190
  4 243.733,243.733,243.733,243.733/                               00000200
  DATA WP/0.,0.,0.,0.,0.,0.,0.,0.,-90.0,-90.0/                   00000210
  DATA TP/0.,-6.,-12.,-18.,0.,-12.,-24.,-36.,-75.,-6.75/        00000220
  DATA XI/23.4,23.4,23.4,23.4,113.4,113.4,113.4,113.4,63.4,63.4/00000230
  DATA B/47.64,57.23,289.73,242.8/                                00000240
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED.              00000250
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED.        00000260
  NUMS=10                                                             00000270
  NUMG=2                                                               00000280
  P=3.1415926                                                         00000290
  RP=3440.                                                            00000300
  RTD=57.29577951                                                    00000310
  WRAD=15.0/RTD                                                       00000320
C CL IS THE VELOCITY OF LIGHT IN NAUTICAL MILES PER SECOND.      00000330
  CL=1.61984*10.**5                                                   00000340
C FR IS THE UPLINK FREQUENCY IN HZ.                                00000350
C FR1 IS THE DOWNLINK FREQUENCY IN HZ.                             00000360
  FR=300.0*10.**6                                                     00000370
  FR1=245.0*10.**6                                                    00000380
  CON=6.987*10.**(-6)                                                 00000390
  DO 900 J=1,NUMS                                                     00000400
  W(J)=W(J)/PTD                                                       00000410
  WP(J)=WP(J)/PTD                                                     00000420
  XI(J)=XI(J)/RTD                                                     00000430
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J.                   00000440
  TAU=CON*A(J)**1.5                                                   00000450
  DO 700 K=1,NUMG                                                     00000460
  WRITE(6,10)                                                          00000470
  10  FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLE',8X,'UPDOPPLER'00000480
  1',8X,'DNDOPPLER',9X,'SUBL',9X,'SUBC',6X,'STATION',//)            00000490
  T=B(K)/RTD                                                           00000500
  G=B(K+2)/RTD                                                         00000510
C I IS THE HOUR.                                                  00000520
  DO 500 I=1,25                                                       00000530
  PI=I                                                                  00000540
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND 00000550
C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE 00000560
C AND EQUATORIAL PLANE.                                           00000570
  CALL ELLIP(FI,E(J),WP(J),TP(J),A(J),TAU,PSP,R)                    00000580
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE 00000590
C SATELLITE J (WITH GEOCENTER AS THE ORIGIN).                      00000600

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```

CALL PRIME(FSP,W(J),XI(J),R,0.,XS,YS,ZS)
C PS IS THE SUBSATELLITE LONGITUDE IN DEGREES.
FS=(DATAN(YS/XS)-WRAD*RI)*RTD
FS=(XS.LT.0.)FS=FS+P*RTD
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES.
TS=RTD*DARCCOS(ZS/R)
F=G+WRAD*RI
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K.
X=RE*DSIN(T)*DCOS(F)
Y=RE*DSIN(T)*DSIN(F)
Z=RE*DCOS(T)
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE
C CENTER OF THE EARTH.
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL
C MILES.
ACC=DARCCOS((X*XS+Y*YS+Z*ZS)/(RE*R))
RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5
ARG=DSIN(ACC)*R/RGE
IF(ARG.GT.1.0000000)ARG=1.0000000
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO
C SATELLITE J.
D=(DARSIN(ARG)-P/2.)*P*RTD
RT=DSQRT(R**2-RE*RE)
IF(RGE.LF.RT)D=-D
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
CALL DOPE(R, F(J), A(J), TAU, FSP, WP(J), W(J), XI(J), XV, YV, ZV)
C (XT, YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND
C STATION K.
XT=-WRAD*PF*DSIN(T)*DSIN(F)/3600.
YT=WPAD*RE*DSIN(T)*DCOS(F)/3600.
DOT=(XV-XT)*(YS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z)
DOT=-DOT/RGE
C UPDOP IS THE UPLINK DOPPLER SHIFT IN HZ.
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ.
UPDOP=DOT*FR/CL
DNDOP=DOT*FR1/CL
WRITE(6,20)J,FI,SGE,D,UPDOP,DNDOP,FS,TS,K
20  FORMAT(1H ,I3,F9.1,F17.3,F14.3,F17.3,F17.3,F17.3,F13.3,F13.3,I10)
500  CONTINUE
WRITE(6,25)
25  FORMAT(1H ,//)
700  CONTINUE
900  CONTINUE
WRITE(6,30)
30  FORMAT(1H ,///// )
L=NUMS-1
IF(L.EQ.0)GO TO 350
C FR IS THE CROSSLINK FREQUENCY IN HZ.
FR=2.83*10.**13
C M1 IS THE FIRST SATELLITE.
C M2 IS THE SECOND SATELLITE.
DO 350 M1=1,L
TAU=CON*A(M1)**1.5
N=M1+1
DO 250 M2=N,NUMS
WRITE(6,40)
40  FORMAT(1H ,2X,'HRS',12X,'RANGE',11X,'L12',12X,'C12',11X,
2  'CRDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//)
TAU2=CON*A(M2)**1.5
DO 300 I=1,25
RI=I
00000610
00000620
00000630
00000640
00000650
00000660
00000670
00000680
00000690
00000700
00000710
00000720
00000730
00000740
00000750
00000760
00000770
00000780
00000790
00000800
00000810
00000820
00000830
00000840
00000850
00000860
00000870
00000880
00000890
00000900
00000910
00000920
00000930
00000940
00000950
00000960
00000970
00000980
00000990
0001000
0001010
0001020
0001030
0001040
0001050
0001060
0001070
0001080
0001090
0001100
0001110
0001120
0001130
0001140
0001150
0001160
0001170
0001180
0001190
0001200
0001210

```

```

C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY          00001220
C AND 1 MEANS VISIBILITY.                                                    00001230
      NOVIZ=1                                                                    00001240
      CALL ELLIP (R1, E (M1), WP (M1), TP (M1), A (M1), TAU, FSP, R)           00001250
      CALL ELLIP (R1, E (M2), WP (M2), TP (M2), A (M2), TAU2, F2P, P2)       00001260
      CALL PRIME (FSP, W (M1), XI (M1), R, 0., XS, YS, ZS)                     00001270
      CALL PRIME (F2P, W (M2), XI (M2), R2, 0., X2, Y2, Z2)                   00001280
      TC1=X2-XS                                                                    00001290
      TC2=Y2-YS                                                                    00001300
      TC3=Z2-ZS                                                                    00001310
C R12 IS THE RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES.                 00001320
C R12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES.     00001330
      R12=(TC1**2+TC2**2+TC3**2)**.5                                             00001340
      F12=RTD*DATAN (TC2/TC1)                                                    00001350
      IF (TC1.LT.0.) F12=F12+P*RTD                                              00001360
      VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)                                       00001370
      IF (VIZ.GT..99999999) VIZ=.99999999                                       00001380
      DEL=DARCOS (VIZ)                                                            00001390
      DELM=DAPSIN (FE/P)                                                         00001400
      IF (DPL.LE.DELM) NOVIZ=0                                                  00001410
      T12=DARCOS (TC3/R12)*RTD                                                  00001420
      CALL DOPE (R, E (M1), A (M1), TAU, FSP, WP (M1), W (M1), XI (M1), XV, YV, ZV) 00001430
      CALL DOPE (R2, E (M2), A (M2), TAU2, F2P, WP (M2), W (M2), XI (M2), S2, U2, V2) 00001440
      DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3                                  00001450
      DOT=DOT/R12                                                                00001460
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ.                                00001470
      DOP12=-DOT*FR/CL                                                           00001480
      WRITE (6,50) RI, R12, F12, T12, DOP12, NOVIZ, M1, M2                    00001490
50      FORMAT (1H, 'F5.1, F17.3, F14.3, F15.3, F20.3, I9, I10, I10)           00001500
300     CONTINUE                                                                00001510
      WRITE (6,60)                                                                00001520
60      FORMAT (1H, '/')                                                         00001530
250     CONTINUE                                                                00001540
350     CONTINUE                                                                00001550
      END                                                                        00001560
SUBROUTINE PRIME (FSP, WS, XIS, XPS, YPS, XS, YS, ZS)                         00001570
      IMPLICIT REAL*P (A-H, O-Z)                                               00001575
      A11=DCOS (FSP) *DCOS (WS) -DCOS (XIS) *DSIN (WS) *DSIN (FSP)           00001580
      A12=-DSIN (FSP) *DCOS (WS) -DCOS (XIS) *DSIN (WS) *DCOS (FSP)           00001590
      A21=DCOS (FSP) *DSIN (WS) +DCOS (XIS) *DCOS (WS) *DSIN (FSP)           00001600
      A22=-DSIN (FSP) *DSIN (WS) +DCOS (XIS) *DCOS (WS) *DCOS (FSP)           00001610
      A31=DSIN (XIS) *DSIN (FSP)                                               00001620
      A32=DSIN (XIS) *DCOS (FSP)                                               00001630
      YS=A11*XPS+A12*YPS                                                         00001640
      YS=A21*YPS+A22*YPS                                                         00001650
      ZS=A31*XPS+A32*YPS                                                         00001660
      RETURN                                                                     00001670
      END                                                                        00001680
SUBROUTINE ELLIP (T, E, WP, TP, A, TAU, FSP, R)                               00001690
      IMPLICIT REAL*P (A-H, O-Z)                                               00001695
      P=3.1415926                                                                00001700
      Z=2.*P*(T-TP)/TAU                                                         00001710
      S5M=DSIN (5.*Z)                                                            00001720
      S6M=DSIN (6.*Z)                                                            00001730
      S7M=DSIN (7.*Z)                                                            00001740
      C5M=DCOS (5.*Z)                                                            00001750
      C6M=DCOS (6.*Z)                                                            00001760
      C7M=DCOS (7.*Z)                                                            00001770
      SM=DSIN (Z)                                                                00001780
      S2M=DSIN (2.*Z)                                                           00001790
      S3M=DSIN (3.*Z)                                                           00001800

```

S4H=DSIN(4.*Z)	00001810
CM=DCOS(Z)	00001820
FSP=Z+2.*E*SM+1.25*(E**2)*S2M+( (E**3)/12.)*(13.*S3M-3.*SM)	00001830
FSP=FSP+WP+( (E**4)/96.)*(103.*S4M-44.*S2M)	00001840
F5=( (E**5)/960.)*(1007.*S5M-645.*S3M+50.*SM)	00001850
F6=( (E**6)/960.)*(1223.*S6M-902.*S4M+85.*S2M)	00001860
F7=( (E**7)/32256.)*(47273.*S7M-41699.*S5M+5985.*S3M+740.*CM)	00001870
FSP=FSP+F5+F6+F7	00001880
R=(A*(1.-E**2))/(1.+E*DCOS(FSP-WP))	00001890
RETURN	00001900
END	00001910
SUBROUTINE DOPE(P,E,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)	00001920
IMPLICIT REAL*8(A-H,O-Z)	00001925
P=3.1415926	00001930
T=FSP-WP	00001940
RD=(A*E*2.*P/(TAU*(1.-E**2)**.5))*DSIN(T)	00001950
TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*DCOS(T))**2	00001960
YPC=RD*DCOS(FSP)-R*TD*DSIN(FSP)	00001970
XPC=XPC/3600.	00001980
YPC=RD*DSIN(FSP)+R*TD*DCOS(FSP)	00001990
YPC=YPC/3600.	00002000
CALL PRIME(0.,WS,XIS,XPC,YPC,XD,YD,ZD)	00002010
RETURN	00002020
END	00002030

\*\*\*\*\*

### APPENDIX 3

#### PROGRAM SATVIZE

SATVIZE is an interactive FORTRAN program which queries the TSO user for the number of satellites, number of ground stations, orbital elements of each satellite, location of each ground station, and frequencies. Default values are included in the program to allow the undecided user a chance to study the form of the output.

Arbitrary Keplerian elements can be entered, with  $0 \leq \text{eccentricity} \leq 0.99$ .

```

DIMENSION A(11),F(11),W(11),WP(11),TP(11),XI(11),C(3),RL(3)      00000010
J1=C                                                                 00000020
DATA A/0.,22767.,22767.,22767.,22767.,36140.36,36140.36,         00000030
1 36140.36,36140.36,14342.3,14342.3/                               00000040
DATA E/0.,.1,.1,.1,.1,.1,.1,.1,.1,.1/                          00000050
DATA W/243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733/ 00000060
2,243.733,243.733,243.733,243.733/                                00000070
DATA WP/0.,0.,0.,0.,0.,0.,0.,0.,-90.,-90./                          00000080
DATA TP/0.,0.,-6.,-12.,-18.,0.,-12.,-24.,-36.,-.75,-6.75/        00000090
DATA XI/23.4,23.4,23.4,23.4,23.4,113.4,113.4,113.4,113.4,63.4, 00000100
163.4/                                                            00000110
DATA C /0.,47.54,57.23/                                           00000120
DATA RL/0.,288.73,242.8/                                           00000130
WRITE(6,110)                                                       00000140
110 FORMAT(1H ,///)                                               00000150
WRITE(6,115)                                                       00000160
115 FORMAT(1H , 'THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR ACO000170
1 MAXIMUM OF 10 SATELLITES AND 2 GROUND STATIONS.',//)         00000180
WRITE(6,120)                                                       00000190
120 FORMAT(1H , 'FOR EACH SATELLITE THE FOLLOWING DATA MUST BE SUPP0000200
1 LIED:','//,' SEMIMAJOR AXIS','//,' ECCENTRICITY','//,' RIGHT ASCENSION',00000210
1/, ' ARGUMENT OF PERIGEE','//,' TIME OF PERIGEE','//,' INCLINATION',//) 00000220
WRITE(6,125)                                                       00000230
125 FORMAT(1H , 'FOR EACH GROUND STATION THE FOLLOWING DATA MUST B00000240
1 R SUPPLIED:','//,' COLATITUDE','//,' LONGITUDE',//)         00000250
WRITE(6,142)                                                       00000260
142 FORMAT(1H , 'ADDITIONAL DATA WHICH MUST BE SUPPLIED:','//,' UPLIN0000270
1 K FREQUENCY','//,' DOWNLINK FREQUENCY','//,' CROSSLINK FREQUENCY',//) 00000280
WRITE(6,130)                                                       00000290
130 FORMAT(1H , 'THE USER IS ASKED TO ANSWER SEVERAL QUESTIONS.',//,00000300
1 ' IF THE USER DOES NOT KNOW THE VALUE OF AN INPUT VARIABLE','//,' H00000310
1 B SHOULD ENTER THE NUMBER 400.0. A DEFAULT VALUE WILL THEN BE USE00000320
1 D.','//,' THE USER IS EXPECTED, HOWEVER, TO SPECIFY THE NUMBER OF SATE00000330
1 LLITES AND GROUND STATIONS TO BE CONSIDERED.',///)         00000340
WRITE(6,145)                                                       00000350
145 FORMAT(1H , 'HOW MANY SATELLITES ARE TO BE CONSIDERED? ENTER IN00000360
1 TEGER WITH RIGHTMOST DIGIT IN COLUMN 2. ')                   00000370
READ 150, M                                                        00000380
WRITE(6,135) M                                                     00000390
135 FORMAT(1H ,I3)                                                00000400
WRITE(6,155)                                                       00000410
155 FORMAT(1H , 'HOW MANY GROUND STATIONS ARE TO BE CONSIDERED? ENT00000420
1 ER INTEGER IN COLUMN 2. ')                                     00000430
READ 150, N                                                        00000440
WRITE(6,135) N                                                    00000450
150 FORMAT(I2)                                                    00000460
WRITE(6,25)                                                       00000470
WRITE(6,25)                                                       00000480
WRITE(6,95)                                                       00000490
95 FORMAT(1H , 'ENTER FOLLOWING DATA IN DECIMAL FORM ANYWHERE IN T00000500
1 HE FIRST 20 COLUMNS.',//)                                     00000510
WRITE(6,140)                                                       00000520
140 FORMAT(1H , 'WHAT IS THE SEMIMAJOR AXIS VALUE IN NAUTICAL MILES00000530
1 FOR SATELLITE 1?')                                            00000540
DO 101 I=1,M                                                       00000550
K=I+1                                                              00000560
READ 170, A(I)                                                    00000570
IF (A(I).NE.400.0)GO TO 605                                       00000580
A(I)=A(K)                                                         00000590
J1=1                                                              00000600
605 WRITE(6,305) A(I)                                             00000610

```

```

305    FORMAT(1H ,F20.8)                00000620
       IF(I.EQ.M)GO TO 101             00000630
       PRINT 310,K                     00000640
310    FORMAT(1H , 'FOR SATELLITE',I3,'?') 00000650
101    CONTINUE                        00000660
       WRITE(6,315)                    00000670
315    FORMAT(1H ,/, ' WHAT IS THE ECCENTRICITY OF SATELLITE 1?') 00000680
       DO 103 I=1,M                     00000690
       K=I+1                            00000700
       READ 170, E(I)                   00000710
       IF(E(I).NE.400.)GO TO 610        00000720
       E(I)=E(K)                        00000730
       J1=1                             00000740
610    WRITE(6,305)E(I)                 00000750
       IF(I.EQ.M)GO TO 103             00000760
       PRINT 310, K                    00000770
103    CONTINUE                        00000780
       WRITE(6,320)                    00000790
320    FORMAT(1H ,/, ' WHAT IS THE RIGHT ASCENSION VALUE IN DEGREES FOR 00000800
1R SATELLITE 1?')                     00000810
       DO 104 I=1,M                     00000820
       K=I+1                            00000830
       READ 170, W(I)                   00000840
       IF(W(I).NE.400.)GO TO 615        00000850
       W(I)=W(K)                        00000860
       J1=1                             00000870
615    WRITE(6,305)W(I)                 00000880
       IF(I.EQ.M)GO TO 104             00000890
       PRINT 310, K                    00000900
104    CONTINUE                        00000910
       WRITE(6,325)                    00000920
325    FORMAT(1H ,/, ' WHAT IS THE ARGUMENT OF PERIGEE VALUE IN DEGREE 00000930
1S FOR SATELLITE 1?')                 00000940
       DO 106 I=1,M                     00000950
       K=I+1                            00000960
       READ 170, WP(I)                   00000970
       IF(WP(I).NE.400.)GO TO 620        00000980
       WP(I)=WP(K)                       00000990
       J1=1                             00001000
620    WRITE(6,305)WP(I)                00001010
       IF(I.EQ.M)GO TO 106             00001020
       PRINT 310, K                    00001030
106    CONTINUE                        00001040
       WRITE(6,330)                    00001050
330    FORMAT(1H ,/, ' WHAT IS THE TIME OF PERIGEE IN HOURS FOR SATELL 00001060
1ITE 1?')                             00001070
       DO 107 I=1,M                     00001080
       K=I+1                            00001090
       READ 170, TP(I)                   00001100
       IF(TP(I).NE.400.)GO TO 625        00001110
       TP(I)=TP(K)                       00001120
       J1=1                             00001130
625    WRITE(6,305)TP(I)                00001140
       IF(I.EQ.M)GO TO 107             00001150
       PRINT 310, K                    00001160
107    CONTINUE                        00001170
       WRITE(6,335)                    00001180
335    FORMAT(1H ,/, ' WHAT IS THE INCLINATION VALUE IN DEGREES FOR SATELL 00001190
1TELLITE 1?')                         00001200
       DO 108 I=1,M                     00001210
       K=I+1                            00001220

```

```

READ 170, XI(I)                               00001230
IF(XI(I).NE.400.0)GO TO 630                   00001240
XI(I)=XI(K)                                   00001250
J1=1                                           00001260
630 WRITE(6,305)XI(I)                          00001270
IF(I.EQ.M)GO TO 108                           00001280
PRINT 310, K                                  00001290
108 CONTINUE                                  00001300
WRITE(6,340)                                   00001310
340 FORMAT(1H ,/, ' WHAT IS THE COLATITUDE IN DEGREES FOR GROUND STATION 1?' ) 00001320
DO 102 I=1, N                                 00001330
K=I+1                                         00001340
READ 170, C(I)                               00001350
IF(C(I).NE.400.)GO TO 635                     00001360
C(I)=C(K)                                     00001370
J1=1                                           00001380
635 WRITE(6,305)C(I)                          00001390
IF(I.EQ.N)GO TO 102                           00001400
PRINT 205, K                                  00001410
205 FORMAT(1H , 'FOR GROUND STATION',I3,'?') 00001420
102 CONTINUE                                  00001430
WRITE(6,345)                                   00001440
345 FORMAT(1H ,/, ' WHAT IS THE LONGITUDE IN DEGREES FOR GROUND STATION 1?' ) 00001450
DO 109 I=1, N                                 00001460
K=I+1                                         00001470
READ 170, RL(I)                              00001480
FORMAT(F20.8)                                00001490
IF(RL(I).NE.400.C)GO TO 640                   00001500
RL(I)=RL(K)                                   00001510
J1=1                                           00001520
640 WRITE(6,305)RL(I)                         00001530
IF(I.EQ.N)GO TO 109                           00001540
PRINT 205, K                                  00001550
109 CONTINUE                                  00001560
WRITE(6,840)                                   00001570
840 FORMAT(1H ,/,/,/, ' ENTER THE FOLLOWING DATA IN EXPONENTIAL FORM (EG. 300.0*10.**6 IS WRITTEN AS 300.0E6) ',/,/, ' WITH THE RIGHTMOST 2DIGIT APPEARING IN COLUMN 10.',/,/) 00001580
WRITE(6,845)                                   00001590
845 FORMAT(1H , 'WHAT IS THE UPLINK FREQUENCY IN HZ?') 00001600
READ 850, FR1                                  00001610
850 FORMAT(E10.2)                              00001620
IF(FR1.EQ.400.0)FR1=300.0E6                  00001630
WRITE(6,855)FR1                                00001640
855 FORMAT(1H ,E20.5)                         00001650
WRITE(6,860)                                   00001660
860 FORMAT(1H ,/, ' WHAT IS THE DOWNLINK FREQUENCY IN HZ?') 00001670
READ 850, FR2                                  00001680
IF(FR2.EQ.400.0)FR2=245.0E6                  00001690
WRITE(6,855)FR2                                00001700
WRITE(6,865)                                   00001710
865 FORMAT(1H ,/, ' WHAT IS THE CROSSLINK FREQUENCY IN HZ?') 00001720
READ 850, FR3                                  00001730
IF(FR3.EQ.400.0)FR3=38.0E9                   00001740
WRITE(6,855)FR3                                00001750
IF(J1.EQ.0)GO TO 660                          00001760
WRITE(6,670)                                   00001770
670 FORMAT(1H ,/,/, ' YOU HAVE NOT USED A COMPLETE DATA SET.',/,/, ' THEREFORE, THE RESULTS ARE FOR DEMONSTRATION PURPOSES ONLY.') 00001780

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660      GO TO 675
        WRITE(6,665)
665      FORMAT(1H,///,' YOUR DATA SET IS COMPLETE. ')
675      WRITE(6,105)
105      FORMAT(1H,///)
        P=3.1415926
        FE=3440.
        RTD=57.29577951
        WRAD=15.0/RTD
        CL=1.61984*10.**5
        CON=6.987*10.**(-6)
        WRITE(6,190)
190      FORMAT(1H,'RESULTS LISTED IN ORDER OF APPEARANCE ARE:',/,,' RAO0001960
2NGE BETWEEN GROUND STATION AND SATELLITE IN NAUTICAL MILES',/,,' ELO0001970
2EVIATION ANGLE IN DEGREES FROM GROUND STATION TO SATELLITE',/,,' UPL00001980
2INK DOPPLER SHIFT IN HZ',/,,' DOWNLINK DOPPLER SHIFT IN HZ',/,,' SUB00001990
2SATELLITE COLATITUDE IN DEGREES',/,,' SUBSATELLITE LONGITUDE IN DEG00002000
2REES',///)
        DO 890 IN=1,M
        W(IN)=W(IN)/RTD
        WP(IN)=WP(IN)/RTD
        XI(IN)=XI(IN)/RTD
890      CONTINUE
        DO 900 J=1,M
        TAU=CON*A(J)**1.5
        DO 700 K=1,N
        WRITE(6,10)
10       FORMAT(1H,'SAT',5X,'HPS',12X,'RANGE',9X,'ANGLE',8X,'UPDOPPLEP00002110
1',9X,'DNDOPPLER',9X,'SUBC',9X,'SUBL',6X,'STATION',//)
        T=C(K)/RTD
        G=RL(K)/RTD
        DO 500 I=1,25
        PI=I
        CALL ELLIP(PI,E(J),WP(J),TP(J),A(J),TAU,FSP,R)
        CALL PRIME(FSP,W(J),XI(J),R,0.,XS,YS,ZS)
        FS=(ATAN(YS/XS)-WRAD*PI)*RTD
        TP(XS.LT.0.) FS=FS+P*RTD
        TS=RTD*ARCOS(ZS/R)
        F=G+WRAD*PI
        X=RE*SIN(T)*COS(F)
        Y=RE*SIN(T)*SIN(F)
        Z=RE*COS(T)
        ACC=ARCOS((X*XS+Y*YS+Z*ZS)/(RE*R))
        RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5
        ARG=SIN(ACC)*R/RGE
        IF(ARG.GT.1.0000000) ARG=1.0000000
        D=(ABSIN(ARG)-P/2.)*RTD
        RT=SQRT(R*R-RE*RE)
        IF(RGE.LE.RT) D=-D
        CALL DOPE(R,F(J),A(J),TAU,FSP,WP(J),W(J),XI(J),XV,YV,ZV)
        XT=-WRAD*RE*SIN(T)*SIN(F)/3600.
        YT=WRAD*RE*SIN(T)*COS(F)/3600.
        DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z)
        DOT=DOT/RGE
        UPDOP=-DOT*FR1/CL
        DNDOP=-DOT*FR2/CL
        WRITE(6,20) J,RI,PGF,D,UPDOP,DNDOP,TS,FS,K
20       FORMAT(1H,'I3,F9.1,F17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10)
500      CONTINUE
        WRITE(6,25)

```

```

25      FORMAT(1H, '/')                                00002440
        IF(J1.EQ.0)GO TO 700                            00002450
        WRITE(6,680)                                    00002460
680     FORMAT(1H, 'DO YOU WANT THIS PART OF THE PPROGRAM TO CONTINUE?'00002470
1,/, ' ENTER AN INTEGER 0 IF THE ANSWER IS NO OR AN INTEGER 1 IF THE
1 ANSWER IS YES IN COLUMN 2.')                        00002480
        READ 150, NO                                     00002490
        IF(NO.EQ.0)GO TO 685                            00002500
        WRITE(6,25)                                     00002510
700     CONTINUE                                       00002520
900     CONTINUE                                       00002530
685     WRITE(6,30)                                     00002540
30      FORMAT(1H, '/////')                            00002550
        L=M-1                                           00002560
        IF(L.EQ.0)GO TO 690                             00002570
        WRITE(6,260)                                    00002580
260     FORMAT(1H, 'THIS PART OF THE PROGRAM COMPUTES CROSSLINK VALUES00002600
7 FOR ALL PAIRS OF SATELLITES.', '////', ' RESULTS LISTED IN ORDER OF AP00002610
1PEARANCE ARE:', '/, ' RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES'00002620
1,/, ' POINTING ANGLES BETWEEN SATELLITES(C12&L12) IN DEGREES', '/, ' D00002630
2DOPPLER SHIFT EXPERIENCED AT SECOND SATELLITE DUE TO SIGNAL TRANSMI00002640
2TTED FROM THE FIPST SATELLITE IN HZ.', '/, ' CROSSLINK VISIBILITY WHE00002650
2RE 0 MEANS THERE IS NO VISIBILITY BETWEEN SATELLITES AND 1 MEANS T00002660
2HERE IS VISIBILITY', '////')                        00002670
        DO 350 M1=1, L                                  00002680
        TAU=CON*A(M1)**1.5                             00002690
        N1=M1+1                                        00002700
        DO 250 M2=N1, M                                00002710
        WRITE(6,40)                                    00002720
40      FORMAT(1H, '2X, 'HRS', '12X, 'RANGF', '11X, 'C12', '12X, 'L12', '11X,
2 'CFDOPPLER', '6X, 'CVIS', '6X, 'SAT1', '6X, 'SAT2', '////) 00002730
        TAU2=CON*A(M2)**1.5                           00002740
        DO 300 I=1, 25                                 00002750
        RI=I                                           00002760
        NOVIZ=1                                        00002770
        CALL ELLIP(RI, F(M1), WP(M1), TP(M1), A(M1), TAU, FSP, R) 00002780
        CALL ELLIP(RI, E(M2), WP(M2), TP(M2), A(M2), TAU2, F2P, R2) 00002790
        CALL PRIME(FSP, W(M1), XI(M1), R, 0., XS, YS, ZS) 00002800
        CALL PRIME(F2P, W(M2), XI(M2), R2, 0., X2, Y2, Z2) 00002810
        TC1=X2-XS                                     00002820
        TC2=Y2-YS                                     00002830
        TC3=Z2-ZS                                     00002840
        R12=(TC1**2+TC2**2+TC3**2)**.5               00002850
        F12=RTD*ATAN(TC2/TC1)                         00002860
        IF(TC1.LT.0.) F12=F12+P*RTD                   00002870
        T12=ARCOS(TC3/R12)*RTD                        00002880
        VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)          00002890
        IF(VIZ.GT..9999999) VIZ=.9999999            00002900
        DEL=ARCOS(VIZ)                                00002910
        DELM=ARSIN(PE/R)                              00002920
        IF(DELM.LE.DELM) NOVIZ=0                     00002930
        CALL DOPF(R, E(M1), A(M1), TAU, FSP, WP(M1), W(M1), XI(M1), XV, YV, ZV) 00002940
        CALL DOPF(R2, E(M2), A(M2), TAU2, F2P, WP(M2), W(M2), XI(M2), S2, U2, V2) 00002950
        DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3      00002960
        DOT=DOT/R12                                  00002970
        DOP12=-DOT*FR3/CL                             00002980
        WRITE(6,50) RI, R12, T12, F12, DOP12, NOVIZ, M1, M2 00002990
50      FORMAT(1H, 'F5.1, F17.3, F14.3, F15.3, F20.3, I9, I10, I10) 00003000
300     CONTINUE                                       00003010
        WRITE(6,60)                                    00003020
        WRITE(6,60)                                    00003030

```

AD-A037 118

MITRE CORP BEDFORD MASS

F/G 17/2

HIGH ALTITUDE SATELLITE COMMUNICATIONS, WITH CROSSLINKS.(U)

JAN 77 P F CHRISTOPHER, E R EDELMAN

F19628-76-C-0001

UNCLASSIFIED

MTR-3161

ESD-TR-76-363

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2 OF 2

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END

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4 - 77

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60      FORMAT(1H, '/')
       IF (J1.EQ.0) GO TO 250
       WRITE(6,68?)
       READ 150, NO
       IF (NO.EQ.?) GO TO 690
       WRITE(6,25)
250    CONTINUE
350    CONTINUE
690    CONTINUE
      END
      SUBROUTINE PRIME(FSP, WS, XIS, XPS, YPS, XS, YS, ZS)
      A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)
      A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)
      A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)
      A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)
      A31=SIN(XIS)*SIN(FSP)
      A32=SIN(XIS)*COS(FSP)
      XS=A11*XPS+A12*YPS
      YS=A21*XPS+A22*YPS
      ZS=A31*XPS+A32*YPS
      RETURN
      END
      SUBROUTINE ELLIP(T, E, WP, TP, A, TAU, FSP, R)
      P=3.1415926
      Z=2.*P*(T-TP)/TAU
      P2=2.*P
2     IF (Z.GT.P2) Z=Z-P2
      IF (Z.GT.P2) GO TO 2
      E1=Z+P*SIN(Z)
      E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1))
      Q=0.
4     E3=(Z+P*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))
      Q=Q+1.
      DE=E3-E2
      DE2=DE**2
      E2=E3
      IF (DE2.GT..00000001) GO TO 4
      TH=ARCOS((COS(P2)-E)/(1.-E*COS(P2)))
      IF (Z.GT.P) TH=2.*P-TH
      FSP=WP+TH
      R=(A*(1.-E**2))/(1.+E*COS(FSP-WP))
      RETURN
      END
      SUBROUTINE DOPE(R, E, A, TAU, FSP, WP, WS, XIS, XD, YD, ZD)
      P=3.1415926
      T=FSP-WP
      RD=(A*E**2.*P/(TAU*(1.-E**2)**.5))*SIN(T)
      TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*COS(T))**2
      XPC=RD*COS(FSP)-R*TD*SIN(FSP)
      XPC=XPC/3600.
      YPC=RD*SIN(FSP)+R*TD*COS(FSP)
      YPC=YPC/3600.
      CALL PRIME(0., WS, XIS, XPC, YPC, XD, YD, ZD)
      RETURN
      END

```

\*\*\*\*\*

## APPENDIX 4

### PROGRAM SATVIZD

This program is similar to SATVIZE but it gives results in double precision. Its CPU time requirements can be more than 50% greater than SATVIZE, so its use has been infrequent and specialized.

The subroutine ELLIP listed here should not be confused with the ELLIP routines of the other appendices. It contains the expansion derived by F. R. Moulton<sup>[3]</sup> for true anomaly, and is accurate only for eccentricity  $\leq 0.5$ .

```

IMPLICIT REAL*8(A-H,O-Z)                                00000005
DIMENSION A(11),P(1),W(11),WP(11),TP(11),XI(11),C(3),RL(3) 00000010
J1=0                                                    00000020
DATA A/0.,22767.,22767.,22767.,22767.,36140.36,36140.36, 00000030
1 36140.36,36140.36,14342.3,14342.3/                    00000040
DATA P/0.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1./              00000050
2,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733,243.733/ 00000060
DATA WP/0.,0.,0.,0.,0.,0.,0.,0.,0.,-90.0,-90.0/         00000080
DATA TP/0.,0.,-6.,-12.,-18.,0.,-12.,-24.,-36.,-6.75,-6.75/ 00000090
DATA XI/23.4,23.4,23.4,23.4,23.4,113.4,113.4,113.4,113.4,63.4,63.4/ 00000100
163.4/                                                  00000110
DATA C/0.,47.54,57.23/                                00000120
DATA PL/0.,288.73,242.8/                              00000130
WRITE(6,110)                                           00000140
110  FORMAT(1H ,///)                                    00000150
WRITE(6,115)                                           00000160
115  FORMAT(1H , 'THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR A00000170
1 MAXIMUM OF 10 SATELLITES AND 2 GROUND STATIONS.',//) 00000180
WRITE(6,120)                                           00000190
120  FORMAT(1H , 'FOR EACH SATELLITE THE FOLLOWING DATA MUST BE SUPP0000200
1LIFE:',//, ' SEMI MAJOR AXIS',//, ' ECCENTRICITY',//, ' RIGHT ASCENSION',0000210
1/,' ARGUMENT OF PERIGEE',//, ' TIME OF PERIGEE',//, ' INCLINATION',//)0000220
WRITE(6,125)                                           0000230
125  FORMAT(1H , 'FOR EACH GROUND STATION THE FOLLOWING DATA MUST B0000240
1E SUPPLIED:',//, ' COLATITUDE',//, ' LONGITUDE',//)   0000250
WRITE(6,142)                                           0000260
142  FORMAT(1H , 'ADDITIONAL DATA WHICH MUST BE SUPPLIED:',//, ' UPLIN0000270
1K FREQUENCY',//, ' DOWNLINK FREQUENCY',//, ' CROSSLINK FREQUENCY',//)0000280
WRITE(6,130)                                           0000290
130  FORMAT(1H , 'THE USER IS ASKED TO ANSWER SEVERAL QUESTIONS.',//,0000300
1' IF THE USER DOES NOT KNOW THE VALUE OF AN INPUT VARIABLE,',//, ' H0000310
1' SHOULD ENTER THE NUMBER 400.0. A DEFAULT VALUE WILL THEN BE USE0000320
1D.',//, ' THE USER IS EXPECTED, HOWEVER, TO SPECIFY THE NUMBER OF SATE0000330
1LLITES AND GROUND STATIONS TO BE CONSIDERED.',///)   0000335
WRITE(6,145)                                           0000340
145  FORMAT(1H , 'HOW MANY SATELLITES ARE TO BE CONSIDERED? ENTER IN0000350
1TEGER WITH RIGHTMOST DIGIT IN COLUMN 2.')            0000360
READ 150, M                                             0000370
WRITE(6,135) M                                         0000380
135  FORMAT(1H , I3)                                   0000390
WRITE(6,155)                                           0000400
155  FORMAT(1H , 'HOW MANY GROUND STATIONS ARE TO BE CONSIDERED? ENT0000410
1ER INTEGER IN COLUMN 2.')                             0000420
READ 150, N                                             0000430
WRITE(6,135) N                                         0000440
150  FORMAT(I2)                                        0000450
WRITE(6,25)                                            0000460
WRITE(6,25)                                            0000465
WRITE(6,95)                                             0000470
95  FORMAT(1H , 'ENTER FOLLOWING DATA IN DECIMAL FORM ANYWHERE IN T0000480
1HE FIRST 20 COLUMNS.',//)                            0000490
WRITE(6,140)                                           0000500
140  FORMAT(1H , 'WHAT IS THE SEMI MAJOR AXIS VALUE IN NAUTICAL MILES0000510
1 FOR SATELLITE 1?')                                  0000520
DO 101 I=1, M                                          0000530
K=I+1                                                  0000540
READ 170, A(I)                                         0000550
IF(A(I).NE.400.0)GO TO 605                            0000560
A(I)=A(K)                                              0000570
J1=1                                                    0000580

```

```

605      WRITE(6,305) A(I)                                C0000590
305      FORMAT(1H,P20.8)                                00000600
           IF(I.EQ.M)GO TO 101                            00000610
           PRINT 310,K                                    C0000620
310      FORMAT(1H,'FOR SATELLITE',I3,'?')              00000630
101      CONTINUE                                         00000640
           WRITE(6,315)                                    C0000650
315      FORMAT(1H,/,,'WHAT IS THE ECCENTRICITY OF SATELLITE 1?') 00000660
           DO 103 I=1,M                                    00000670
           K=I+1                                          C0000680
           READ 170, E(I)                                  00000690
           IF(E(I).NE.400.0)GO TO 610                    00000700
           E(I)=E(K)                                       00000710
           J1=1                                           00000720
610      WRITE(6,315) E(I)                                00000730
           IF(I.EQ.M)GO TO 103                            00000740
           PRINT 310, K                                    00000750
103      CONTINUE                                         00000760
           WRITE(6,320)                                    00000770
320      FORMAT(1H,/,,'WHAT IS THE RIGHT ASCENSION VALUE IN DEGREES FOR
1R SATELLITE 1?')
           DO 104 I=1,M                                    00000790
           K=I+1                                          00000800
           READ 170, W(I)                                  00000820
           IF(W(I).NE.400.0)GO TO 615                    00000830
           W(I)=W(K)                                       00000840
           J1=1                                           00000850
615      WRITE(6,305) W(I)                                00000860
           IF(I.EQ.M)GO TO 104                            00000870
           PRINT 310, K                                    00000880
104      CONTINUE                                         00000890
           WRITE(6,325)                                    00000900
325      FORMAT(1H,/,,'WHAT IS THE ARGUMENT OF PERIGEE VALUE IN DEGREE
1S FOR SATELLITE 1?')
           DO 106 I=1,M                                    00000920
           K=I+1                                          00000930
           READ 170, WP(I)                                 00000940
           IF(WP(I).NE.400.0)GO TO 620                  00000950
           WP(I)=WP(K)                                    00000960
           J1=1                                           00000970
620      WRITE(6,305) WP(I)                               00000980
           IF(I.EQ.M)GO TO 106                            00000990
           PRINT 310, K                                    00010000
106      CONTINUE                                         00010010
           WRITE(6,330)                                    00010020
330      FORMAT(1H,/,,'WHAT IS THE TIME OF PERIGEE IN HOURS FOR SATELLI
1IT? 1?')
           DO 107 I=1,M                                    00010050
           K=I+1                                          00010060
           READ 170, TP(I)                                 00010070
           IF(TP(I).NE.400.0)GO TO 625                  00010080
           TP(I)=TP(K)                                    00010090
           J1=1                                           00010100
625      WRITE(6,305) TP(I)                               00010110
           IF(I.EQ.M)GO TO 107                            00010120
           PRINT 310, K                                    00010130
107      CONTINUE                                         00010140
           WRITE(6,335)                                    00010150
335      FORMAT(1H,/,,'WHAT IS THE INCLINATION VALUE IN DEGREES FOR SA
1TELLITE 1?')
           DO 108 I=1,M                                    00010160

```

	K=I+1	00001200
	READ 170, XI(I)	00001210
	IF(XI(I).NE.400.0)GO TO 630	00001220
	XI(I)=XI(K)	00001230
	J1=1	00001240
630	WRITE(6,305)XI(I)	00001250
	IF(I.EQ.M)GO TO 108	00001260
	PRINT 310, K	00001270
108	CONTINUE	00001280
	WRITE(6,340)	00001290
340	FORMAT(1H ,/, 'WHAT IS THE COLATITUDE IN DEGREES FOR GROUND STATION 1?')	00001300
	DO 102 I=1,N	00001310
	K=I+1	00001320
	READ 170, C(I)	00001330
	IF(C(I).NE.400.0)GO TO 635	00001340
	C(I)=C(K)	00001350
	J1=1	00001360
635	WRITE(6,305)C(I)	00001370
	IF(I.EQ.N)GO TO 102	00001380
	PRINT 205, K	00001390
205	FORMAT(1H , 'FOR GROUND STATION',I3,'?')	00001400
102	CONTINUE	00001410
	WRITE(6,345)	00001420
345	FORMAT(1H ,/, 'WHAT IS THE LONGITUDE IN DEGREES FOR GROUND STATION 1?')	00001430
	DO 109 I=1,N	00001440
	K=I+1	00001450
	READ 170, RL(I)	00001460
170	FORMAT(F20.8)	00001470
	IF(RL(I).NE.400.0)GO TO 640	00001480
	RL(I)=RL(K)	00001490
	J1=1	00001500
640	WRITE(6,305)RL(I)	00001510
	IF(I.EQ.N)GO TO 100	00001520
	PRINT 205, K	00001530
100	CONTINUE	00001540
	WRITE(6,840)	00001550
840	FORMAT(1H ,////, 'ENTER THE FOLLOWING DATA IN EXPONENTIAL FORM (E.G. 300.0*10.**6 IS WRITTEN AS 300.0D6)',/, 'WITH THE RIGHTMOST 2 DIGIT APPEARING IN COLUMN 10.',/,)	00001560
	WRITE(6,845)	00001570
845	FORMAT(1H , 'WHAT IS THE UPLINK FREQUENCY IN HZ?')	00001580
	READ 850, FR1	00001590
850	FORMAT(D10.2)	00001600
	IF(FR1.EQ.400.0)FR1=300.0D6	00001610
	WRITE(6,855)FR1	00001620
855	FORMAT(1H ,D20.5)	00001630
	WRITE(6,860)	00001640
860	FORMAT(1H ,/, 'WHAT IS THE DOWNLINK FREQUENCY IN HZ?')	00001650
	READ 850, FR2	00001660
	IF(FR2.EQ.400.0)FR2=245.0D6	00001670
	WRITE(6,855)FR2	00001680
	WRITE(6,865)	00001690
865	FORMAT(1H ,/, 'WHAT IS THE CROSSLINK FREQUENCY IN HZ?')	00001700
	READ 850, FR3	00001710
	IF(FR3.EQ.400.0)FR3=38.0D0	00001720
	WRITE(6,855)FR3	00001730
	IF(J1.EQ.0)GO TO 660	00001740
	WRITE(6,670)	00001750
670	FORMAT(1H ,/, 'YOU HAVE NOT USED A COMPLETE DATA SET.',/, ' TH00001760	00001770
		00001780
		00001790
		00001800

```

'BEFORE, THE RESULTS ARE FOR DEMONSTRATION PURPOSES ONLY.')      00001810
GO TO 675                                                           00001820
660 WRITE(5,665)                                                  00001830
665 FORMAT(1H ,/,/, ' YOUR DATA SET IS COMPLETE.')             00001840
675 WRITE(6,105)                                                  00001850
105 FORMAT(1H ,/,/,/,)                                           00001860
P=3.1415926                                                       00001870
RE=3440.                                                           00001880
RTD=57.29577951                                                  00001890
WPAD=15.0/RTD                                                    00001900
CL=1.61984*10.**5                                               00001910
CON=6.987*10.**(-6)                                             00001920
WRITE(6,190)                                                      00001930
100 FORMAT(1H , 'RESULTS LISTED IN ORDER OF APPEARANCE ARE: ',/,/, ' RA00001940
2NGE BETWEEN GROUND STATION AND SATELLITE IN NAUTICAL MILES ',/,/, ' FLO0001950
2EVA TION ANGLE IN DEGREES FROM GROUND STATION TO SATELLITE ',/,/, ' UPL00001960
2LINK DOPPLER SHIFT IN HZ ',/,/, ' DOWNLINK DOPPLER SHIFT IN HZ ',/,/, ' SUB00001970
2SATELLITE COLATITUDE IN DEGREES ',/,/, ' SUBSATELLITE LONGITUDE IN DEG00001980
2REES ',/,/,/
DO 890 IN=1,N                                                     00002000
W(IN)=W(IN)/RTD                                                  00002010
WP(IN)=WP(IN)/RTD                                                00002020
XI(IN)=XI(IN)/RTD                                                00002030
890 CONTINUE                                                     00002040
DO 900 J=1,M                                                      00002050
TAU=CON*A(J)**1.5                                               00002060
DO 700 K=1,N                                                      00002070
WRITE(6,10)                                                       00002080
10 FORMAT(1H , 'SAT ',5X, 'HPS ',12X, 'FANGP ',9X, 'ANGLE ',8X, 'UPDOPPLER00002090
1',8X, 'DNDOPPLER ',9X, 'SUBC ',9X, 'SUBL ',6X, 'STATION ',/,/) 00002100
T=C(K)/RTD                                                        00002110
G=R1(K)/RTD                                                       00002120
DO 500 I=1,25                                                    00002130
PI=I                                                              00002140
CALL ELLIP(RI,F(J),WP(J),TP(J),A(J),TAU,PSP,P)                 00002150
CALL PRIME(PSP,W(J),XI(J),R,O.,XS,YS,ZS)                      00002160
FS=(DATAN(YS/XS)-WEAD*PI)*RTD                                     00002170
IP(XS.LT.O.) FS=FS+PI*RTD                                        00002180
TS=RTD*DAPCOS(ZS/P)                                             00002190
F=G+WRAD*PI                                                      00002200
X=RE*DSIN(T)*DCOS(P)                                           00002210
Y=R*DSIN(T)*DSIN(P)                                             00002220
Z=RE*DCOS(T)                                                     00002230
ACC=DARCOS((X*XS+Y*YS+Z*ZS)/(R*R))                             00002240
RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5                         00002250
ARG=DSIN(ACC)*R/RGE                                             00002260
IF(ARG.GT.1.0000000) ARG=1.0000000                             00002270
D=(DAPCOS(ARG)-P/2.)*RTD                                        00002280
R1=DSQRT(R*R-RE*RE)                                             00002290
IF(RGE.LE.RT) D=-D                                              00002300
CALL DOPE(R,F(J),A(J),TAU,PSP,W(J),W(J),XI(J),XV,YV,ZV)      00002310
XT=-WRAD*RE*DSIN(T)*DSIN(P)/3600.                             00002320
YT=WRAD*RP*DSIN(T)*DCOS(P)/3600.                               00002330
DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z)                  00002340
DOT=DOT/RGE                                                      00002350
UPDOP=-DOT*PI/CL                                                 00002360
DNDOP=-DOT*PI/CL                                                 00002370
WRITE(6,20) J,PI,RGE,D,UPDOP,DNDOP,TS,FS,K                    00002380
20 FORMAT(1H ,I3,F8.1,F17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10) 00002390
500 CONTINUE                                                     00002400

```

```

25      WRITE(6,25)                                00002410
      FORMAT(1H,///)                                00002420
      IF(J1.EQ.0) GO TO 700                          00002430
      WRITE(6,680)                                    00002440
680    FORMAT(1H, 'DO YOU WANT THIS PART OF THE PROGRAM TO CONTINUE?' 00002450
1,/, ' ENTER AN INTEGER 0 IF THE ANSWER IS NO OR AN INTEGER 1 IF THE
1 ANSWER IS YES IN COLUMN 2. ')                    00002470
      READ 150, NO                                     00002480
      IF(NO.EQ.0) GO TO 685                          00002490
      WRITE(6,25)                                    00002500
700    CONTINUE                                     00002510
900    CONTINUE                                     00002520
685    WRITE(6,3^ )                                  00002530
30     FORMAT(1H,///// )                          00002540
      L=M-1                                           00002550
      IF(L.EQ.0) GO TO 690                           00002560
      WRITE(6,260)                                   00002570
260    FORMAT(1H, 'THIS PART OF THE PROGRAM COMPUTES CROSSLINK VALUES
7 FOR ALL PAIRS OF SATELLITES.',/,/, ' RESULTS LISTED IN ORDER OF AP00002590
1PEARANCE ARE:',/, ' RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILFS'00002600
1,/, ' POINTING ANGLES BETWEEN SATELLITES (C12&L12) IN DEGREES',/, ' D00002610
20PPLR SHIF EXPERIENCED AT SECOND SATELLITE DUE TO SIGNAL TRANSMI0002620
2TTED FROM THE FIRST SATELLITE IN HZ.',/, ' CROSSLINK VISIBILITY WHE00002630
2RE 0 MEANS THERE IS NO VISIBILITY BETWEEN SATELLITES AND 1 MEANS "00002640
2HRE IS VISIBILITY',/,/)
      DO 350 M1=1,L                                  00002650
      TAU=CON*A(M1)**1.5                             00002670
      N1=M1+1                                       00002680
      DO 250 M2=N1,M                                00002690
      WRITE(6,40)                                    00002700
40     FORMAT(1H, 2X, 'RES', 12X, 'RANGE', 11X, 'C12', 12X, 'L12', 11X,
2 ' CRDOPPLR', 6X, 'CVIS', 6X, 'SAT1', 6X, 'SAT2', //) 00002710
      TAU2=CON*A(M2)**1.5                           00002730
      DO 300 I=1,25                                 00002740
      RI=I                                           00002750
      NOVIZ=1                                        00002760
      CALL ELLIP(RI, F(M1), WP(M1), TP(M1), A(M1), TAU, FSP, R) 00002770
      CALL ELLIP(RI, F(M2), WP(M2), TP(M2), A(M2), TAU2, F2P, R2) 00002780
      CALL PRIME(FSP, W(M1), XI(M1), R, C., XS, YS, ZS) 00002790
      CALL PRIME(F2P, W(M2), XI(M2), R2, C., X2, Y2, Z2) 00002800
      TC1=X2-XS                                     00002810
      TC2=Y2-YS                                     00002820
      TC3=Z2-ZS                                     00002830
      R12=(TC1**2+TC2**2+TC3**2)**.5                00002840
      P12=RTD*ATAN(TC2/TC1)                          00002850
      IF(TC1.LT.0.) P12=P12+P*RTD                    00002860
      T12=DARCOS(TC3/R12)*RTD                        00002870
      VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)           00002880
      IF(VIZ.GT..9999999) VIZ=.9999999              00002890
      DEL=DARCOS(VIZ)                                00002900
      DELM=DARSIN(RE/R)                              00002910
      IF(DELM.LE.DELM) NOVIZ=0                       00002920
      CALL DOPE(R, E(M1), A(M1), TAU, FSP, WP(M1), W(M1), XI(M1), XV, YV, ZV) 00002930
      CALL DOPE(R2, E(M2), A(M2), TAU2, F2P, WP(M2), W(M2), XI(M2), S2, U2, V2) 00002940
      DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3       00002950
      DOT=DOT/R12                                    00002960
      DOP12=-DOT*P12/CL                              00002970
      WRITE(6,50) RI, R12, T12, F12, DOP12, NOVIZ, M1, M2 00002980
50     FORMAT(1H, F5.1, F17.3, F14.3, F15.3, F20.3, I9, I10, I10) 00002990
300    CONTINUE                                     00003000

```

60	WRITE(6,60) FORMAT(1H, //) IF(J1.EQ.0) GO TO 250 WRITE(6,680) PEAD 150, NO IF(NO.EQ.0) GO TO 690 WRITE(6, 25)	00003010 00003020 00003030 00003040 00003050 00003060 00003070
250	CONTINUE	00003080
350	CONTINUE	00003090
690	CONTINUE END	00003100 00003110

SUBROUTINE PRIME(FSP, WS, XIS, XPS, YPS, XS, YS, ZS)  
IMPLICIT REAL\*8(A-H, O-Z)  
A11=DCOS(FSP)\*DCOS(WS)-DCOS(XIS)\*DSIN(WS)\*DSIN(FSP)  
A12=-DSIN(FSP)\*DCOS(WS)-DCOS(XIS)\*DSIN(WS)\*DCOS(FSP)  
A21=DCOS(FSP)\*DSIN(WS)+DCOS(XIS)\*DCOS(WS)\*DSIN(FSP)  
A22=-DSIN(FSP)\*DSIN(WS)+DCOS(XIS)\*DCOS(WS)\*DCOS(FSP)  
A31=DSIN(XIS)\*DSIN(FSP)  
A32=DSIN(XIS)\*DCOS(FSP)  
XS=A11\*XPS+A12\*YPS  
YS=A21\*XPS+A22\*YPS  
ZS=A31\*XPS+A32\*YPS  
RETURN  
END

SUBROUTINE ELLIP(T, E, WP, TP, A, TAU, FSP, P)  
IMPLICIT REAL\*8(A-H, O-Z)  
P=3.1415926  
Z=2.\*P\*(T-TP)/TAU  
S5M=DSIN(5.\*Z)  
S6M=DSIN(6.\*Z)  
S7M=DSIN(7.\*Z)  
C5M=DCOS(5.\*Z)  
C6M=DCOS(6.\*Z)  
C7M=DCOS(7.\*Z)  
SM=DSIN(Z)  
S2M=DSIN(2.\*Z)  
S3M=DSIN(3.\*Z)  
S4M=DSIN(4.\*Z)  
CM=DCOS(Z)  
PSP=Z+2.\*E\*SM+1.25\*(P\*\*2)\*S2M+((E\*\*3)/12.)\*(13.\*S3M-3.\*SM)  
PSP=PSP+WP+((P\*\*4)/96.)\*(103.\*S4M-44.\*S2M)  
P5=((P\*\*5)/960.)\*(1097.\*S5M-645.\*S3M+50.\*SM)  
P6=((P\*\*6)/960.)\*(1223.\*S6M-902.\*S4M+85.\*S2M)  
P7=((P\*\*7)/32256.)\*(47273.\*S7M-41699.\*S5M+5985.\*S3M+749.\*CM)  
PSP=PSP+P5+P6+P7  
R=(A\*(1.-E\*\*2))/(1.+E\*DCOS(FSP-WP))  
RETURN  
END

SUBROUTINE DOPE(P, F, A, TAU, FSP, WP, WS, XIS, XD, YD, ZD)  
IMPLICIT REAL\*8(A-H, O-Z)  
P=3.1415926  
T=FSP-WP  
RD=(A\*E\*2.\*P/(TAU\*(1.-E\*\*2)\*\*.5))\*DSIN(T)  
TD=(2.\*P/TAU)\*((1.-E\*\*2)\*\*(-1.5))\*((1.+E\*DCOS(T))\*\*2)  
XPC=RD\*DCOS(FSP)-P\*TD\*DSIN(FSP)  
XPC=XPC/3600.  
YPC=PD\*DSIN(FSP)+R\*TD\*DCOS(FSP)  
YPC=YPC/3600.  
CALL PRIME(C., WS, XIS, XPC, YPC, XD, YD, ZD)  
RETURN

END

00003580



## APPENDIX 5

### PROGRAM PERTP

PERTP calculates the secular changes in argument of perigee, right ascension, eccentricity, and semi-major axis as a function of lunar perturbations. A normalized apogee distance ( $V_5$ ) is plotted on the CALCOMP plotter as a function of time.

Unlike Appendices 1 through 4 which require distances in nautical miles, PERTP requires distances in kilometers.

```

//PERTP JOE (6360,D91,DESK),'EDELMAN F',NOTIFY=TS0141,      00000010
// CLASS=F,TIME=2,TYPRUN=HOLD                                00000020
/*SETUP TAPE PLYXXX                                          00000030
// EXEC FORTGCLG                                             00000040
//FORT.SYSIN DD *                                           00000050
C THIS PROGRAM PRODUCES THE SECULAR VARIANCE OF ,AN INITIALLY, 0000006C
C HIGH ALTITUDE ORBIT, AND AT THE SAME TIME GENERATES STABILITY OF 00000070
C ECCENTRICITY, RIGHT ASCENSION AND ARGUMENT OF PERIGEE. IT ALSO 0000008C
C PRODUCES THE EVER CHANGING SEMI-MAJOR AXIS.                00000090
C AND THEN, USING THE CALCOMP PLOTTER                        0000010C
C PRODUCES PLOTS FOR DIFFERENT ANGLES                       00000110
C OF INCLINATION, GRAPHING V5 VS. DAYS.                     00000120
C ALL VALUES IN THIS PROGRAM HAVE BEEN                    00000130
C CONVERTED TO THE METRIC SYSTEM,                            00000140
C WHERE 1 NAUTICAL MILE=1.852 KM.                             00000150
      DIMENSION IBUF(2000),XARRAY(42),YARRAY(42)             0000016C
      CON=2.77218*10.**(-6)                                   00000170
      PI=3.1415926                                           00000180
      PTD=57.29577051                                        00000190
      RHO=383364.0000                                        00000200
      DO 200 J=45,135,45                                     00000210
      RJ=J                                                     00000220
      XI=RJ                                                    00000230
      AO=256452.9085                                         00000240
      TAU=CON*AO**1.5                                       00000250
      V=(24./TAU)*10.                                        00000260
      PO=.15                                                 00000270
      V5O=AO*(1.+PO)                                        00000280
      XI=XI/PTD                                              00000290
      W=0.                                                    00000300
      WP=45.                                                 00000310
      WS=W/PTD                                               00000320
      WP=WP/RTD                                              00000330
      CALL APGPER(AO,XI,WP,WS,V1)                             00000340
      IF(V1.GT.0.) WP=WS                                     00000350
      XID=XI*PTD                                             00000360
      WRITE(6,10)                                            00000370
10  FORMAT(1H ,9X,'R',17X,'WD',15X,'WPD',17X,'DE',11X,'V5',15X, 00000380
      1 'DMPD',9X,'XI',6X,'DAYS')                             00000390
      WRITE(6,15) XID                                        0000040C
15  FORMAT(1H ,105X,F6.2)                                    00000410
      DO 100 I=1,40                                          00000420
      PI=I                                                    00000430
      IF(I.P0.1) E=PO                                         00000440
      DAYS=PI*10.                                            00000450
      XARRAY(I)=DAYS                                         00000460
      IF(I.GT.1) AO=A                                         00000470
      CALL MOON(AO,XI,A)                                       00000480
      UP3=PI*(1./R1.)*((A/RHO)**3)                           00000490
      A2=((A/RHO)**2)                                         00000500
      A4=((A/RHO)**4)                                         00000510
      CI2=(COS(XI))**2                                        00000520
      CI4=(COS(XI))**4                                        00000530
      SP2=(SIN(WP))**2                                       00000540
      SI2=(SIN(XI))**2                                       00000550
      PAR1=((-135./128.)+(315./128.)*CI2)                    00000560
      PAR2=((2625./2048.)-(7875./1024.)*CI2+(17325./2048.)*CI4) 00000570
      PAR3=((315./128.)-(315./16.)*CI2+(2205./128.)*CI4)    00000580
      PAR4=(3.-(15./2.)*SP2*SI2)                             00000590
      PAR5=((225./32.)-(315./8.)*SP2)                       00000600
      PAR6=(-45./32.)*(315./64.)*SP2+PAR5*CI2+(2205./64.)*SP2*CI4 00000610

```

```

DW=-2*UPA3*COS(XI)*((3./4.)+A2*PAR1+(A4*PAR2))*V          00000620
DE=-UPA3*E*SIN(2*WP)*((-15./4.)*SI2+A2*PAR3)*V           00000630
DWP=UPA3*(PAR4+A2*PAP6)*V                                  00000640
W=W+DW                                                       00000650
E=E+DE                                                       00000660
V5=(A*(1.+E))/V50                                           00000670
WP=W+DWP                                                      00000680
WD=W*RTD                                                       00000690
WPD=W*RTD                                                      00000700
DWD=DW*RTD                                                      00000710
DWPD=DWP*RTD                                                   00000720
YARPAY(I)=V5                                                  00000730
WRITE(6,20)E,WD,WPD,DE,V5,DWPD,DAYS                        00000740
20  FORMAT(1H ,6E17.7,P17.2)                                00000750
100 CONTINUE                                                 00000760
WRITE(6,25)                                                  00000770
25  FORMAT(1H ,//)                                           00000780
CALL PLOTS(IBUF,2000,6)                                       00000790
CALL PLOT(0.0,1.0,-3)                                         00000800
CALL SCALE(XARRAY,10.0,40,1)                                   00000810
CALL SCALE(YARPAY,8.0,40,1)                                    00000820
CALL AXIS(0.0,0.0,12HTIME IN DAYS,-12,10.0                 00000830
1 ,0.0,XARRAY(41),YARPAY(42))                                00000840
C DELTA APOGEE, IS THE NEW SEMI-MAJOR AXIS                   00000850
C TIMES, THE NEW ECCENTRICITY PLUS ONE, DIVIDED            00000860
C BY THE INITIAL VALUE OF THE SEMI-MAJOR AXIS               00000870
C TIMES, THE INITIAL ECCENTRICITY PLUS ONE;                 00000880
C OR IN EQUATION FORM, (A*(1.+E))/(AO*(1.+EO))             00000890
CALL AXIS(0.0,0.0,12HDELTA APOGEE,+12,9.0                   00000900
1 ,90.0,YARRAY(41),YARPAY(42))                                00000910
CALL LINE(XARRAY,YARPAY,40,1,0,0)                             00000920
CALL PLOT(18.0,-30.0,-3)                                       00000930
200 CONTINUE                                                 00000940
CALL PLOT(12.0,0.0,999)                                         00000950
RETURN                                                         00000960
END                                                            00000970
SUBROUTINE ARGPER(AO,XI,WP,WS,V1)                               00000980
PI=3.14159265                                                  00000990
RHO=383364.0000                                                00001000
PTD=57.29577951                                               00001010
V1=0.                                                           00001020
WS=0.                                                           00001030
A2=(AO/RHO)**2                                                 00001040
V1=XI                                                           00001050
IF(V4.EQ.0.)V4=.0001                                           00001060
NUM=-3.+A2*((45./32.)-(225./32.)*(COS(V4))**2)               00001070
DEN=-7.5*(SIN(V4))**2+A2*((315./64.)-(315./8.)*(COS(V4))**2 00001080
1 +(2205./64.)*(COS(V4))**2)
RAT2=NUM/DEN                                                   00001100
IF(RAT2.LE.0.)RETURN                                           00001110
IF(PAT2.GT.1.)RETURN                                           00001120
ARG=SQRT(RAT2)                                                 00001130
WS=ARSIN(ARG)                                                  00001140
V1=1.                                                           00001150
RETURN                                                         00001160
END                                                            00001170
SUBROUTINE MOON(AO,XI,A)                                       00001180
PI=3.14159265                                                  00001190
P2=PI/2                                                        00001200
TP=.3                                                           00001210
MUE=.3986*10.**6                                              00001220

```

```

PM=383364.0000
C2=(4.8998*10.**3)/((PM-AO)**2)
WS=630.7828*(AO**(-1.5))
WM=2.66381*(10.**(-6))
W=(WS*COS(XI)-WM)
IF(W.LT.C.)W=-W
WRFL=((W)**2+(WS*SIN(XI))**2)
WRFL=SQRT(WRFL)
RAT=AO/(PM-AO)
PAR=.33333333*SIN(TE*RAT)*(COS(TE*RAT)**2+2.)
DVR=2.*C2*PAR/(WRFL*RAT)
DA=((DVR)**2)*(AO**2)/MUF
V=SIN(XI)
IF(V.EQ.C.)V=.000000001
ANG=TE/V
IF(ANG.GT.P2)ANG=P2
DAD=86400.*(WRFL*ANG/(PI**2))*DA
DADY=365.*DAD
RATA=DADY/AO
A=AO*10.*DAD
RETURN
END
//LKED.SYSLIB DD DISP=SHR
// DD DSN=SYS1.CALCCMP,DISP=SHR
//GO.PLOTTAPE DD DSN=PLOT,DISP=(,KEEP),
// UNIT=(TAPE7,,DEFER),DCB=DEB=1,
// VOL=SER=PLXXXX,LABEL=(,NI)
00001230
00001240
00001250
00001260
00001270
00001280
00001290
00001300
00001310
00001320
00001330
00001340
00001350
00001360
00001370
00001380
00001390
00001400
00001410
00001420
00001430
00001440
00001450
00001460
00001470
00001480
00001490

```

\*\*\*\*\*

## APPENDIX 6

### PROGRAM SATLUNAE

SATLUNAE has the same purpose as SCOREE, (App. 7), but approximate integrations rather than the time iterations of SCOREE are used. Its utility, then, is for time  $>5$  years or when very stringent CPU requirements are imposed.

The future time of interest for the perturbed elements is entered on line 350 in days.

SATLUNAE also includes a more convenient crosslink pointing angle coordinate system than SATE. See Figure 11. TU12 and FU12 are chosen in a local satellite coordinate system.

```

//TS0420A JOB (6360,D31,DESK),'CHRISTOPHER P',NOTIFY=TS0420,      00000010
// TIME=2                                                              00000020
// EXEC FORTGCG                                                       00000030
//POPT.SYSIN DE *                                                     00000040
C THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR A MAXIMUM OF     00000050
C TEN SATELLITES AND TWO GROUND STATIONS.                            00000060
C THE APRAYS CONTAIN THE FOLLOWING INFORMATION FOR EACH SATELLITE:   00000070
C A--SEMI-MAJOR AXIS IN KM                                           00000080
C E--ECCENTRICITY                                                    00000090
C W--RIGHT ASCENSION IN DEGREES                                     00000100
C WP--ARGUMENT OF PERIGEE IN DEGREES                                00000110
C TP--TIME OF PERIGEE IN HOURS                                       00000120
C XI--INCLINATION IN DEGREES                                        00000130
C ARRAY B CONTAINS THE LATITUDE AND LONGITUDE FOR EACH GROUND STATION.00000140
  DIMENSION A(10),EC(10),WC(10),WPO(10),TP(10),XI(10),B(4)         00000150
  DATA A/26561.,26561.,42164.,42164.,42164.,42164.,                00000160
  3 106247.,106247.,106247.,106247./                                00000170
  DATA EC/.725,.725,.0,.0,.0,.0,.0,.0,.0,.0./                    00000180
  DATA WC/0.,270.,0.,0.,0.,0.,                                00000190
  4 0.,0.,0.,0./                                                    00000200
  DATA WPO/-90.,-90.,0.,0.,0.,0.,0.,0.,0.,0./                    00000210
  DATA TP/0.,-6.,-3.,-9.,-15.,-21.,                                00000220
  1 0.,-24.,-48.,-72./                                              00000230
  DATA XI/63.435,63.435,0.,0.,0.,0.,90.,90.,90.,90./              00000240
  DATA B/47.54,57.23,288.73,242.8/                                  00000250
  WPITF(6,4)                                                         00000260
  4  FORMAT('H','ABIG',13X,'E1',13X,'W',13X,'WPS',13X,'V5',/)      00000270
  DIMENSION E(10),WP(10),ABIG(10),E1(10),W(10),WPS(10),V5(10)    00000280
  DIMENSION XM(10)                                                    00000290
  RTD=57.29578                                                         00000300
  DO 8 JR=1,10                                                         00000310
  WC(JR)=WC(JR)/RTD                                                  00000320
  WPO(JR)=WPO(JR)/PTD                                                00000330
  XM(JR)=(XI(JR)-23.4)/RTD                                           00000340
  DAYS=400.                                                            00000350
  CALL LUNA(A(JR),E1(JR),W(JR),WPO(JR),XM(JR),DAYS,ABIG(JR))        00000360
  1 ,E1(JR),W(JR),WPS(JR),V5(JR))                                   00000370
  WD=W(JR)*RTD                                                         00000380
  WPSD=WPS(JR)*RTD                                                    00000390
  WPITF(6,0)ABIG(JR),E1(JR),WD,WPSD,V5(JR)                         00000400
  9  FORMAT('H',1F14.1,1F14.9,1F14.6,1F14.6,1F14.7)               00000410
  8  CONTINUE                                                         00000420
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED.                00000430
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED.           00000440
  NUMS=10                                                              00000450
  NUMG=2                                                                00000460
  P=3.1415926                                                           00000470
  RE=6370.8                                                             00000480
  RTD=57.29577951                                                      00000490
  WPAO=15.0/RTD                                                         00000500
C CL IS THE VELOCITY OF LIGHT IN NAUTICAL MILES PER SECOND.         00000510
  CL=2.99793*10.**5                                                    00000520
C FP IS THE UPLINK FREQUENCY IN HZ.                                   00000530
C FR1 IS THE DOWNLINK FREQUENCY IN HZ.                               00000540
  FP=200.0*10.**6                                                       00000550
  FR1=245.0*10.**6                                                      00000560
  CON=2.77218*10.**(-6)                                                00000570
  DO 900 J=1,NUMS                                                       00000580
  XI(J)=XI(J)/RTD                                                      00000590
  E(J)=E1(J)                                                            00000600
  A(J)=ABIG(J)                                                          00000610

```

```

      WP(J)=WPS(J)
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J.
      TAU=CON*A(J)**1.5
      DO 700 K=1, NUMG
      WRITE(6,10)
10    FORMAT(1H , 'SAT',5X, 'HPS',12X, 'RANGE',9X, 'ANGLE',8X, 'UPDOPPLER',
      1',8X, 'DNDOPPLER',9X, 'SUBL',9X, 'SUBC',6X, 'STATION',//)
      T=B(K)/PTD
      G=B(K+2)/PTD
C I IS THE HOUR.
      DO 500 I=3,51,3
      RI=I
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GOCENTER TO SATELLITE J AND
C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE
C AND EQUATORIAL PLANE.
      CALL ELLIP(PI,F(J),WP(J),TP(J),A(J),TAU,PSP,R)
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE
C SATELLITE J (WITH GEOCENTER AS THE ORIGIN).
      CALL PRIME(FSP,W(J),XI(J),R,O.,XS,YS,ZS)
C FS IS THE SUBSATELLITE LONGITUDE IN DEGREES.
      FS=(ATAN(YS/XS)-WPAD*PI)*RTD
      IF(XS.LT.O.)FS=FS+P*RTD
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES.
      TS=RTD*ARCOS(ZS/R)
      F=G+WRAD*RI
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K.
      X=R*F*SIN(T)*COS(F)
      Y=R*F*SIN(T)*SIN(F)
      Z=P*F*COS(T)
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE
C CENTER OF THE EARTH.
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL
C MILES.
      ACC=ARCOS((X*XS+Y*YS+Z*ZS)/(R*F*R))
      RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5
      ARG=SIN(ACC)*R/PGE
      IF(ARG.GT.1.0000000)ARG=1.0000000
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO
C SATELLITE J.
      D=(ARSIN(ARG)-P/2.)*PTD
      RT=SQRT(R*R-R*E*E)
      IF(RGE.LE.RT)D=-D
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
      CALL DOPE(R,F(J),A(J),TAU,PSP,WP(J),W(J),XI(J),XV,YV,ZV)
C (XT,YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND
C STATION K.
      XT=-WPAD*RE*SIN(T)*SIN(F)/3600.
      YT=WRAD*RE*SIN(T)*COS(F)/3600.
      DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z)
      DOT=-DOT/RGE
C UPDOP IS THE UPLINK DOPPLER SHIFT IN HZ.
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ.
      UPDOP=DOT*FP/CL
      DNDOP=DOT*FP1/CL
      WRITE(6,20)J,RI,PGE,D,UPDOP,DNDOP,FS,TS,K
20    FORMAT(1H ,I3,F8.1,'17.3,F14.3,'17.3,F17.3,F13.3,F13.3,I10)
500   CONTINUE
      WRITE(6,25)
25    FORMAT(1H ,//)
700   CONTINUE
900   CONTINUE

```

```

WRITE(6,30)
30  FORMAT(1H ,/////)
    L=NUMS-1
    IF(L.EQ.0)GO TO 350
C FP IS THE CROSSLINK FREQUENCY IN HZ.
  FR=60.*10.**9
C M1 IS THE FIRST SATELLITE.
C M2 IS THE SECOND SATELLITE.
  DO 350 M1=1,L
    TAU=CON*A(M1)**1.5
    N=M1+1
    DO 250 M2=N,NUMS
      WRITE(6,40)
40  FORMAT(1H ,2X,'HRS',12X,'RANGE',5X,'L12',5X,'C12',3X,'FU12',
        2  8X,'TU12',4X,'CPDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//)
      TAU2=CON*A(M2)**1.5
      DO 300 I=3,150,3
        RI=I
C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY
C AND 1 MEANS VISIBILITY.
      NOVIZ=1
      CALL ELLIP(P1,F(M1),WP(M1),TP(M1),A(M1),TAU,FSP,R)
      CALL ELLIP(P2,F(M2),WP(M2),TP(M2),A(M2),TAU2,F2P,R2)
      CALL PRIME(FSP,W(M1),XI(M1),R,0.,XS,YS,ZS)
      CALL PRIME(F2P,W(M2),XI(M2),R2,0.,X2,Y2,Z2)
      TC1=X2-XS
      TC2=Y2-YS
      TC3=Z2-ZS
C F12 IS THE RANGE BETWEEN TWO SATELLITES IN KM.
C F12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES.
      F12=(TC1**2+TC2**2+TC3**2)**.5
      CALL UNPRIM(TC1,TC2,TC3,FSP,W(M1),XI(M1),R12,FU12,TU12)
      F12=RTD*ATAN(TC2/TC1)
      IF(TC1.LT.0.)F12=F12+P*RTD
      VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)
      IF(VIZ.GT..99999999)VIZ=.99999999
      IF(VIZ.LT.-.99999999)VIZ=-.99999999
      DEL=ARCOS(VIZ)
      DELM=ARSIN(RF/R)
      IF(DELM.LE.DELM)NOVIZ=0
      TR3=TC3/R12
      IF(TR3.GE.1.)TR3=.99999999
      IF(TR3.LE.-1.)TR3=-.99999999
      T12=ARCOS(TR3)*RTD
      CALL DOPE(R,F(M1),A(M1),TAU,FSP,WP(M1),W(M1),XI(M1),XV,YV,ZV)
      CALL DOPE(R2,F(M2),A(M2),TAU2,F2P,WP(M2),W(M2),XI(M2),S2,U2,V2)
      DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3
      DOT=DOT/R12
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ.
      DOP12=-DOT*FR/CL
      WRITE(6,50)PI,R12,F12,T12,FU12,TU12,DOP12,NOVIZ,M1,M2
50  FORMAT(1H ,F5.1,F17.3,F9.1,F7.1,F10.1,F6.1,F17.3,I9,I10,I10)
      CONTINUE
      WRITE(6,60)
60  FORMAT(1H ,//)
      CONTINUE
      CONTINUE
      END
SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)
  A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)
  A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)

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```

A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)
A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)
A31=SIN(XIS)*SIN(FSP)
A32=SIN(XIS)*COS(FSP)
XS=A11*XPS+A12*YPS
YS=A21*XPS+A22*YPS
ZS=A31*XPS+A32*YPS
RE TURN
END
SUBROUTINE ELLIP(T,E,WP,TP,A,TAU,FSP,P)
P=3.1415926
Z=2.*P*(T-TP)/TAU
P2=2.*P
2 IF(Z.GT.P2)Z=Z-P2
IF(Z.GT.P2)GO TO 2
E1=Z+E*SIN(Z)
E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1))
Q=0.
4 E3=(Z+E*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))
Q=Q+1.
DE=E3-E2
DE2=DE**2
E2=E3
IF(DE2.GT..00000001)GO TO 4
TH=ARCOS((COS(E2)-E)/(1.-E*COS(E2)))
IF(Z.GT.P)TH=2.*P-TH
FSP=WP+TH
R=(A*(1.-E**2))/(1.+E*COS(FSP-WP))
RE TURN
END
SUBROUTINE DOPE(R,E,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)
P=3.1415926
T=FSP-WP
PD=(A*E**2.*P/(TAU*(1.-E**2)**.5))*SIN(T)
TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*((1.+E*COS(T))**2)
XPC=PD*COS(FSP)-P*TD*SIN(FSP)
YPC=PD*SIN(FSP)+P*TD*COS(FSP)
YPC=YPC/3600.
CALL PRIMP(C.,WS,XIS,XPC,YPC,XD,YD,ZD)
RE TURN
END
SUBROUTINE UNPRIM(TC1,TC2,TC3,FSP,WS,XIS,R12,FU12,TU12)
A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)
A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)
A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)
A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)
A31=SIN(XIS)*SIN(FSP)
A32=SIN(XIS)*COS(FSP)
A13=SIN(XIS)*SIN(WS)
A23=-SIN(XIS)*COS(WS)
A33=COS(XIS)
Z1=A11*TC1+A21*TC2+A31*TC3
X1=A12*TC1+A22*TC2+A32*TC3
Y1=A13*TC1+A23*TC2+A33*TC3
XU=X1
YU=-Y1
ZU=-Z1
RTD=57.29577951
P=3.14159265

```

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FU12=RTD*ATAN(YU/XU)
IF(XU.LT.0.)FU12=FU12+P*RTD
ZR=ZU/P12
IF(ZR.GE.1.)ZR=.99999999
IF(ZR.LE.-1.)ZR=-.99999999
TU12=ARCCOS(ZR)*RTD
RETURN
END
SUBROUTINE LUNA(A,E0,W0,WPC,XI,T,ABIG,E1,W,WPS,V5)
P=3.14159265
T=24.*T
P2=P/2.
P1D=57.29578
WM=2.6538*10.**(-6)
WS=630.7828*A**(-1.5)
RM=383368.8
MUE=.3986*10.**6
TE=.3
IF(XI.LT..0001)XI=.0001
IF(XI.EQ.0)XI=P-.0001
RAT=A/(RM-A)
PAR=.33333333*SIN(TE*PAT)*((COS(TE*FAT))**2+2.)
WREL=SQRT((WS*COS(XI)-WM)**2+(WS*SIN(XI))**2)
C2=(4.8999*10.**3)/((RM-A)**2)
DVP=2.*C2*PAR/(WREL*RAT)
V7=SIW(XI)
IF(V7.EQ.0.)V7=.00000001
ANG=TE/V7
IF(ANG.GT.P2)ANG=P2
DAH=360.*(WREL*ANG/P**2)*((DVP**2)*A**2)/MUE
C5=DAH
DAY=P760.*DAH
AB=A+(C5*T)/2.
RHO=RM
C6=P*(1./81.)*(1./RHO)**3
C7=2.77219*10.**(-6)
S2I=(SIN(XI))**2
C2I=(COS(XI))**2
C4I=C2I**2
AR2=(AB/RHO)**2
C9=3.+AR2*((-45./32.)+(225./32.)*C2I)
C10=-7.5*S2I+AP2*((315./64.)-(315./8.)*C2I+(2205./64.)*C4I)
RATIO=-C9/C10
C11=-(15./4.)*S2I+AR2*((315./128.)-(315./16.)*C2I+(2205./128.)*C4I)
1 I)
WPS=0.
IF(RATIO.LT.0.)GO TO 50
IF(RATIO.GT.1.)GO TO 50
WPS=ARSIN(SQRT(RATIO))
E1=EO*EXP(-C6*(AB**1.5)*(SIN(2.*WPS))*(C11/C7)*T)
GO TO 100
50 WPC=(P/4.)-.001
CR=3.-((15./4.)*S2I+AR2*(1.054688-22.5*C2I+17.22656*C4I)
WANG=C6*C8*(AB**1.5)/C7
C21=2.*C6*(AB**1.5)*C8/C7
C20=2.*WPC
E1=EO*EXP(-C6*(AB**1.5)*(C11/C7)*(-(1./C21)*COS(C20)+(1./C21)*
2 COS(C20+C21*T)))
100 DW=-2.*C6*(AB**3)*COS(XI)*(.75+AR2*(-(135./128.)+(315./128.)*C2I)
3 )+(AR2**2)*((2625./2048.)-(7975./1024.)*C2I+(17325./2048.)*C4I
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u ))
DWH=DW/(C7*AB**1.5)
W=W0+DWH*T
ABIG=A+(C5*T)
V50=A*(1.+EC)
V5=ABIG*(1.+E1)/V50
RETURN
END
```

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APPENDIX 7

PROGRAM SCOREE

The lunar perturbation results of PERTP are combined with the link program SATE to calculate new crosslink relations after a long period (e.g., a few years). The future time of interest is entered on line 260 as EPOCH, in days.

Semi-major axes are in kilometers.

```

//SCORE JOB (6360,D91,DESK),'EDELMAN E',NOTIFY=TS0141,          00000010
// TIME=2                                                         00000020
// EXEC FORTGCG                                                  00000030
//PORT.SYSIN DD *                                              00000040
C TEN SATELLITES AND TWO GROUND STATIONS.                       00000050
C THE ARRAYS CONTAIN THE FOLLOWING INFORMATION FOR EACH SATELLITE: 00000060
C A--SEMI-MAJOR AXIS IN NAUTICAL MILES                          00000070
C E--ECCENTRICITY                                               00000080
C W--RIGHT ASCENSION IN DEGREES                                00000090
C WP--ARGUMENT OF PERIGEE IN DEGREES                            00000100
C TP--TIME OF PERIGEE IN HOURS                                  00000110
C XI--INCLINATION IN DEGREES                                    00000120
C ARRAY B CONTAINS THE COLATITUDE AND LONGITUDE FOR EACH GROUND STATION. 00000130
  DIMENSION AO(10),EO(10),WO(10),WPO(10),TP(10),XI(10),B(4)   00000140
  DATA AO/20000.,20000.,20000.,20000.,20000.,20000.,20000.,20000.,20000.,20000., 00000150
    1 250000.,250000.,250000.,250000./                          00000160
  DATA EO/.1,.1,.1,.1,.1,.1,.1,.1,.1,.1./                    00000170
  DATA WO/0.,0.,0.,0.,0.,0.,0.,0.,0.,0./                      00000180
    4 0.,72.,144.,216./                                           00000190
  DATA WPO/0.,0.,0.,0.,0.,0.,0.,0.,0.,0./                    00000200
  DATA TP/0.,-80.,-160.,-40.,-120.,-200./                     00000210
    1 0.,-57.6,-115.2,-172.8/                                       00000220
  DATA XI/23.4,23.4,23.4,203.4,203.4,203.4,113.4,113.4,113.4,113.4/ 00000230
  DATA B/47.54,57.23,288.73,242.8/                               00000240
C EPOCH, IS THE TIME IN DAYS.                                    00000250
  EPOCH=400.                                                       00000260
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED.           00000270
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED.     00000280
  NUMS=10                                                           00000290
  NUMG=2                                                            00000300
  P=3.1415926                                                       00000310
  RE=6370.8800                                                       00000320
  RTD=57.29577951                                                    00000330
  WRAD=15.0/RTD                                                       00000340
  WRITE(6,15)                                                         00000350
15  FORMAT(1H,'2X','V5',24X,'A',24X,'E',24X,'W',23X,'WP')      00000360
  DIMENSION A(10),E(10),W(10),WP(10),V5(10)                      00000370
  DO 3 JP=1,10                                                         00000380
    XI(JP)=XI(JP)/RTD                                                 00000390
    WO(JP)=WO(JP)/RTD                                                 00000400
    WPO(JP)=WPO(JP)/RTD                                               00000410
    CALL PERT(EPOCH,AO(JP),EO(JP),WO(JP),WPO(JP),XI(JP),          00000420
      1 A(JP),E(JP),W(JP),WP(JP),V5(JP))                             00000430
    WD=W(JP)*RTD                                                       00000440
    WPD=WP(JP)*RTD                                                     00000450
    WRITE(6,25)V5(JP),A(JP),E(JP),WD,WPD                             00000460
25  FORMAT(1H,'5E24.9')                                               00000470
3  CONTINUE                                                            00000480
C CL IS THE VELOCITY OF LIGHT IN KILOMETERS PER SECOND.       00000490
  CL=2.99994*10.**5                                                  00000500
C FR IS THE UPLINK FREQUENCY IN HZ.                              00000510
C FR1 IS THE DOWNLINK FREQUENCY IN HZ.                          00000520
  FR=300.0*10.**6                                                    00000530
  FR1=245.0*10.**6                                                    00000540
  CON=2.77218*10.**(-6)                                              00000550
  WRITE(6,27)                                                         00000560
27  FORMAT(1H,'////////')                                             00000570
  DO 900 J=1,NUMS                                                     00000580
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J.                00000590
  TAU=CON*A(J)**1.5                                                  00000600
  DO 700 K=1,NUMG                                                     00000610

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WRITE(6,10) 00000620
10 FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLP',8X,'UPDOPPLER 00000630
1',8X,'DNDOPPLR',9X,'SUBL',0X,'SUBC',6X,'STATION',//) 00000640
T=B(K)/RTD 00000650
G=B(K+2)/PTD 00000660
C I IS THE HOUR. 00000670
DO 500 I=3,150,3 00000680
RI=I 00000690
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND 00000700
C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE 00000710
C AND EQUATORIAL PLANE. 00000720
CALL ELLIP(RI,E(J),WP(J),TP(J),A(J),TAU,PSP,R) 00000730
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE 00000740
C SATELLITE J (WITH GEOCENTER AS THE ORIGIN). 00000750
CALL PRIME(PSP,W(J),XI(J),E,0.,XS,YS,ZS) 00000760
C FS IS THE SUBSATELLITE LONGITUDE IN DEGREES. 00000770
FS=(ATAN(YS/XS)-WRAD*PI)*RTD 00000780
IF(XS.LT.0.)FS=FS+PI*RTD 00000790
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES. 00000800
TS=RTD*ARCOS(ZS/R) 00000810
F=G+WRAD*PI 00000820
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K. 00000830
X=RE*SIN(T)*COS(F) 00000840
Y=RE*SIN(T)*SIN(F) 00000850
Z=RE*COS(T) 00000860
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE 00000870
C CENTER OF THE EARTH. 00000880
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL 00000890
C MILES. 00000900
ACC=ARCOS((X*XS+Y*YS+Z*ZS)/(RE*R)) 00000910
RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5 00000920
ARG=SIN(ACC)*R/RGE 00000930
IF(ARG.GT.1.0000000)ARG=1.0000000 00000940
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO 00000950
C SATELLITE J. 00000960
D=(ARSIN(ARG)-PI/2.)*RTD 00000970
RT=SQRT(R*R-PE*PE) 00000980
IF(PGE.LE.RT)D=-D 00000990
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY. 00001000
CALL DOPE(R,E(J),A(J),TAU,PSP,WP(J),W(J),XI(J),XV,YV,ZV) 00001010
C (XT,YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND 00001020
C STATION K. 00001030
XT=-WRAD*PE*SIN(T)*SIN(F)/3600. 00001040
YT=WRAD*PE*SIN(T)*COS(F)/3600. 00001050
DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z) 00001060
DOT=-DOT/RGE 00001070
C UPDOP IS THE UPLINK DOPPLER SHIFT IN HZ. 00001080
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ. 00001090
UPDOP=DOT*FR/CL 00001100
DNDOP=DOT*FR1/CL 00001110
WRITE(6,20)J,RI,RGE,D,UPDOP,DNDOP,FS,TS,K 00001120
20 FORMAT(1H,I3,F8.1,P17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10) 00001130
500 CONTINUE 00001140
WRITE(6,26) 00001150
26 FORMAT(1H,)//) 00001160
700 CONTINUE 00001170
900 CONTINUE 00001180
WRITE(6,30) 00001190
30 FORMAT(1H,//////) 00001200
L=WUMS-1 00001210
IF(L.EQ.0)GO TO 350 00001220

```

```

C FR IS THE CROSSLINK FREQUENCY IN HZ.                                00001230
FR=60.*10.**9                                                         00001240
C M1 IS THE FIRST SATELLITE.                                         00001250
C M2 IS THE SECOND SATELLITE.                                        00001260
DO 350 M1=1,L                                                         00001270
TAU=CON*A(M1)**1.5                                                    00001280
N=M1+1                                                                00001290
DO 250 M2=N,NUMS                                                      00001300
WRITE(6,40)                                                           00001310
40  FORMAT(1H ,2X,'HRS',12X,'RANGE',5X,'L12',5X,'C12',23X,         00001320
2  'CPDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//)                   00001330
TAU2=CON*A(M2)**1.5                                                  00001340
DO 300 I=3,150,3                                                      00001350
RI=I                                                                    00001360
C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY 00001370
C AND 1 MEANS VISIBILITY.                                           00001380
NOVIZ=1                                                                00001390
CALL ELLIP(RI, P(M1), WP(M1), TP(M1), A(M1), TAU, FSP, R)             00001400
CALL ELLIP(RI, P(M2), WP(M2), TP(M2), A(M2), TAU2, F2P, R2)         00001410
CALL PRIME(FSP, W(M1), XI(M1), R, 0., XS, YS, ZS)                   00001420
CALL PRIME(F2P, W(M2), XI(M2), R2, 0., X2, Y2, Z2)                  00001430
TC1=X2-XS                                                              00001440
TC2=Y2-YS                                                              00001450
TC3=Z2-ZS                                                              00001460
C R12 IS THE RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES.       00001470
C P12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES. 00001480
R12=(TC1**2+TC2**2+TC3**2)**.5                                         00001490
CALL UNPRIM(TC1, TC2, TC3, FSP, W(M1), XI(M1), P12, PU12, TU12)     00001500
F12=RTD*ATAN(TC2/TC1)                                                 00001510
IF(TC1.LT.0.) F12=F12+P*PTD                                           00001520
VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)                                   00001530
IF(VIZ.GT..99999999) VIZ=.99999999                                   00001540
IF(VIZ.LT.-.99999999) VIZ=-.99999999                                00001550
DEL=ARCCOS(VIZ)                                                       00001560
DFLM=ARSIN(RE/F)                                                       0000157C
IF(DEL.LT.DFLM) NOVIZ=0                                              00001580
TR3=TC3/R12                                                            00001590
IF(TR3.GE.1.) TR3=.99999999                                           00001600
IF(TR3.LT.-1.) TR3=-.99999999                                         00001610
T12=ARCCOS(TR3)*PTD                                                   00001620
CALL DOPE(R, P(M1), A(M1), TAU, FSP, WP(M1), W(M1), XI(M1), XV, YV, ZV) 00001630
CALL DOPE(R2, P(M2), A(M2), TAU2, F2P, WP(M2), W(M2), XI(M2), S2, U2, V2) 00001640
DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3                               00001650
DOT=DOT/R12                                                            00001660
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ.                       00001670
DOP12=-DOT*FR/CI                                                      00001680
WRITE(6,50) RI, R12, F12, T12, PU12, TU12, DOP12, NOVIZ, M1, M2     00001690
50  FORMAT(1H ,F5.1,F17.3,F9.1,F7.1,F10.1,F6.1,F17.3,I9,I10,I10)    00001700
300 CONTINUE                                                           00001710
WRITE(6,60)                                                            00001720
60  FORMAT(1H ,//)                                                    00001730
250 CONTINUE                                                           00001740
350 CONTINUE                                                           00001750
END                                                                      00001760
SUBROUTINE PRIME(FSP, WS, XIS, XPS, YPS, XS, YS, ZS)                 00001770
A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)                    00001780
A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)                  00001790
A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)                   00001800
A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)                  00001810
A31=SIN(XIS)*SIN(FSP)                                                00001820
A32=SIN(XIS)*COS(FSP)                                                00001830

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	XS=A11*XPS+A12*YPS	00001840
	YS=A21*XPS+A22*YPS	00001850
	ZS=A31*XPS+A32*YPS	00001860
	RF*TURN	00001870
	END	00001880
	SUBROUTINE ELLIP (T, E, WP, TP, A, TAU, FSP, R)	00001890
	P=3.1415926	00001900
	Z=2.*P*(T-TP)/TAU	00001910
	P2=2.*P	00001920
2	IF (Z.GT.P2) Z=Z-P2	00001930
	IF (Z.GT.P2) GO TO 2	00001940
	E1=Z+P*SIN (Z)	00001950
	E2=(Z+P*(SIN (E1)) - (P*COS (E1)) *E1)/(1.-P*COS (E1))	00001960
	Q=0.	00001970
4	F3=(Z+P*(SIN (E2)) - (P*COS (E2)) *E2)/(1.-P*COS (E2))	00001980
	Q=Q+1.	00001990
	DE=E3-E2	00002000
	DE2=DE**2	00002010
	F2=F3	00002020
	IF (DE2.GT..00000001) GO TO 4	00002030
	TH=ARCOS ((COS (F2) - P)/(1.-P*COS (E2)))	00002040
	IF (Z.GT.P) TH=2.*P-TH	00002050
	FSP=WP+TH	00002060
	R=(A*(1.-P**2))/(1.+P*COS (FSP-WP))	00002070
	RETURN	00002080
	END	00002090
	SUBROUTINE DOP (R, E, A, TAU, FSP, WP, WS, XIS, XD, YD, ZD)	00002100
	P=3.1415926	00002110
	T=P*SP-WP	00002120
	PD=(A*P**2.*P/(TAU*(1.-P**2)**.5))*SIN (T)	00002130
	TD=(2.*P/TAU)*((1.-P**2)**(-1.5))*(1.+P*COS (T))**2	00002140
	XPC=PD*COS (FSP) -R*TD*SIN (FSP)	00002150
	XPC=XPC/3600.	00002160
	YPC=PD*SIN (FSP) +R*TD*COS (FSP)	00002170
	YPC=YPC/3600.	00002180
	CALL PRIN (0., WS, XIS, XPC, YPC, XD, YD, ZD)	00002190
	RETURN	00002200
	END	00002210
	SUBROUTINE UNPRIN (TC1, TC2, TC3, FSP, WS, XIS, R12, PU12, TU12)	00002220
	A11=COS (FSP) *COS (WS) -COS (XIS) *SIN (WS) *SIN (FSP)	00002230
	A12=-SIN (FSP) *COS (WS) -COS (XIS) *SIN (WS) *COS (FSP)	00002240
	A21=COS (FSP) *SIN (WS) +COS (XIS) *COS (WS) *SIN (FSP)	00002250
	A22=-SIN (FSP) *SIN (WS) +COS (XIS) *COS (WS) *COS (FSP)	00002260
	A31=SIN (XIS) *SIN (FSP)	00002270
	A32=SIN (XIS) *COS (FSP)	00002280
	A13=SIN (XIS) *SIN (WS)	00002290
	A23=-SIN (XIS) *COS (WS)	00002300
	A33=COS (XIS)	00002310
	Z1=A11*TC1+A21*TC2+A31*TC3	00002320
	X1=A12*TC1+A22*TC2+A32*TC3	00002330
	Y1=A13*TC1+A23*TC2+A33*TC3	00002340
	XU=X1	00002350
	YU=-Y1	00002360
	ZU=-Z1	00002370
	PTD=57.20577951	00002380
	P=3.1415926	00002390
	PU12=PTD*ATAN (YU/XU)	00002400
	IF (XU.LT.0.) PU12=PU12+P*PTD	00002410
	ZR=ZU/R12	00002420
	IF (ZR.GE.1.) ZP=.99999999	00002430

```

IF(ZR.LE.-1.)ZR=-.9999999
TU12=ARCOS(ZR)*RTD
PRTURN
END
SUBROUTINE PERT(EPOCH,AC,EO,WO,WPO,XI,
1 A,E,W,WP,V5)
C THIS SUBROUTINE PRODUCES THE SECULAR VARIANCE OF AN INITIALLY,
C HIGH ALTITUDE ORBIT, AND AT THE SAME TIME GENERATES STABILITY OF
C ECCENTRICITY, RIGHT ASCENSION AND ARGUMENT OF PERIGEE. IT ALSO
C PRODUCES THE EVER CHANGING SEMI-MAJOR AXIS.
C ALL VALUES IN THIS PROGRAM HAVE BEEN
C CONVERTED TO THE METRIC SYSTEM,
C WHERE 1 NAUTICAL MILE=1.852 KM.
CON=2.77218*10.**(-6)
PI=3.1415926
PTD=57.29577951
RHO=393364.0000
W=WO
WP=WPO
IF(WP.EQ.0.)WF=.00001
V6=EPOCH/400.
DO 200 I=1,40
TAU=CON**I**1.5
V=(24./TAU)*10.
V=V*V6
V50=40*(1.+EO)
CALL ARGPER(AO,XI,WS,V1)
IF(V1.GT.0.)WP=WS
IF(I.EQ.1)E=EO
C MOON REQUIRES A NEW SEMI-MAJOR AXIS 'A'
C AT EACH NEW ITERATION. THEREFORE FOR EVERY ITERATION AFTER THE
C FIRST, AC IS REALLY THE NEW 'A' AS COMPUTED BY THE PREVIOUS ITERATION.
C SO FOR THE SECOND ITERATION AC REALLY EQUALS A1, FOR THE THIRD
C A2 AND SO ON. THUS THE LOGIC STATEMENT IS REQUIRED.
IF(I.GT.1)AO=A
CALL MOON(AO,XI,A)
UPA3=PI*(1./81.)*((A/RHO)**3)
A2=((A/RHO)**2)
A4=((A/RHO)**4)
CI2=(COS(XI)**2)
CI4=(COS(XI)**4)
SP2=(SIN(WP)**2)
SI2=(SIN(XI)**2)
PAR1=((-125./128.)+(315./128.)*CI2)
PAR2=((2625./2048.)-(7875./1024.)*CI2+(17325./2048.)*CI4)
PAR3=((315./128.)-(315./16.)*CI2+(2205./128.)*CI4)
PAR4=(3.-(15./2.)*SP2*SI2)
PAR5=((225./32.)-(315./8.)*SP2)
PAR6=((-45./32.)+(315./64.)*SP2+PAR5*CI2+(2205./64.)*SP2*CI4)
DW=-2*UPA3*COS(XI)*((3./4.)+A2*PAR1+(A4*PAR2))*V
DE=-UPA3*P*SIN(2*WP)*((-15./4.)*SI2+A2*PAR3)*V
DWP=UPA3*(PAR4+32*PAR6)*V
W=W+DW
E=E+DE
V5=(A*(1.+E))/V50
WP=WP+DWP
200 CONTINUE
C DELTA APOGEE, IS THE NEW SEMI-MAJOR AXIS
C TIMES, THE NEW ECCENTRICITY PLUS ONE, DIVIDED
C BY THE INITIAL VALUE OF THE SEMI-MAJOR AXIS

```

C TIMES, THE INITIAL ECCENTRICITY PLUS ONE;	00003040
C OR IN EQUATION FORM, (A*(1.+E))/(AO*(1.+EO))	00003050
RETURN	00003060
END	00003070
SUBROUTINE ARGPER(AO,XI,WS,V1)	00003080
PI=3.14159265	00003090
RHO=383364.0000	00003100
PTD=57.29577951	00003110
V1=C.	00003120
WS=0.	00003130
A2=(AO/RHO)**2	00003140
V4=XI	00003150
IF(V4.EQ.0.)V4=.0001	00003160
NUM=-3.+A2*((45./32.)-(225./32.)*(COS(V4))**2)	00003170
DEN=-7.5*(SIN(V4))**2+A2*((315./64.)-(315./8.)*(COS(V4))**2	00003180
+ (2205./64.)*(COS(V4))**4)	00003190
RAT2=NUM/DEN	00003200
IF(PAT2.LF.0.)RETURN	00003210
IF(PAT2.GT.1.)RETURN	00003220
ARG=SQRT(RAT2)	00003230
WS=AP SIN(ARG)	00003240
V1=1.	00003250
RETURN	00003260
END	00003270
SUBROUTINE MOON(AO,XI,A)	00003280
PI=3.14159265	00003290
P2=PI/2	00003300
TE=.3	00003310
MUE=.3986*10.**6	00003320
RM=383364.0000	00003330
C2=(4.8998*10.**3)/((PM-AO)**2)	00003340
WS=630.7828*(AO**(-1.5))	00003350
WM=2.66381*(10.**(-6))	00003360
W=(WS*COS(XI)-WM)	00003370
IF(W.LT.0.)W=-W	00003380
WRFL=((W)**2+(WS*SIN(XI))**2)	00003390
WRFL=SQRT(WRFL)	00003400
RAT=AO/(PM-AO)	00003410
PAR=.33333333*SIN(TE*PAR)**((COS(TE*PAT))**2+2.)	00003420
DVR=2.*C2*PAR/(WRFL*PAR)	00003430
DA=((DVR)**2)*(AO**2)/MUE	00003440
V=SIN(XI)	00003450
IF(V.EQ.0.)V=.00000001	00003460
ANG=TE/V	00003470
IF(ANG.GT.P2)ANG=P2	00003480
DAD=86400.*(WRFL*ANG/(PI**2))*DA	00003490
DADY=365.*DAD	00003500
RATA=DADY/AO	00003510
A=AO+10.*DAD	00003520
RETURN	00003530
END	00003540

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APPENDIX 8

PROGRAM AZ1

A ground station azimuth angle calculation is added (lines 870-1025) to program SATE.

```

//TS0420A JOB (6360,D91,DESK),'CHRISTOPHER P',
// TIME=1
// EXEC PORTGCG
//PORT.SYSIN DD *
C AZ1 (APP 75) GIVES AZIMUTH ANGLE
C THIS SATELLITE VISIBILITY PROGRAM IS WRITTEN FOR A MAXIMUM OF
C TEN SATELLITES AND TWO GROUND STATIONS.
C THE ARRAYS CONTAIN THE FOLLOWING INFORMATION FOR EACH SATELLITE:
C A--SEMI-MAJOR AXIS IN NAUTICAL MILES
C E--ECCENTRICITY
C W--RIGHT ASCENSION IN DEGREES
C WP--ARGUMENT OF PERIGEE IN DEGREES
C TP--TIME OF PERIGEE IN HOURS
C XI--INCLINATION IN DEGREES
C ARRAY B CONTAINS THE COLATITUDE AND LONGITUDE FOR EACH GROUND STATION.
      DIMENSION A(10),E(10),W(10),WP(10),TP(10),XI(10),B(4)
      DATA A/14342.,14342.,14342.,61421.,61421.,61421.,
3 61421.,119402.,119402.,119402./
      DATA E/.725.,.725.,.725.,.4.,.4.,.4.,.4.,.5.,.5.,.5./
      DATA W/0.,270.0,63.435,63.435,63.435,63.435,
4 243.733,243.733,243.733,243.733/
      DATA WP/-90.0,-90.0/
      DATA TP/0.,-6.0,-12.,0.,-26.587,-53.173,-79.76,0.,
1 -96.08,-192.16/
      DATA XI/63.435,63.435,23.4,90.,90.,90.,90.,0.,0.,0./
      DATA B/45.0,0.0/
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED.
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED.
      NUMS=2
      NUMG=1
      P=3.1415926
      P12=.5*P
      P32=1.5*P
      P2=2.*P
      RE=3440.
      RTD=57.29577051
      WRAD=15.0/RTD
C CL IS THE VELOCITY OF LIGHT IN NAUTICAL MILES PER SECOND.
      CL=1.61984*10.**5
C FR IS THE UPLINK FREQUENCY IN HZ.
C FR1 IS THE DOWNLINK FREQUENCY IN HZ.
      FR=300.0*10.**6
      FR1=245.0*10.**6
      CON=6.987*10.**(-6)
      DO 900 J=1, NUMS
      W(J)=W(J)/RTD
      WP(J)=WP(J)/RTD
      XI(J)=XI(J)/RTD
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J.
      TAU=CON*A(J)**1.5
      DO 700 K=1, NUMG, 2
      WRITE(6,10)
10  FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLE',8X,'AZIMUTH',
19X,'UPDOPPLER',9X,'DNDOPPLER',9X,'SUBL',9X,'SUBC',6X,'STATION',//)
      T=B(K)/RTD
      K1=K+1
      G=B(K1)/PTD
C I IS THE HOUR.
      DO 500 I=1, 25
      PI=I
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND

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C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE      00000580
C AND EQUATORIAL PLANE.                                                  00000590
      CALL ELLIP (PI, F (J), WP (J), TP (J), A (J), TAU, PSP, R)          00000600
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE    00000610
C SATELLITE J (WITH GEOCENTER AS THE ORIGIN).                             00000620
      CALL PRIME (PSP, W (J), XI (J), R, O., XS, YS, ZS)                   00000630
C FS IS THE SUBSATELLITE LONGITUDE IN DEGREES.                           00000640
      FS = (ATAN (YS/XS) - WRAD*RI) *RTD                                  00000650
      IF (XS.LT.0.) FS = FS + P*RTD                                       00000660
11  IF (FS.LT.-360.) FS = FS + 360.                                       00000662
      IF (FS.LT.-360.) GO TO 11                                           00000664
C TS IS THE SUBSATELLITE CLATITUDE IN DEGREES.                            00000670
      TS = RTD*ARCOS (ZS/P)                                               00000680
      F = G + WRAD*RI                                                    00000690
C (X, Y, Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K.  00000700
      X = RE*SIN (T) *COS (F)                                             00000710
      Y = RE*SIN (T) *SIN (F)                                             00000720
      Z = RE*COS (T)                                                      00000730
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE    00000740
C CENTER OF THE EARTH.                                                    00000750
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL    00000760
C MILES.                                                                    00000770
      ACC = ARCOS ((X*XS + Y*YS + Z*ZS) / (RE*P))                         00000780
      RGE = ((XS-X)**2 + (YS-Y)**2 + (ZS-Z)**2)**.5                       00000790
      ARG = SIN (ACC) *P/RGE                                              00000800
      IF (ARG.GT.1.0000000) ARG = 1.0000000                               00000810
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO          00000820
C SATELLITE J.                                                            00000830
      D = (ARCSIN (ARG) - P/2.) *PTD                                       00000840
      RT = SQRT (R*P - RE*RE)                                             00000850
      IF (PGE.LT.P*RT) D = -D                                             00000860
C AZIMUTH IS THE AZIMUTH ANGLE.                                           00000870
      SLAT = TS/RTD                                                       00000880
      SLOM = FS/RTD                                                       00000890
      ARG = G - SLOM                                                       00000900
      ALPHA = (SLAT - T) / 2.0                                             00000910
      BETA = (SLAT + T) / 2.0                                             00000920
      GAMMA = ABS (ARG) / 2.0                                             00000930
      IF (GAMMA.GT.P/2. AND. GAMMA.LT.P) GAMMA = P - GAMMA              00000932
      SINA = SIN (ALPHA)                                                  00000940
      SINB = SIN (BETA)                                                   00000950
      COSA = COS (ALPHA)                                                  00000960
      COSB = COS (BETA)                                                  00000970
      COTG = COTAN (GAMMA)                                               00000980
      U1 = SINA *COTG / SINB                                              00000990
      ALPHA = ATAN (U1)                                                  00000995
      U2 = COSA *COTG / COSB                                             00001000
      BETA = ATAN (U2)                                                   00001005
      IF (BETA.GT.P/2. AND. BETA.LT.P/2) BETA = BETA + P                 00001007
      IF (BETA.GT.-P/2. AND. BETA.LT.0.) BETA = BETA + P                  00001009
      AZIMUT = (ALPHA + BETA) *RTD                                        00001015
      ARG = SIN (ARG)                                                    00001020
      IF (ARG.GT.0.0) AZIMUT = 360.0 - AZIMUT                             00001025
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.        00001030
      CALL DOPE (R, E (J), A (J), TAU, PSP, WP (J), W (J), XI (J), XV, YV, ZV) 00001040
C (XT, YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND        00001050
C STATION K.                                                                00001060
      XT = -WRAD*PE*SIN (T) *SIN (F) / 3600.                            00001070
      YT = WPAD*PE*SIN (T) *COS (F) / 3600.                              00001080
      DOT = (XV - XT) * (XS - X) + (YV - YT) * (YS - Y) + (ZV) * (ZS - Z) 00001090
      DOT = -DOT/PGE                                                     00001100

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C UFDOP IS THE UPLINK DOPPLER SHIFT IN HZ. 00001110
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ. 00001120
  UPDOP=DOT*FP/CL 00001130
  DNDOP=DOT*FR1/CL 00001140
  WRITE(6,20) J,RI,RGF,D,AZINUT,UPDOP,DNDOP,FS,TS,K 00001150
20  FORMAT(1H ,I3,F8.1,F17.3,F14.3,F15.3,F17.3,F17.3,F13.3,F13.3, 00001160
  1I10) 00001170
500  CONTINUE 00001180
  WRITE(6,25) 00001190
25  FORMAT(1H ,//) 00001200
700  CONTINUE 00001210
900  CONTINUE 00001220
  WRITE(6,30) 00001230
30  FORMAT(1H ,///// ) 00001240
  L=NUMS-1 00001250
  IF(L.EQ.0) GO TO 350 00001260
C FP IS THE CROSSLINK FREQUENCY IN HZ. 00001270
  FP=39.*10.**9 00001280
C M1 IS THE FIRST SATELLITE. 00001290
C M2 IS THE SECOND SATELLITE. 00001300
  DO 350 M1=1,L 00001310
  TAU=CON*A(M1)**1.5 00001320
  N=M1+1 00001330
  DO 250 M2=N,NUMS 00001340
  WRITE(6,40) 00001350
40  FORMAT(1H ,2X,'HPS',12X,'RANGF',11X,'L12',12X,'C12',11X, 00001360
  2  'CRDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//) 00001370
  TAU2=CON*A(M2)**1.5 00001380
  DO 300 I=1,25 00001390
  RI=I 00001400
C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY 00001410
C AND 1 MEANS VISIBILITY. 00001420
  NOVIZ=1 00001430
  CALL ELLIP(RI,E(M1),WP(M1),TP(M1),A(M1),TAU,FSP,F) 00001440
  CALL ELLIP(RI,F(M2),WP(M2),TP(M2),A(M2),TAU2,F2P,F2) 00001450
  CALL PRIME(FSP,W(M1),XI(M1),P,C.,XS,YS,ZS) 00001460
  CALL PRIME(F2P,W(M2),XI(M2),R2,C.,X2,Y2,Z2) 00001470
  TC1=X2-XS 00001480
  TC2=Y2-YS 00001490
  TC3=Z2-ZS 00001500
C R12 IS THE RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES. 00001510
C F12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES. 00001520
  F12=(TC1**2+TC2**2+TC3**2)**.5 00001530
  F12=RTD*ATAN(TC2/TC1) 00001540
  IF(TC1.LT.0.) F12=F12+P*RTD 00001550
  VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R) 00001560
  IF(VIZ.GT..99999999) VIZ=.99999999 00001570
  DEL=ARCOS(VIZ) 00001580
  DELM=ARCSIN(RE/R) 00001590
  IF(DEL.LE.DELM) NOVIZ=0 00001600
  T12=ARCOS(TC3/F12)*RTD 00001610
  CALL DOPE(R,F(M1),A(M1),TAU,FSP,WP(M1),W(M1),XI(M1),XV,YV,ZV) 00001620
  CALL DOPE(R2,E(M2),A(M2),TAU2,F2P,WP(M2),W(M2),XI(M2),S2,U2,V2) 00001630
  DOT=(S2-XV)*TC1+(U2-YV)*TC2+(V2-ZV)*TC3 00001640
  DOT=DOT/F12 00001650
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ. 00001660
  DOP12=-DOT*FP/CL 00001670
  WRITE(6,50) RI,F12,T12,DOP12,NOVIZ,M1,M2 00001680
50  FORMAT(1H ,F5.1,F17.3,F14.3,F15.3,F20.3,I9,I10,I10) 00001690
300  CONTINUE 00001700
  WRITE(6,60) 00001710

```

```

60      FORMAT(1H ,//)
250     CONTINUE
350     CONTINUE
      END
      SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)
      A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)
      A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)
      A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)
      A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)
      A31=SIN(XIS)*SIN(FSP)
      A32=SIN(XIS)*COS(FSP)
      XS=A11*XPS+A12*YPS
      YS=A21*XPS+A22*YPS
      ZS=A31*XPS+A32*YPS
      RETURN
      END
      SUBROUTINE ELLIP(T,P,WP,TP,A,TAU,FSP,R)
      P=3.1415926
      Z=2.*P*(T-TP)/TAU
      P2=2.*P
      2   IF(Z.GT.P2)Z=Z-P2
      IF(Z.GT.P2)GO TO 2
      E1=Z+P*SIN(Z)
      E2=(Z+E*(SIN(E1))-(Z*COS(E1))*E1)/(1.-E*COS(E1))
      Q=0.
      4   E3=(Z+E*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))
      Q=Q+1.
      DE=E3-E2
      DE2=DE**2
      E2=E3
      IF(DE2.GT..00000001)GO TO 4
      TH=ARCCOS((COS(E2)-E)/(1.-E*COS(E2)))
      IF(Z.GT.P)TH=2.*P-TH
      FSP=WP+TH
      P=(A*(1.-E**2))/(1.+E*COS(FSP-WP))
      RETURN
      END
      SUBROUTINE DOPE(P,P,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)
      P=3.1415926
      T=FSP-WP
      RD=(A*E*2.*P/(TAU*(1.-E**2)**.5))*SIN(T)
      TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*COS(T))**2
      XPC=PD*COS(FSP)-R*TD*SIN(FSP)
      XPC=YPC/3600.
      YPC=RD*SIN(FSP)+R*TD*COS(FSP)
      YPC=YPC/3600.
      CALL PRIME(P,WS,XIS,XPC,YPC,XD,YD,ZD)
      RETURN
      END
00001720
00001730
00001740
00001750
00001760
00001770
00001780
00001790
00001800
00001810
00001820
00001830
00001840
00001850
00001860
00001870
00001880
00001890
00001900
00001910
00001920
00001930
00001940
00001950
00001960
00001970
00001980
00001990
00002000
00002010
00002020
00002030
00002040
00002050
00002060
00002070
00002080
00002090
00002100
00002110
00002120
00002130
00002140
00002150
00002160
00002170
00002180
00002190
00002200

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APPENDIX 9

PROGRAM NOLINKE

NOLINKE searches for any visible satellite at regular intervals around the earth. If no satellite is visible, the coordinates of that unfortunate location are printed out in the foreground. A good 10-satellite system can require thousands of elevation angle calculations for very little printout. Care should be used with NOLINKE or large CPU time and expense will result.

The orbital elements (A in nautical miles) are entered on lines 20-70. Elevation angle requirements are entered on line 210 as EM, in degrees. Time intervals of one hour are examined (RI = time in hours on line 230).

```

DIMENSION A(10),P(10),W(10),WP(10),TP(10),XI(10)
DATA A/14342.,14342.,22767.,22767.,22767.,22767.,
3 57369.,57369.,57369.,57369./
DATA P/.725.,.725.,0.,0.,0.,0.,0.,0.,0.,0./
DATA W/0.,270.,0.,0.,0.,0.,0.,0.,0.,0./
DATA WP/-90.,-90.,0.,0.,0.,0.,0.,0.,0.,0./
DATA TP/0.,-6.,-3.,-9.,-15.,-21.,
1 0.,-24.,-48.,-72./
DATA XI/63.435,63.435,0.,0.,0.,0.,90.,90.,90.,90./
WRITE(6,7)
7  FORMAT(1H,5X,'T1',8X,'P1',13X,'NO.',13X,'T',/)
RTD=57.2957795
DO 11 M=1,10
W(M)=W(M)/RTD
WP(M)=WP(M)/RTD
XI(M)=XI(M)/RTD
11 CONTINUE
P=3.1415926
PE=3440.
WPA0=15./RTD
EM=35.
DO 600 I=1,6
RI=T-1.
DO 500 J=1,13
RJ=J
T=(RJ-1.)*15./PTD
DO 400 K=1,25
RK=K
FIN=((RK-1.)*15./PTD)+RI*WPA0
F=FIN-RI*WPA0
CON=6.987*10.**(-6)
SATNO=0.
DO 300 L=1,10
RL=L
TAU=CON*A(L)**1.5
CALL ELLIP(RI,P(L),WP(L),TP(L),A(L),TAU,PSP,R)
CALL PRIME(PSP,W(L),YI(L),P,0.,XS,YS,ZS)
Y=PT*SIN(T)*COS(FIN)
Y=RE*SIN(T)*SIN(FIN)
Z=RE*COS(T)
ACC=APCOS((X*XS+Y*YS+Z*ZS)/(RE*P))
RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5
ARG=SIN(ACC)*R/RGE
IF(ARG.GT..9999999)ARG=.9999999
D=(ARSIN(ARG)-P/2.)*PTD
RT=SQRT(R*P-RE*RE)
IF(PGE.LE.RT)D=-D
IF(D.GT.EM)SATNO=SATNO+1.
IF(SATNO.GT.1)GO TO 400
IF(PL.LT.9.9)GO TO 300
T1=T*PTD
P1=F*RTD
20 WRITE(6,20)T1,P1,SATNO,RI
300 FORMAT(1H,4F12.3)
CONTINUE
IF(RJ.LE.1.)GO TO 500
IF(RJ.GT.12.)GO TO 500
400 CONTINUE
500 CONTINUE
600 CONTINUE
END
0000010
0000020
0000025
0000030
0000040
0000050
0000060
0000065
0000070
0000100
0000110
0000120
0000130
0000140
0000150
0000160
0000170
0000180
0000190
0000200
0000210
0000220
0000230
0000240
0000250
0000260
0000270
0000280
0000290
0000300
0000310
0000320
0000330
0000340
0000350
0000360
0000370
0000380
0000390
0000400
0000410
0000420
0000430
0000440
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0000490
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0000520
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0000580
0000590
0000600
0000610

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	SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)	0000620
	A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)	0000630
	A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)	0000640
	A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)	0000650
	A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)	0000660
	A31=SIN(XIS)*SIN(FSP)	0000670
	A32=SIN(XIS)*COS(FSP)	0000680
	XS=A11*XPS+A12*YPS	0000690
	YS=A21*XPS+A22*YPS	0000700
	ZS=A31*XPS+A32*YPS	0000710
	RETURN	0000720
	END	0000730
	SUBROUTINE ELLIP(T,E,WP,TP,A,TAU,FSP,R)	0000740
	P=3.1415926	0000750
	Z=2.*P*(T-TP)/TAU	0000760
	P2=2.*P	0000770
2	IF(Z.GT.P2)Z=Z-P2	0000780
	IF(Z.GT.P2)GO TO 2	0000790
	E1=Z+P*SIN(Z)	0000800
	E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1))	0000810
	Q=0.	0000820
4	E3=(Z+P*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))	0000830
	Q=Q+1.	0000840
	DE=E3-E2	0000850
	E2=DE**2	0000852
	E2=E3	0000860
	IF(DE2.GT..0000001)GO TO 4	0000870
	TH=ARCOS((COS(E2)-E)/(1.-E*COS(E2)))	0000880
	IF(Z.GT.P)TH=2.*P-TH	0000890
	FSP=WP+TH	0000900
	R=(A*(1.-E**2))/(1.+E*COS(FSP-WP))	0000910
	RETURN	0000920
	END	0000930

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