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HIGH ALTITUDE SATELLITE COMMUNICATIONS, WITH CROSSLINKS.(U)

JAN 77 P F CHRISTOPHER, E R EDELMAN

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HIGH ALTITUDE
SATELLITE COMMUNICATIONS,
WITH CROSSLINKS

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JANUARY 1977

Prepared for

DEPUTY FOR CONTROL AND COMMUNICATIONS SYSTEMS

ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

Hanscom Air Force Base, Bedford, Massachusetts



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20. Abstract (Continued)

time on a 370/158 computer. General Keplerian orbits are allowed ($0 \leq$ eccentricity ≤ 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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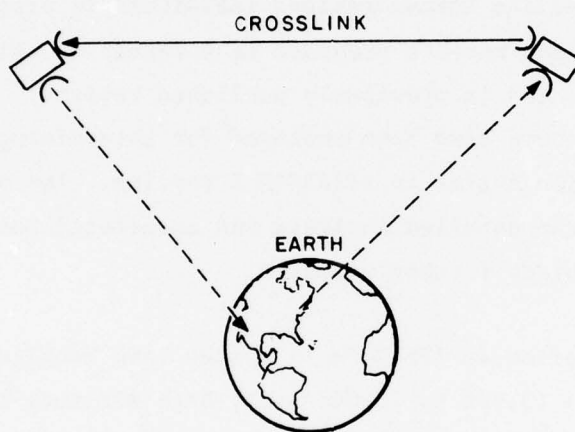
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INTRODUCTION AND SUMMARY

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.^[1] 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.

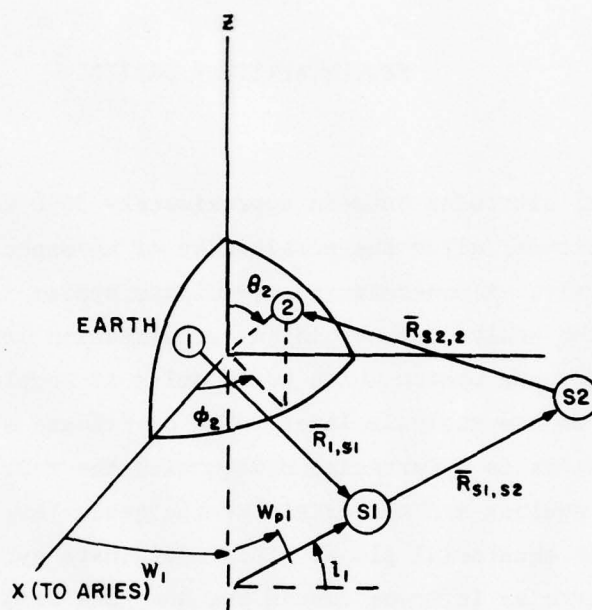
PART I

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

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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:^[2]

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:

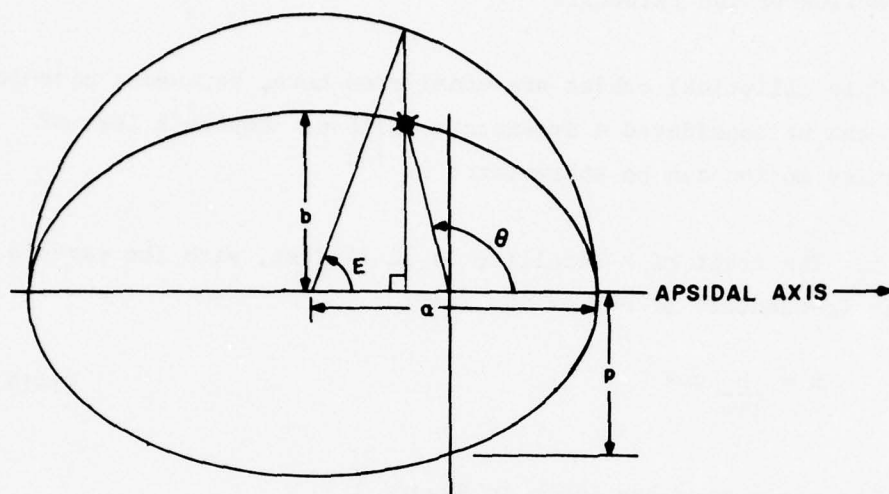
$$R^2 \dot{\theta} = \text{constant} = \sqrt{\mu p} \quad \text{where } \mu = Gm_e \quad (1-2)$$

= 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:

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

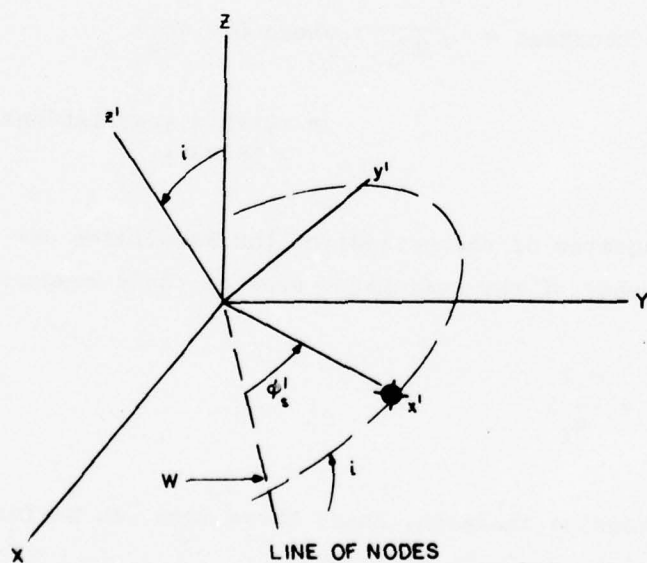
After extensive analysis, these three laws can be interpreted as a single equation (Kepler's equation):



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

Figure 3 RELATION OF TRUE ANOMALY θ TO ECCENTRIC ANOMALY E



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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.

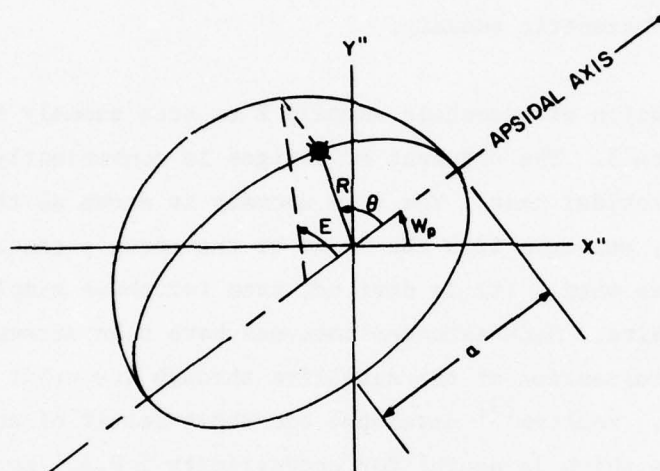
The relation of eccentric anomaly E to true anomaly θ can be seen in Figure 5. The argument of perigee is conveniently located here on the apsidal axis. The true anomaly is shown as the angle from perigee, measured from the focus at the earth's center. Serious problems arise when $\theta(t)$ is desired, 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^[3] 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,

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



1A-45,623 THE DOUBLE PRIME COORDINATE SYSTEM IS STATIONARY, WITH THE x'' AXIS ON
 THE LINE OF NODES (EQUATORIAL PLANE AND ORBITAL PLANE)
 θ = 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 θ is related^[2] 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.^[4] In the subroutine, M becomes

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

Also, $\phi'_s = Wp + \theta$ since θ is measured from the argument of perigee, but ϕ'_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 θ) 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.^[5] 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 ξ ; again, this rotation is counterclockwise. This rotation is an angle i , where i here corresponds to orbital inclination. Finally, a rotation (ϕ'_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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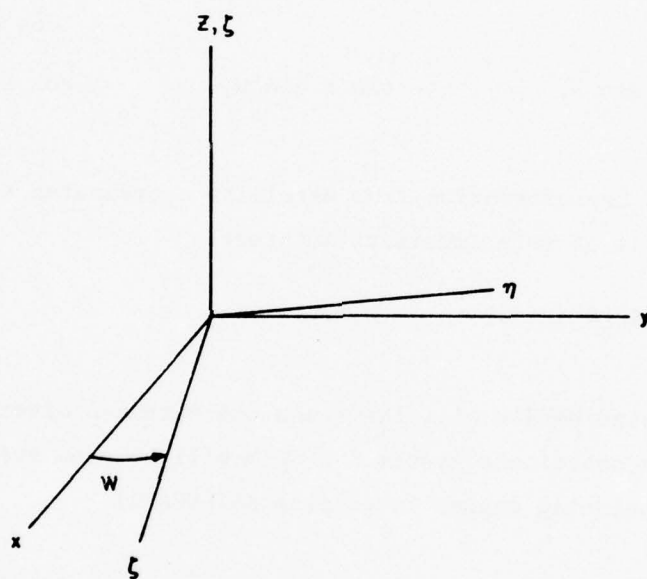


Figure 6 THE FIRST ROTATION OF EULER ANGLE W ABOUT THE Z AXIS

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

$$\cos \phi'_s \cos W - \cos i \sin W \sin \phi'_s, \cos \phi'_s \sin W + \cos i \cos W \sin \phi'_s, \\ + \sin W \sin i$$

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

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⁻¹ is found from the transpose of A because the magnitude of A is unity. The elements of A⁻¹ are then

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

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

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

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

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

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

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

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

$$a_{33} = \cos i \quad (1-10)$$

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 θ (its angle measured from perigee) since $R(\theta)$ is determined by the Keplerian ellipse. Expressions directly related to velocity^[2] 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° ahead in the orbit plane) can give the x'' component of velocity and the y'' component of velocity. The symbol ϕ'_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^[6] 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 θ_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))

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

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

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

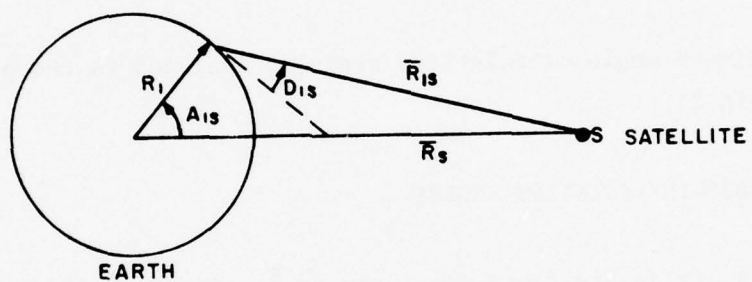
This calculation is done in the attached programs after the sub-routine DOPE is called.

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° 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).

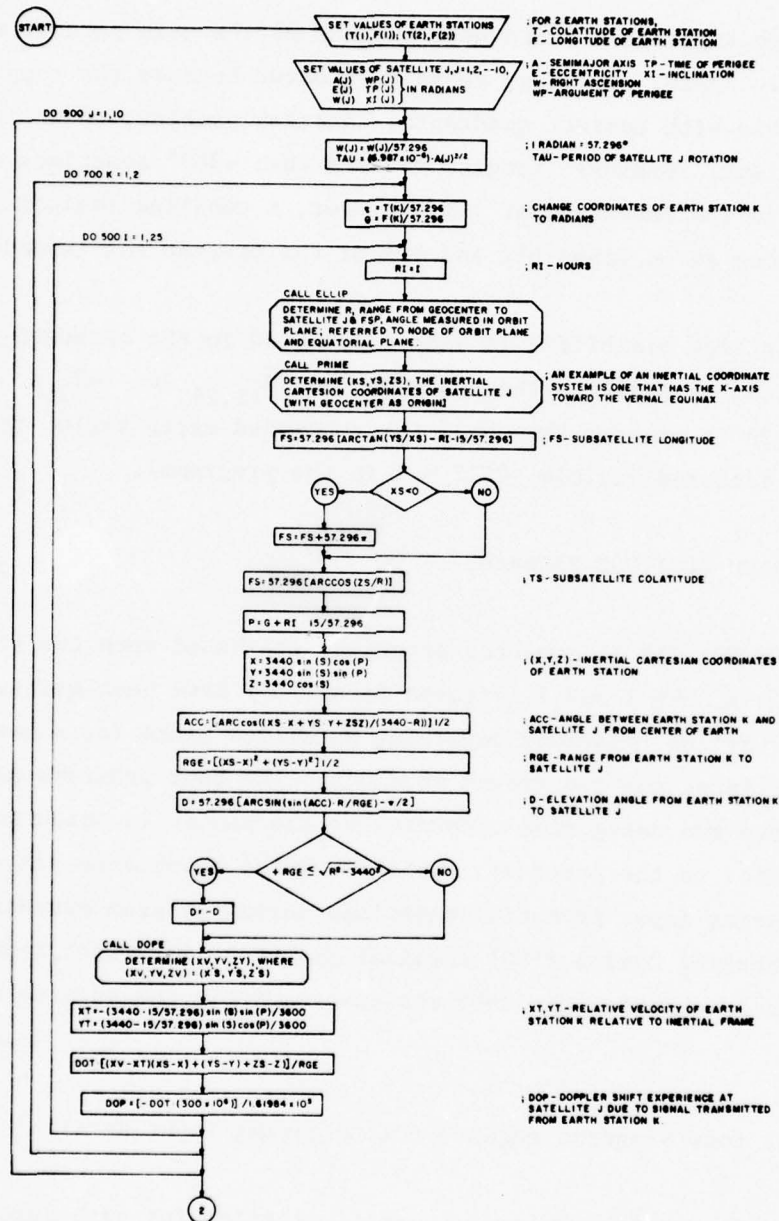
Crosslink visibility is also calculated in the attached programs. It is found by checking the angle between $\bar{R}_{1S,2S}$ and $(-\bar{R}_{1S})$; if this angle is greater than half the subtended earth angle, the crosslink is declared visible (CVIS = 1 in the programs).

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.



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Figure 8a FLOWCHART, BLOCK I

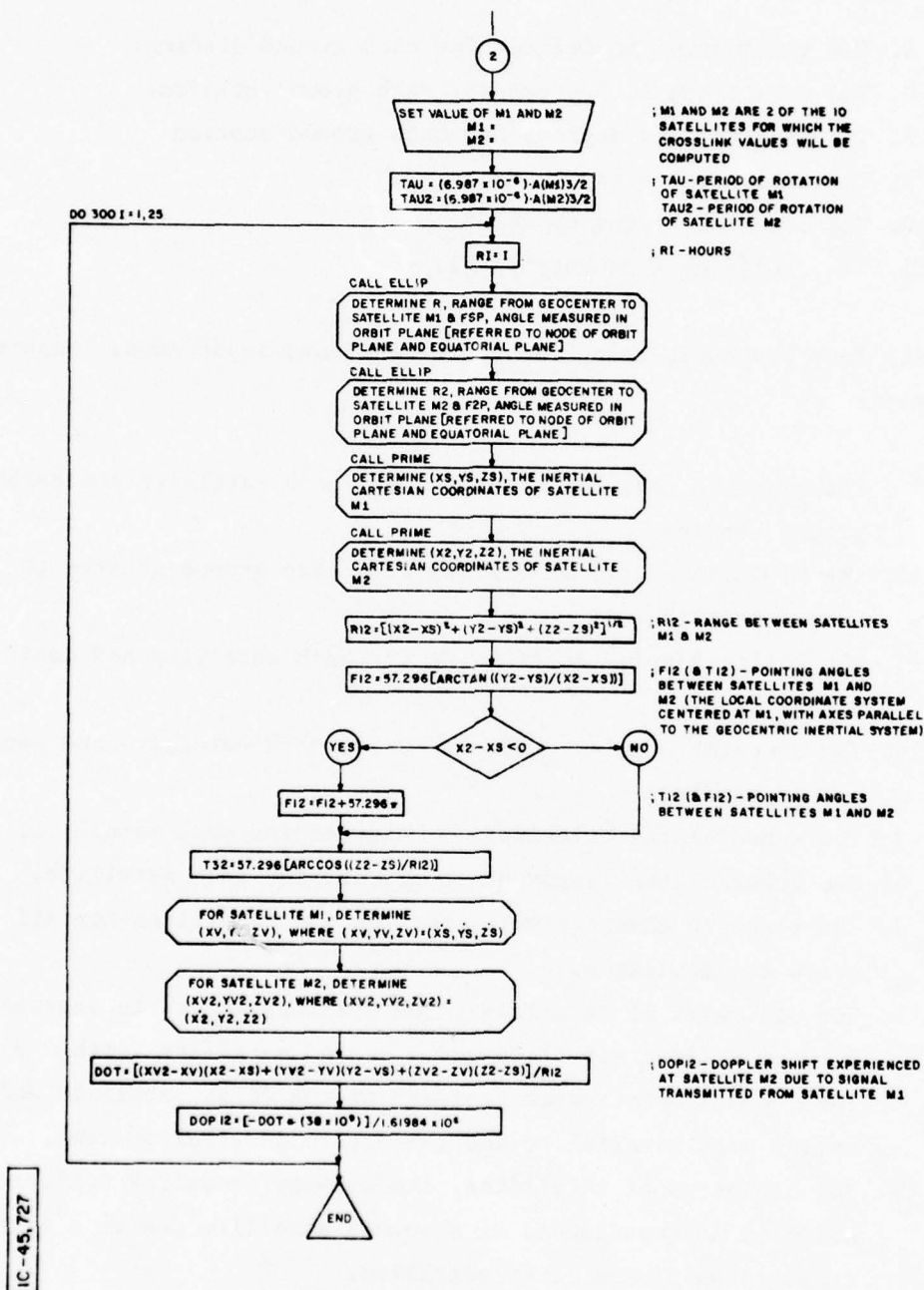


Figure 8b FLOWCHART, BLOCK 2

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^[1] 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,

a = semi-major axis

e = eccentricity

I = inclination with respect to lunar plane

Ω = right ascension of ascending node on lunar plane

W_p = argument of perigee

M = mean anomaly

μ_m = gravitational constant times lunar mass

μ = gravitational constant times mass of earth

$n = \mu^{1/2} a^{-3/2}$ = mean motion, rad/hr

θ = true anomaly

p = semi-latus rectum

$r = \frac{p}{1 + e \cos \psi}$ = radius from geocenter

ρ = lunar radius

$\eta = \theta + W_p$

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:

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

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

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

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. ΔW_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, ΔW_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 Δe 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^[2]. 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.

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

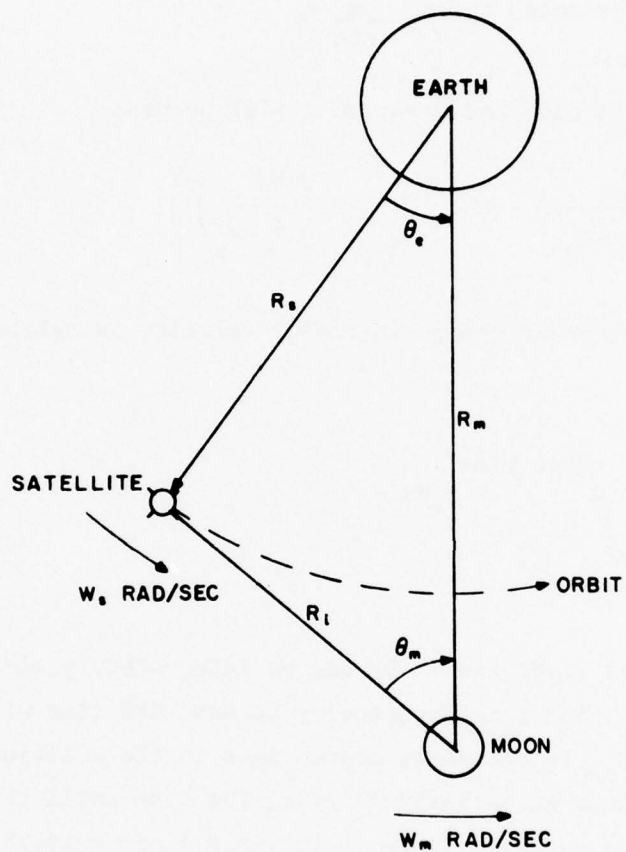
where

r_{ij} = distance between satellite and lunacenter

G = gravitational constant

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

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 $\theta_e \lesssim 0.15$ rad, and Equation (2-7a) becomes

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

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 θ_{eo} 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 $\theta_{eo}(\omega_s - \omega_m)$. Using the small angle approximation, Equation (2-7b), and substituting Equation (2-8) into Equation (2-9) yields:

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

where ω_{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, θ_{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 ΔV_r is proportional to interaction time, the square of ΔV_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 $\Delta a / \text{yr}$
 $\propto \omega_{\text{rel}}$.

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° has approximately the same value for V_5 (1.003) as a 12-day orbit at inclination 180° .

It appears that the gross secular results for orbital instability^[1] 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 ω_p existed, a simple exponential growth in eccentricity resulted. This is similar to the result of the 1974 Ash report^[2]. A less simple result occurred (on line 3020) if ω_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^[7] satellites selected to give polar coverage. These 12-hour orbits differ in right ascension (W) by 90° 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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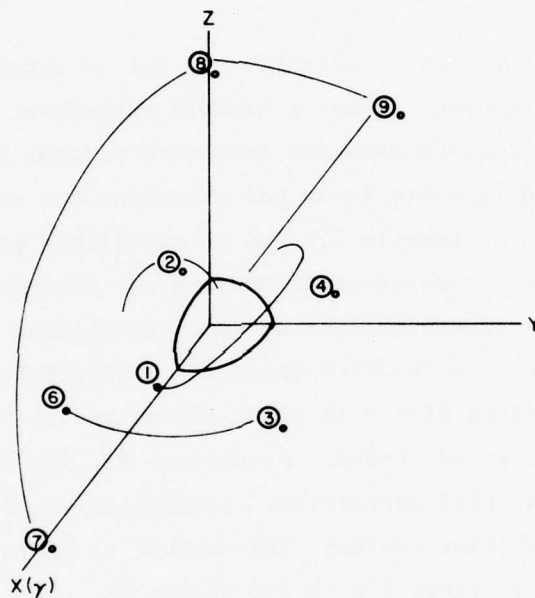


Figure 10 ARRAY OF SATELLITES AT $T = 0$ HRS FOR THREE EXAMPLES.
TEN SATELLITES TOTAL. (NOT TO SCALE; 5 AND 10 NOT SHOWN)

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/o., 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° longitude (90° 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° and the argument of perigee is -90° for Satellite #2, the perigee occurred at 180° 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^[8], 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	DNDOPLER	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	-1560.874	-1291.247	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	15498.333	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	-461.954	-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° 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° 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° 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.

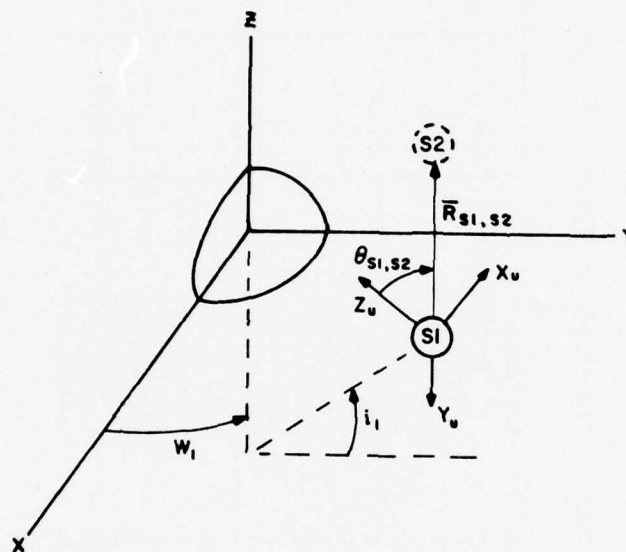
TABLE 4b

SATELLITES #3 THROUGH #10, INITIAL ECCENTRICITY = 0.05

ABIG	E1	W	WPS	V ₅
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 $\theta_{si,s2}$ 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}

1A-45,024

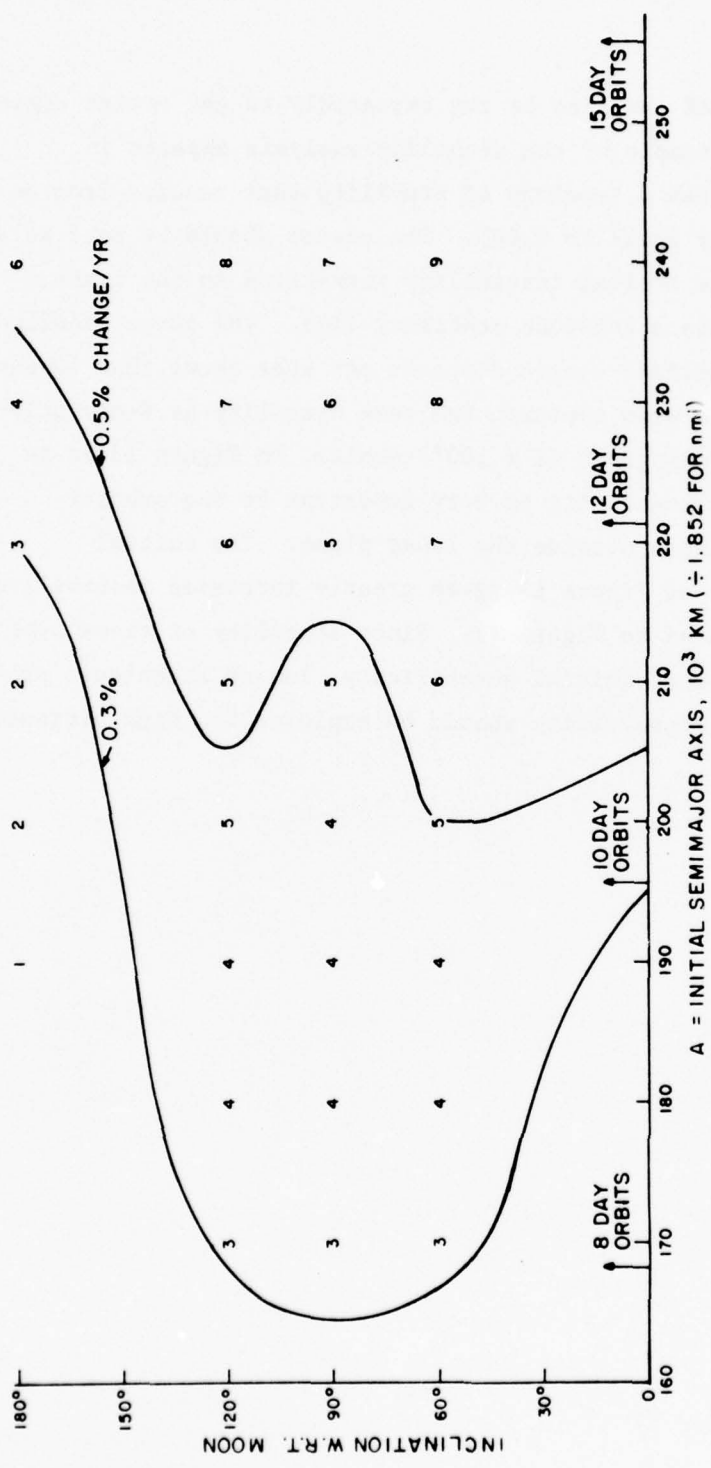
Figure II LOCAL COORDINATE SYSTEM FOR SATELLITE CROSSLINK

TABLE 5
CROSSLINK RELATIONS FROM PROGRAM SATLUNAE
(FUI2 and TUI2 are local satellite crosslink pointing angles)

HRS	RANGE	L12	C12	FUI2	TUI2	CRODPLER	CVIS	SAT1	SAT2
3.0	66205.875	67.6	65.4	105.0	36.1	-125757.425	1	1	3
6.0	67722.588	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	-43.3	55.5	1145508.000	0	1	3
15.0	44591.199	-94.7	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	39494.520	41.3	99.2	136.2	107.1	-1323487.000	1	1	3
27.0	66208.438	67.6	65.4	105.0	36.1	-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	173.9	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	44593.375	-94.7	51.3	-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	49391.406	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	-125340.125	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	176.9	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.

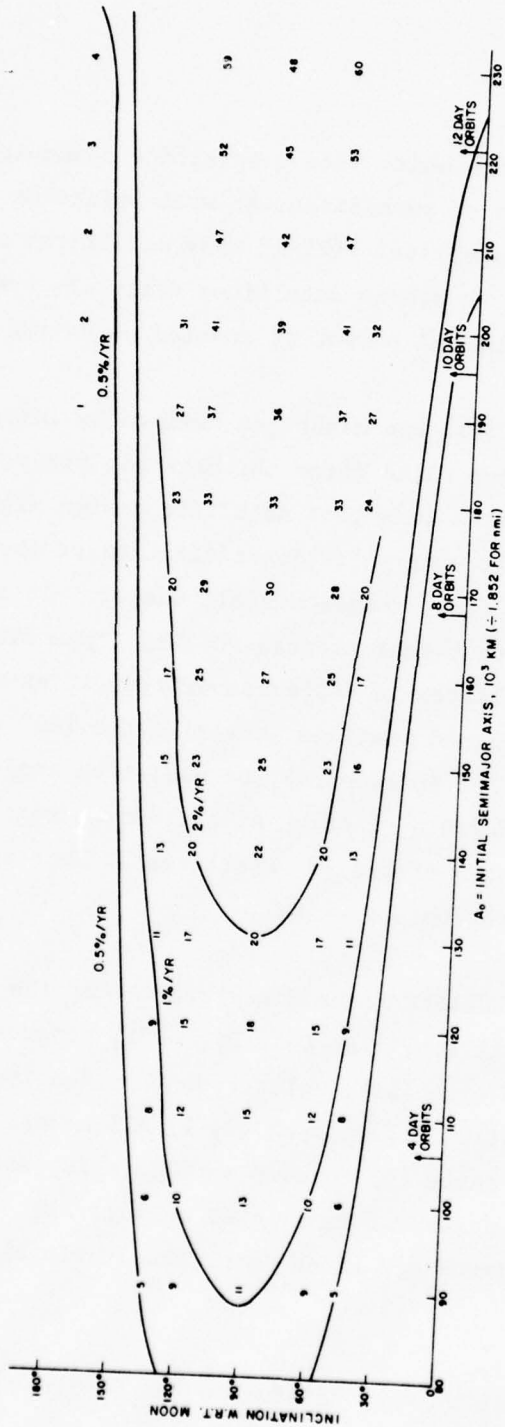
1A-45,478



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)

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

FROM PROGRAM SATLUNAE

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 12×24 grid of possible ground stations (covering the $180^\circ \times 360^\circ$ Mercator projection in 15° 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° 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° 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 = 1.6187×10^5 nmi/sec	

D_{1S}	elevation angle from ground station to satellite, degrees	
Δ	denotes small changes in orbital elements (e.g. Δe =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	
ϕ'_s	same as FSP	$\phi'_s = W_p + \theta$
G	gravitational constant = 6.6732×10^{-11} newton meter $^2/\text{kg}^2$	
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	
μ	GM_e	
μ_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 (≥ 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	

τ	period for Keplerian orbit (subscripts are added for particular satellites)	
TU12, FU12	crosslink angles in a local satellite coordinate system	
θ	true anomaly	
$\dot{\theta}$	$\frac{d}{dt} ()$	
θ_j	angle between relative velocity vector and pointing vector	
θ_1, ϕ_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 $\theta_{S1, S2}; \phi_{S1, S2}$.
θ_e	angle of satellite with respect to earth-moon vector	
θ_{eo}	bounding angle for lunar pertur- bations (representatively, 0.3 radians)	
θ_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	
ω	earth rotation rate - $15^\circ/\text{solar hour} = 15.04^\circ/\text{sidereal hour}$	
ω_s	angular rotation rate of satellite about earth, rad/hr	
ω_m	angular rotation rate of moon about earth, rad/hr	
ω_{rel}	vector difference of ω_s, ω_m	ω_{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

REFERENCES AND NOTES

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

5. H. Goldstein, Classical Mechanics, Addison-Wesley Publishing Co., Reading, Mass., 1962

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° colatitude, 288.73° E. Long.) and San Diego, California (57.34° colatitude, 242.8° E. Long.) are entered as:

DATA B/47.54, 57.23, 288.73, 242.8/

240

```

//TS0420A JOB (6360,D91,DESK),'CHRISTOPHER P',NOTIFY=TS0420, 00000010
// TIME=1 00000020
// EXEC PORTGCG 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),E(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/C.,-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
      EE=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 FP1 IS THE DOWNLINK FREQUENCY IN HZ. 00000370
      FR=300.0*10.**6 00000380
      FR1=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(6,10) 00000480
10  FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLE',9X,'UPDOPPLER'00000490
1',8X,'DNDOPPLER',9X,'SHEL',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)
C PS IS THE SUBSATELLITE LONGITUDE IN DEGREES.
      PS=(ATAN(YS/XS)-WRAD*RI)*RTD
      IF(XS.LT.0.) PS=PS+P*PTD
11      IF(PS.LT.-360.) PS=PS+360.
      IF(PS.LT.-360.) GO TO 11
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES.
      TS=RTD*APCOS(ZS/R)
      F=G*WRAD*RI
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K.
      X=RE*SIN(T)*COS(F)
      Y=RE*SIN(T)*SIN(F)
      Z=RE*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=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.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.)*RTD
      RT=SQRT(R*R-RE*RE)
      IF(RGE.LE.RT) D=-D
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
      CALL DOPE(R,X(J),Y(J),Z(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*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 INDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ.
      UPDOP=DOT*FP/CL
      DNDOP=DOT*FP1/CL
20      WRITE(6,20)J,RI,RGE,D,UPDOP,DNDOP,PS,TS,K
500      FORMAT(1H ,I3,F8.1,F17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10)
      CONTINUE
25      WRITE(6,25)
700      FORMAT(1H ,//)
      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.
      FP=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
40      WRITE(6,40)
2      FORMAT(1H ,2X,'HFS',12X,'RANGE',11X,'L12',12X,'C12',11X,
      'CDOPPLER',6X,'CVIS',6X,'SAT1',6X,'SAT2',//)
      TAU2=CON*A(M2)**1.5

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0001200

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      DO 300 I=1,25                                00001210
      RI=1                                           00001220
C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY
C AND 1 MEANS VISIBILITY.                          00001230
      NOVIZ=1                                       00001240
      CALL ELLIP(PI,F(M1),WP(M1),TP(M1),A(M1),TAU,FSP,R) 00001250
      CALL ELLIP(RI,F(M2),WP(M2),TP(M2),A(M2),TAU2,F2P,R2) 00001260
      CALL PRIME(FSP,W(M1),XT(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 F12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES. 00001330
      R12=(TC1**2+TC2**2+TC3**2)**.5                00001340
      F12=RTD*ATAN(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=ARCOS(VIZ)                                  00001390
      DELM=ASIN(PE/R)                                  00001400
      IF(DE.LI.DELM) NOVIZ=0                          00001410
      T12=ARCOS(TC3/R12)*RTD                          00001420
      CALL DOPE(F,E(M1),A(M1),TAU,FSP,WP(M1),W(M1),XI(M1),XV,YV,ZV) 00001430
      CALL DOPE(S2,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*PE/CL                                00001480
      WRITE(6,50) RI,P12,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
      A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP) 00001580
      A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP) 00001590
      A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP) 00001600
      A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP) 00001610
      A31=SIN(XIS)*SIN(FSP)                          00001620
      A32=SIN(XIS)*COS(FSP)                          00001630
      XS=A11*XPS+A12*YPS                              00001640
      YS=A21*XPS+A22*YPS                              00001650
      ZS=A31*XPS+A32*YPS                              00001660
      RETURN                                           00001670
      END                                           00001680
      SUBROUTINE ELLIP(T,E,WP,TP,A,TAU,FSP,v)        00001690
      P=3.1415926                                     00001700
      Z=2.*P*(T-TP)/TAU                               00001710
      P2=2.*P                                          00001720
2     IF(Z.GT.P2) Z=Z-P2                             00001730
      IF(Z.GT.P2) GO TO 2                             00001740
      E1=Z+E*SIN(Z)                                   00001750
      E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1)) 00001760
      Q=0.                                             00001770
4     E3=(Z+E*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2)) 00001780
      Q=Q+1.                                           00001790
      DE=E3-E2                                         00001800
      DE=E3-E2                                         00001810

```


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 (O.,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 STATION. 00000140
      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,.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
        RI=I 00000540
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND 00000550
C THE ANGLE MEASURED IN ORBIT PLANE; REPERRED TO NODE OF ORBIT PLANE 00000560
C AND EQUATORIAL PLANE. 00000570
      CALL ELLIP(RI,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.
      PS=(DATAN(YS/XS)-WRAD*RI)*RTD
      IF(XS.LT.0.) PS=PS+P*PTD
C TS IS THE SUBSATELLITE COLATITUDE IN DEGREES.
      TS=RTD*DARCCS(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=DARCCS((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.)*PTD
      RT=DSQRT(R*R-RE*RE)
      IF(RGE.LF.RT) D=-D
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
      CALL DOPE(R,E(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,PI,EGE,D,UPDOP,DNDOP,FS,TS,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,/)
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

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```

C NOVIZ DETERMINES CROSSLINK VISIBILITY WHERE 0 MEANS NO VISIBILITY 00001220
C AND 1 MEANS VISIBILITY. 00001230
NOVIZ=1 00001240
CALL ELLIP(RI,F(M1),WP(M1),TP(M1),A(M1),TAU,FSP,R) 00001250
CALL ELLIP(RI,F(M2),WP(M2),TP(M2),A(M2),TAU2,F2P,R2) 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 F12 AND T12 ARE THE POINTING ANGLES BETWEEN TWO SATELLITES IN DEGREES. 00001330
R12=(TC1**2+TC2**2+TC3**2)**.5 00001340
F12=RTD*ATAN(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=DAP SIN(PE/P) 00001400
IF(DPL.LF.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*8(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*XPS+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*8(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
CH=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**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
XPC=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),E(11),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 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/ 00000060
2,243.733,243.733,243.733,243.733/ 00000070
DATA WP/0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,-90.,-90.0/ 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 ACC0000170
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',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
1 R SUPPLIED:',//, ' COLATITUDE',//, ' LONGITUDE',//) 0000250
WRITE(6,142) 0000260
142 FORMAT(1H, 'ADDITIONAL DATA WHICH MUST BE SUPPLIED:',//, ' UPLINK0000270
1 K 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 B SHOULD ENTER THE NUMBER 400.0. A DEFAULT VALUE WILL THEN BE USE0000320
1 D.',//, ' THE USER IS EXPECTED, HOWEVER, TO SPECIFY THE NUMBER OF SATE0000330
1 LLITES AND GROUND STATIONS TO BE CONSIDERED.',//) 0000340
WRITE(6,145) 0000350
145 FORMAT(1H, 'HOW MANY SATELLITES ARE TO BE CONSIDERED? ENTER IN0000360
1 TEGER WITH RIGHTMOST DIGIT IN COLUMN 2.') 0000370
READ 150, M 0000380
WRITE(6,135) M 0000390
135 FORMAT(1H, '13) 0000400
WRITE(6,155) 0000410
155 FORMAT(1H, 'HOW MANY GROUND STATIONS ARE TO BE CONSIDERED? ENT0000420
1 ER INTEGER IN COLUMN 2.') 0000430
READ 150, N 0000440
WRITE(6,135) N 0000450
150 FORMAT(I2) 0000460
WRITE(6,25) 0000470
WRITE(6,25) 0000480
WRITE(6,95) 0000490
95 FORMAT(1H, 'ENTER FOLLOWING DATA IN DECIMAL FORM ANYWHERE IN T0000500
1 HE FIRST 20 COLUMNS.',//) 0000510
WRITE(6,140) 0000520
140 FORMAT(1H, 'WHAT IS THE SEMIMAJOR AXIS VALUE IN NAUTICAL MILES0000530
1 FOR SATELLITE 1?') 0000540
DO 101 I=1,M 0000550
K=I+1 0000560
READ 170, A(I) 0000570
IF (A(I).NE.400.0) GO TO 605 0000580
A(I)=A(K) 0000590
J1=1 0000600
605 WRITE(6,305) A(I) 0000610

```

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)=F(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 SATELLITE 1?')	00000800
1R	DO 104 I=1,M	00000810
	K=I+1	00000820
	READ 170, W(I)	00000830
	IF(W(I).NE.400.0)GO TO 615	00000840
	W(I)=W(K)	00000850
	J1=1	00000860
615	WRITE(6,305)W(I)	00000870
	IF(I.EQ.M)GO TO 104	00000880
	PRINT 310, K	00000890
104	CONTINUE	00000900
	WRITE(6,325)	00000910
325	FORMAT(1H ,/, ' WHAT IS THE ARGUMENT OF PERIGEE VALUE IN DEGREES FOR SATELLITE 1?')	00000920
1S	DO 106 I=1,M	00000930
	K=I+1	00000940
	READ 170, WP(I)	00000950
	IF(WP(I).NE.400.0)GO TO 620	00000960
	WP(I)=WP(K)	00000970
	J1=1	00000980
620	WRITE(6,305)WP(I)	00000990
	IF(I.EQ.M)GO TO 106	00010000
	PRINT 310, K	00010010
106	CONTINUE	00010020
	WRITE(6,330)	00010030
330	FORMAT(1H ,/, ' WHAT IS THE TIME OF PERIGEE IN HOURS FOR SATELLITE 1?')	00010040
1TE	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 SATELLITE 1?')	00010160
1TELLITE	DO 108 I=1,M	00010170
	K=I+1	00010180
		00010190
		00010200
		00010210
		00010220

	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 12')	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 12')	00001450
	DO 109 I=1,N	00001460
	K=I+1	00001470
	READ 170, RL(I)	00001480
170	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 ,E20.6)	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
		00001790
		00001800
		00001810
		00001820
		00001830


```

660      GO TO 675                                00001840
665      WRITE(6,665)                             00001850
665      FORMAT(1H ,///,' YOUR DATA SET IS COMPLETE.')
```

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675      WRITE(6,105)                             00001860
105      FORMAT(1H ,///)                          00001870
        P=3.1415926                               00001880
        PE=3440.                                  00001890
        RTD=57.29577951                           00001900
        WRAD=15.0/RTD                             00001910
        CL=1.61984*10.**5                          00001920
        CON=6.987*10.**(-6)                       00001930
        WRITE(6,190)                               00001940
190      FORMAT(1H , 'RESULTS LISTED IN ORDER OF APPEARANCE ARE:',/, ' RAO0001950
        2NGE BETWEEN GROUND STATION AND SATELLITE IN NAUTICAL MILES',/, ' ELO0001960
        2EVATION ANGLE IN DEGREES FROM GROUND STATION TO SATELLITE',/, ' UPL00001970
        2INK DOPPLER SHIFT IN HZ',/, ' DOWNLINK DOPPLER SHIFT IN HZ',/, ' SUBC0001980
        2SATELLITE COLATITUDE IN DEGREES',/, ' SUBSATELLITE LONGITUDE IN DEG00001990
        2REES',///)                               00002000
        DO 890 IN=1,M                             00002010
        W(IN)=W(IN)/RTD                            00002020
        WP(IN)=WP(IN)/RTD                          00002030
        XI(IN)=XI(IN)/RTD                          00002040
        CONTINUE                                  00002050
890      DO 900 J=1,M                              00002060
        TAU=CON*A(J)**1.5                          00002070
        DO 700 K=1,N                              00002080
        WRITE(6,10)                                00002090
10      FORMAT(1H , 'SAT',5X,'HPS',12X,'RANGE',9X,'ANGLE',8X,'UPDOPPLEP00002100
        1',9X,'DNDOPPLER',9X,'SUBC',9X,'SUBL',6X,'STATION',//) 00002110
        T=C(K)/RTD                                00002120
        G=RL(K)/RTD                                00002130
        DO 500 I=1,25                             00002140
        PI=I                                        00002150
        CALL ELLIP(PI,E(J),WP(J),TP(J),A(J),TAU,FSP,R) 00002160
        CALL PRIME(FSP,W(J),XI(J),R,0.,XS,YS,ZS) 00002170
        FS=(ATAN(YS/XS)-WRAD*PI)*RTD               00002180
        TP(XS.LT.0.) FS=FS+P*RTD                  00002190
        TS=RTD*ARCOS(ZS/R)                         00002200
        P=G+WRAD*PI                                00002210
        X=RE*SIN(T)*COS(F)                          00002220
        Y=RE*SIN(T)*SIN(F)                          00002230
        Z=RE*COS(T)                                00002240
        ACC=ARCOS((X*XS+Y*YS+Z*ZS)/(RE*R))          00002250
        RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5     00002260
        ARG=SIN(ACC)*R/RGE                          00002270
        IF(ARG.GT.1.0000000) ARG=1.0000000        00002280
        D=(ABSIN(ARG)-P/2.)*RTD                    00002290
        RT=SQRT(R*R-RE*RE)                          00002300
        IF(RGE.LE.RT) D=-D                          00002310
        CALL DOPE(R,P(J),A(J),TAU,FSP,WP(J),W(J),XI(J),XV,YV,ZV) 00002320
        XT=-WRAD*RE*SIN(T)*SIN(F)/3600.           00002330
        YT=WRAD*RE*SIN(T)*COS(F)/3600.            00002340
        DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z) 00002350
        DOT=DOT/RGE                                 00002360
        UPDOP=-DOT*FR1/CL                           00002370
        DNDOP=-DOT*FR2/CL                           00002380
        WRITE(6,20) J,RI,PGE,D,UPDOP,DNDOP,TS,FS,K 00002390
        FORMAT(1H ,I3,F9.1,F17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10) 00002400
        CONTINUE                                  00002410
500      WRITE(6,25)                               00002420
        00002430

```

```

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 PROGRAM 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
2OPPLER 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(DEM.LE.DELM) NOVIZ=0                          00002930
      CALL DOPE(R,E(M1),A(M1),TAU,FSP,WP(M1),W(M1),XI(M1),XV,YV,ZV) 00002940
      CALL DOPE(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

```

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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

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MTR-3161

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60	FORMAT(1H, //)	00003040
	IF (J1.EQ.0) GO TO 250	00003050
	WRITE(6,687)	00003060
	READ 150, NO	00003070
	IF (NO.EQ.0) GO TO 690	00003080
	WRITE(6,25)	00003090
250	CONTINUE	00003100
350	CONTINUE	00003110
690	CONTINUE	00003120
	END	00003130
	SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)	00003140
	A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)	00003150
	A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)	00003160
	A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)	00003170
	A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)	00003180
	A31=SIN(XIS)*SIN(FSP)	00003190
	A32=SIN(XIS)*COS(FSP)	00003200
	XS=A11*XPS+A12*YPS	00003210
	YS=A21*XPS+A22*YPS	00003220
	ZS=A31*XPS+A32*YPS	00003230
	RETURN	00003240
	END	00003250
	SUBROUTINE ELLIP(T,E,WP,TP,A,TAU,FSP,R)	00003260
	P=3.1415926	00003270
	Z=2.*P*(T-TP)/TAU	00003280
	P2=2.*P	00003290
2	IF (Z.GT.P2) Z=Z-P2	00003300
	IF (Z.GT.P2) GO TO 2	00003310
	E1=Z+P*SIN(Z)	00003320
	E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1))	00003330
	Q=0.	00003340
4	E3=(Z+P*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))	00003350
	Q=Q+1.	00003360
	DE=E3-E2	00003370
	DE2=DE**2	00003380
	E2=E3	00003390
	IF (DE2.GT..00000001) GO TO 4	00003400
	TH=ARCOS((COS(P2)-E)/(1.-E*COS(P2)))	00003410
	IF (Z.GT.P) TH=2.*P-TH	00003420
	FSP=WP+TH	00003430
	R=(A*(1.-E**2))/(1.+E*COS(FSP-WP))	00003440
	RETURN	00003450
	END	00003460
	SUBROUTINE DOPE(R,E,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)	00003470
	P=3.1415926	00003480
	T=FSP-WP	00003490
	RD=(A*E**2.*P/(TAU*(1.-E**2)**.5))*SIN(T)	00003500
	TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*COS(T))**2	00003510
	XPC=RD*COS(FSP)-R*TD*SIN(FSP)	00003520
	XPC=XPC/3600.	00003530
	YPC=RD*SIN(FSP)+R*TD*COS(FSP)	00003540
	YPC=YPC/3600.	00003550
	CALL PRIME(0.,WS,XIS,XPC,YPC,XD,YD,ZD)	00003560
	RETURN	00003570
	END	00003580

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^[3] for true anomaly, and is accurate only for eccentricity ≤ 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
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.,0.,0.,-90.0,-90.0/      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 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 SUPP00000200
1LIFD:',//,' 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
1E SUPPLIED:',//,' COLATITUDE',//,' LONGITUDE',//)      00000250
WRITE(6,142)                                              00000260
142 FORMAT(1H,'ADDITIONAL DATA WHICH MUST BE SUPPLIED:',//,' UPLIN00000270
1K 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' SHOULD ENTER THE NUMBER 400.0. A DEFAULT VALUE WILL THEN BE USE00000320
10.',//,' THE USER IS EXPECTED, HOWEVER, TO SPECIFY THE NUMBER OF SATE00000330
1LLITES AND GROUND STATIONS TO BE CONSIDERED.',///)     00000335
WRITE(6,145)                                              00000340
145 FORMAT(1H,'HOW MANY SATELLITES ARE TO BE CONSIDERED? ENTER IN00000350
1TEGER WITH RIGHTMOST DIGIT IN COLUMN 2.')              00000360
READ 150, M                                               00000370
WRITE(6,135) M                                           00000380
135 FORMAT(1H, I3)                                       00000390
WRITE(6,155)                                              00000400
155 FORMAT(1H,'HOW MANY GROUND STATIONS ARE TO BE CONSIDERED? ENT00000410
1ER INTEGER IN COLUMN 2.')                               00000420
READ 150, N                                               00000430
WRITE(6,135) N                                           00000440
150 FORMAT(I2)                                           00000450
WRITE(6,25)                                              00000460
WRITE(6,25)                                              00000465
WRITE(6,95)                                              00000470
95 FORMAT(1H,'ENTER FOLLOWING DATA IN DECIMAL FORM ANYWHERE IN T00000480
1HE FIRST 20 COLUMNS.',//)                             00000490
WRITE(6,140)                                              00000500
140 FORMAT(1H,'WHAT IS THE SEMIMAJOR AXIS VALUE IN NAUTICAL MILES00000510
1 FOR SATELLITE 12')                                    00000520
DO 101 I=1,M                                             00000530
K=I+1                                                    00000540
READ 170, A(I)                                           00000550
IF (A(I).NE.400.0) GO TO 605                             00000560
A(I)=A(K)                                                 00000570
J1=1                                                      00000580

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605	WRITE(6,305) A(I)	00000590
305	FORMAT(1H ,P20.8)	00000600
	IF(I.EQ.M)GO TO 101	00000610
	PRINT 310,K	00000620
310	FORMAT(1H , 'FOR SATELLITE',I3,'?')	00000630
101	CONTINUE	00000640
	WRITE(6,315)	00000650
315	FORMAT(1H ,/, ' WHAT IS THE ECCENTRICITY OF SATELLITE 1?')	00000660
	DO 103 I=1,M	00000670
	K=I+1	00000680
	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(6,305) 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 SATELLITE 1?')	00000780
	DO 104 I=1,M	00000790
	K=I+1	00000800
	READ 170, W(I)	00000810
	IF(W(I).NE.400.0)GO TO 615	00000820
	W(I)=W(K)	00000830
	J1=1	00000840
615	WRITE(6,305) W(I)	00000850
	IF(I.EQ.M)GO TO 104	00000860
	PRINT 310, K	00000870
104	CONTINUE	00000880
	WRITE(6,325)	00000890
325	FORMAT(1H ,/, ' WHAT IS THE ARGUMENT OF PERIGEE VALUE IN DEGREES FOR SATELLITE 1?')	00000900
	DO 106 I=1,M	00000910
	K=I+1	00000920
	READ 170, WP(I)	00000930
	IF(WP(I).NE.400.0)GO TO 620	00000940
	WP(I)=WP(K)	00000950
	J1=1	00000960
620	WRITE(6,305) WP(I)	00000970
	IF(I.EQ.M)GO TO 106	00000980
	PRINT 310, K	00000990
106	CONTINUE	00001000
	WRITE(6,330)	00001010
330	FORMAT(1H ,/, ' WHAT IS THE TIME OF PERIGEE IN HOURS FOR SATELLITE 1?')	00001020
	DO 107 I=1,M	00001030
	K=I+1	00001040
	READ 170, TP(I)	00001050
	IF(TP(I).NE.400.0)GO TO 625	00001060
	TP(I)=TP(K)	00001070
	J1=1	00001080
625	WRITE(6,305) TP(I)	00001090
	IF(I.EQ.M)GO TO 107	00001100
	PRINT 310, K	00001110
107	CONTINUE	00001120
	WRITE(6,335)	00001130
335	FORMAT(1H ,/, ' WHAT IS THE INCLINATION VALUE IN DEGREES FOR SATELLITE 1?')	00001140
	DO 108 I=1,M	00001150
		00001160
		00001170
		00001180
		00001190

	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 109	00001520
	PRINT 205, K	00001530
109	CONTINUE	00001540
	WRITE(6,840)	00001550
840	FORMAT(1H ,/,/,/, ' ENTER THE FOLLOWING DATA IN EXPONENTIAL FORM (PG. 300.0*10.**6 IS WRITTEN AS 300.0D6)',/,/, ' WITH THE RIGHTMOST 2DIGIT 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.',/,/, ' TH00001800	00001760


```

'BEFORE, THE RESULTS ARE FOR DEMONSTRATION PURPOSES ONLY.')      00001810
GO TO 675                                                            00001820
660  WRITE(6,665)                                                    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:',//, 00001940
      '2NCE BETWEEN GROUND STATION AND SATELLITE IN NAUTICAL MILES',//, 00001950
      '2EVAATION ANGLE IN DEGREES FROM GROUND STATION TO SATELLITE',//, 00001960
      '2INK DOPPLER SHIFT IN HZ',//, ' DOWNLINK DOPPLER SHIFT IN HZ',//, 00001970
      '2SATELLITE COLATITUDE IN DEGREES',//, ' SUBSATELLITE LONGITUDE IN DEGREES', 00001980
      '2REES',///)                                                  00001990
      DO 890 IN=1,M                                                  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, 'UPDOPPLER' 00002090
      '1',8X, 'DNDOPPLER',9X, 'SUBC',9X, 'SUBL',6X, 'STATION',//) 00002100
      T=C(K)/RTD                                                    00002110
      G=RL(K)/RTD                                                    00002120
      DO 500 I=1,25                                                 00002130
      PY=I                                                            00002140
      CALL ELLIP(RI,P(J),WP(J),TP(J),A(J),TAU,PSP,P)              00002150
      CALL PRIME(PSP,W(J),XI(J),R,O.,XS,YS,ZS)                    00002160
      PS=(DATAN(YS/XS)-HEAD*PI)*RTD                                  00002170
      IF(XS.LT.0.) PS=PS+P*RTD                                       00002180
      TS=RTD*DAPCOS(ZS/P)                                           00002190
      F=G+WRAD*PI                                                    00002200
      X=RE*DSIN(T)*DCOS(P)                                           00002210
      Y=RE*DSIN(T)*DSIN(P)                                           00002220
      Z=RE*DCOS(T)                                                   00002230
      ACC=DARCOS((X*XS+Y*YS+Z*ZS)/(RE*R))                          00002240
      RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5                      00002250
      ARG=DSIN(ACC)*R/PGE                                            00002260
      IF(ARG.GT.1.0000000) ARG=1.0000000                          00002270
      D=(DARSIN(ARG)-P/2.)*RTD                                       00002280
      RI=DSQRT(R*R-RE*RE)                                           00002290
      IF(RGE.LE.RT) D=-D                                             00002300
      CALL DOPE(R,P(J),A(J),TAU,PSP,WP(J),W(J),XI(J),XV,YV,ZV) 00002310
      XT=-WRAD*RE*DSIN(T)*DSIN(P)/3600.                          00002320
      YT=WRAD*RE*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,RI,RGE,D,UPDOP,DNDOP,TS,PS,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

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```

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 00002460
1 ANSWER IS YES IN COLUMN 2. ')
      READ 15C, NO                                    00002480
      IF(NO.EQ.0) GO TO 685                          00002490
      WRITE(6,25)                                    00002500
700     CONTINUE                                    00002510
900     CONTINUE                                    00002520
685     WRITE(6,30)                                  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 00002580
7 FOR ALL PAIRS OF SATELLITES.', '////, ' RESULTS LISTED IN ORDER OF AP 00002590
1PEARANCE ARE: ', ' ', ' RANGE BETWEEN TWO SATELLITES IN NAUTICAL MILES' 00002600
1, '//, ' POINTING ANGLES BETWEEN SATELLITES (C12&L12) IN DEGREES ', ' ', ' DO 00002610
20PPLR SHIFT EXPERIENCED AT SECOND SATELLITE DUE TO SIGNAL TRANSMI 00002620
2TTED FROM THE FIRST SATELLITE IN HZ. ', ' ', ' CROSSLINK VISIBILITY WHE 00002630
2RE 0 MEANS THERE IS NO VISIBILITY BETWEEN SATELLITES AND 1 MEANS ' 00002640
2HFRF IS VISIBILITY', '////')
      DO 350 M1=1, L                                00002650
      TAU=CON*A(M1)**1.5                            00002660
      N1=M1+1                                         00002670
      DO 250 M2=N1, M                                00002680
      WRITE(6,40)                                     00002690
40      FORMAT(1H, '2X, 'HES', 12X, 'RANG', 11X, 'C12', 12X, 'L12', 11X,
2      'CRDOPPLR', 6X, 'CVIS', 6X, 'SAT1', 6X, 'SAT2', //) 00002700
      TAU2=CON*A(M2)**1.5                            00002710
      DO 300 I=1, 25                                00002720
      RI=I                                             00002730
      NOVIZ=1                                         00002740
      CALL ELLIP(RI, F(M1), WP(M1), TP(M1), A(M1), TAU, FSP, R) 00002750
      CALL ELLIP(RI, F(M2), WP(M2), TP(M2), A(M2), TAU2, F2P, R2) 00002760
      CALL PRIME(FSP, W(M1), XI(M1), R, C., XS, YS, ZS) 00002770
      CALL PRIME(F2P, W(M2), XI(M2), R2, C., X2, Y2, Z2) 00002780
      TC1=X2-XS                                       00002790
      TC2=Y2-YS                                       00002800
      TC3=Z2-ZS                                       00002810
      R12=(TC1**2+TC2**2+TC3**2)**.5                 00002820
      P12=RTD*ATAN(TC2/TC1)                          00002830
      IF(TC1.LT.0.) P12=P12+P*RTD                    00002840
      T12=DARCOS(TC3/R12)*RTD                        00002850
      VIZ=(-XS*TC1-YS*TC2-ZS*TC3)/(R12*R)            00002860
      IF(VIZ.GT..9999999) VIZ=.9999999              00002870
      DEL=DARCOS(VIZ)                                00002880
      DELM=DARSIN(RE/R)                              00002890
      IF(DEM.LE.DELM) NOVIZ=0                        00002900
      CALL DOPE(R, F(M1), A(M1), TAU, FSP, WP(M1), W(M1), XI(M1), XV, YV, ZV) 00002910
      CALL DOPE(R2, F(M2), A(M2), TAU2, F2P, WP(M2), W(M2), XI(M2), S2, U2, V2) 00002920
      DOT=(S2-XV)*TC1+(Y2-YV)*TC2+(V2-ZV)*TC3        00002930
      DOT=DOT/R12                                    00002940
      DOP12=-DOT*P12/CL                              00002950
      WRITE(6,50) RI, R12, T12, F12, DOP12, NOVIZ, M1, M2 00002960
50      FORMAT(1H, 'F5.1, F17.3, F14.3, F15.3, F20.3, I9, I10, I10) 00002970
300     CONTINUE                                    00002980

```


60	WRITE(6,60)	00003010
	FORMAT(1H, //)	00003020
	IF(J1.EQ.0) GO TO 250	00003030
	WRITE(6,680)	00003040
	READ 150, NO	00003050
	IF(NO.EQ.0) GO TO 690	00003060
	WRITE(6,25)	00003070
250	CONTINUE	00003080
350	CONTINUE	00003090
690	CONTINUE	00003100
	END	00003110
	SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)	00003120
	IMPLICIT REAL*8(A-H,O-Z)	00003125
	A11=DCOS(FSP)*DCOS(WS)-DCOS(XIS)*DSIN(WS)*DSIN(FSP)	00003130
	A12=-DSIN(FSP)*DCOS(WS)-DCOS(XIS)*DSIN(WS)*DCOS(FSP)	00003140
	A21=DCOS(FSP)*DSIN(WS)+DCOS(XIS)*DCOS(WS)*DSIN(FSP)	00003150
	A22=-DSIN(FSP)*DSIN(WS)+DCOS(XIS)*DCOS(WS)*DCOS(FSP)	00003160
	A31=DSIN(XIS)*DSIN(FSP)	00003170
	A32=DSIN(XIS)*DCOS(FSP)	00003180
	XS=A11*XPS+A12*YPS	00003190
	YS=A21*XPS+A22*YPS	00003200
	ZS=A31*XPS+A32*YPS	00003210
	RETURN	00003220
	END	00003230
	SUBROUTINE ELLIP(T,E,WP,TP,A,TAU,FSP,P)	00003240
	IMPLICIT REAL*8(A-H,O-Z)	00003245
	P=3.1415926	00003250
	Z=2.*P*(T-TP)/TAU	00003260
	S5H=DSIN(5.*Z)	00003270
	S6H=DSIN(6.*Z)	00003280
	S7H=DSIN(7.*Z)	00003290
	C5H=DCOS(5.*Z)	00003300
	C6H=DCOS(6.*Z)	00003310
	C7H=DCOS(7.*Z)	00003320
	SH=DSIN(Z)	00003330
	S2H=DSIN(2.*Z)	00003340
	S3H=DSIN(3.*Z)	00003350
	S4H=DSIN(4.*Z)	00003360
	CH=DCOS(Z)	00003370
	FSP=Z+2.*E*SH+1.25*(F**2)*S2H+((E**3)/12.)*(13.*S3H-3.*SH)	00003380
	FSP=FSP+WP+((F**4)/96.)*(103.*S4H-44.*S2H)	00003390
	F5=((F**5)/960.)*(1097.*S5H-645.*S3H+50.*SH)	00003400
	F6=((F**6)/960.)*(1223.*S6H-902.*S4H+85.*S2H)	00003410
	F7=((F**7)/32256.)*(47273.*S7H-41699.*S5H+5985.*S3H+749.*CH)	00003420
	FSP=FSP+F5+F6+F7	00003430
	R=(A*(1.-F**2))/(1.+E*DCOS(FSP-WP))	00003440
	RETURN	00003450
	END	00003460
	SUBROUTINE DOPE(P,F,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)	00003470
	IMPLICIT REAL*8(A-H,O-Z)	00003475
	P=3.1415926	00003480
	T=FSP-WP	00003490
	RD=(A*E*2.*P/(TAU*(1.-E**2)**.5))*DSIN(T)	00003500
	TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*DCOS(T))**2	00003510
	XPC=RD*DCOS(FSP)-P*TD*DSIN(FSP)	00003520
	XPC=XPC/3600.	00003530
	YPC=PD*DSIN(FSP)+R*TD*DCOS(FSP)	00003540
	YPC=YPC/3600.	00003550
	CALL PRIME(C.,WS,XIS,XPC,YPC,XD,YD,ZD)	00003560
	RETURN	00003570

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),'EDELMA F',NOTIFY=TS0141,
// CLASS=F,TIME=2,TYPRUN=HOLD
/*SETUP TAPE PLXXXX
// EXEC FORTGCLG
//FORT.SYSIN DD *
C THIS PROGRAM 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 AND THEN,USING THE CALCOMP PLOTTER
C PRODUCES PLOTS FOR DIFFERENT ANGLES
C OF INCLINATION,GRAPHING V5 VS. DAYS.
C ALL VALUES IN THIS PROGRAM HAVE BEEN
C CONVERTED TO THE METRIC SYSTEM,
C WHERE 1 NAUTICAL MILE=1.852 KM.
      DIMENSION IBUF(2000),XARRAY(42),YARRAY(42)
      CON=2.77218*10.**(-6)
      PI=3.1415926
      PTD=57.29577951
      RHO=383364.0000
      DO 200 J=45,135,45
      RJ=J
      XI=RJ
      AO=256452.9085
      TAU=CON*AO**1.5
      V=(24./TAU)*10.
      EO=.15
      VEO=AO*(1.+EO)
      XI=XI/PTD
      W=0.
      WP=45.
      W=W/PTD
      WP=WP/PTD
      CALL APGPER(AO,XI,WP,WS,V1)
      IF(V1.GT.0.) WP=WS
      XID=XI*PTD
      WRITE(6,10)
10  FORMAT(1H ,9X,'P',17X,'WD',15X,'WPD',17X,'DE',11X,'V5',15X,
1  'DMPD',9X,'XI',6X,'DAYS')
      WRITE(6,15) XID
15  FORMAT(1H ,105X,F6.2)
      DO 100 I=1,40
      PI=I
      IF(I.EQ.1) E=EO
      DAYS=PI*10.
      XARRAY(I)=DAYS
      IF(I.GT.1) AO=A
      CALL MOON(AO,XI,A)
      UP3=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=(((-135./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)
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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*PAR6)*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,F17.2)                             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
RTD=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
1+(2205./64.)*(COS(V4))**2)                             00001080
RAT2=NUM/DEN                                              00001090
IF(RAT2.LE.0.)RETURN                                       00001100
IF(RAT2.GT.1.)RETURN                                       00001110
ARG=SQRT(RAT2)                                             00001120
WS=ARSIN(ARG)                                             00001130
V1=1.                                                      00001140
RETURN                                                    00001150
END                                                       00001160
SUBROUTINE MOON(AO,XI,A)                                  00001170
PI=3.14159265                                             00001180
P2=PI/2                                                    00001190
TP=.3                                                      00001200
MUE=.3986*10.**6                                           00001210
00001220

```


PM=383364.0000	00001230
C2=(4.8998*10.**3)/((PM-AO)**2)	00001240
WS=630.7828*(AO**(-1.5))	00001250
WM=2.66381*(10.**(-6))	00001260
W=(WS*COS(XI)-WM)	00001270
IF(W.LT.0.)W=-W	00001280
WPFL=((W)**2+(WS*SIN(XI))**2)	00001290
WREL=SQRT(WPFL)	00001300
RAT=AO/(PM-AO)	00001310
PAR=.33333333*SIN(TE*RAT)*(COS(TE*RAT)**2+2.)	00001320
DVR=2.*C2*PAR/(WREL*RAT)	00001330
DA=((DVR)**2)*(AO**2)/MUF	00001340
V=SIN(XI)	00001350
IF(V.EQ.0.)V=.000000001	00001360
ANG=TE/V	00001370
IF(ANG.GT.P2)ANG=P2	00001380
DAD=86400.*(WREL*ANG/(PI**2))*DA	00001390
DADY=365.*DAD	00001400
RATA=DADY/AO	00001410
A=AO+10.*DAD	00001420
RETURN	00001430
END	00001440
//LKED.SYSLIB DD DISP=SHR	00001450
// DD DSN=SYS1.CALCCMP,DISP=SHR	00001460
//GO.PLOTTAPE DD DSN=PLOT,DISP=(,KEEP),	00001470
// UNIT=(TAPE7,,DEFER),DCB=DEB=1,	00001480
// VOL=SER=PLXXXX,LABEL=(,NL)	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,
// TIME=2
// EXEC FORTGCG
//POPT.SYSIN DE *
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 KM
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 LATITUDE AND LONGITUDE FOR EACH GROUND STATION.
  DIMENSION A(10),E(10),W(10),WP(10),TP(10),XI(10),B(4)
  DATA A/26561.,26561.,42164.,42164.,42164.,42164.,
  3 106247.,106247.,106247.,106247./
  DATA E/.725.,.725.,.0.,.0.,.0.,.0.,.0.,.0.,.0.,.0./
  DATA W/0.,270.,0.,0.,0.,0.,
  4 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./
  DATA B/47.54,57.23,288.73,242.8/
  WRITE(6,4)
  4 FORMAT('H','ABIG',13X,'E1',13X,'W',13X,'WPS',13X,'V5',/)
  DIMENSION E(10),WP(10),ABIG(10),E1(10),W(10),WPS(10),V5(10)
  DIMENSION XM(10)
  RTD=57.29578
  DO P JR=1,10
    WC(JR)=W(JR)/RTD
    WPC(JR)=WP(JR)/PTD
    XM(JR)=(XI(JR)-23.4)/RTD
    DAYS=400.
    CALL LUNA(A(JR),E(JR),W(JR),WPC(JR),XM(JR),DAYS,ABIG(JR)
  1 ,E1(JR),W(JR),WPS(JR),V5(JR))
    WD=W(JR)*RTD
    WPSD=WPS(JR)*RTD
    WRITE(6,9)ABIG(JR),E1(JR),WD,WPSD,V5(JR)
  9 FORMAT(1H,1F14.1,1F14.9,1F14.6,1F14.6,1F14.7)
  8 CONTINUE
C NUMS IS THE NUMBER OF SATELLITES TO BE CONSIDERED.
C NUMG IS THE NUMBER OF GROUND STATIONS TO BE CONSIDERED.
  NUMS=10
  NUMG=2
  P=3.1415926
  RE=6370.8
  RTD=57.29577951
  WPA=15.0/RTD
C CL IS THE VELOCITY OF LIGHT IN NAUTICAL MILES PER SECOND.
  CL=2.99793*10.**5
C FP IS THE UPLINK FREQUENCY IN HZ.
C FR1 IS THE DOWNLINK FREQUENCY IN HZ.
  FP=300.0*10.**6
  FR1=245.0*10.**6
  CON=2.77218*10.**(-6)
  DO 900 J=1,NUMS
    XI(J)=XI(J)/RTD
    E(J)=E1(J)
    A(J)=ABIG(J)

```

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      WP(J)=WPS(J)                                00000620
C TAU IS THE PERIOD OF ROTATION OF SATELLITE J.    00000630
      TAU=CON*A(J)**1.5                            00000640
      DO 700 K=1,NUNG                               00000650
      WRITE(6,10)                                    00000660
10    FORMAT(1H,'SAT',5X,'WPS',12X,'RANGE',9X,'ANGLE',8X,'UPDOPPLER', 0000067C
      1',8X,'DNDOPPLER',9X,'SUBL',9X,'SUBC',6X,'STATION',//) 00000680
      T=B(K)/PTD                                    00000690
      G=B(K+2)/PTD                                  00000700
C I IS THE HOUR.                                    00000710
      DO 500 I=3,51,3                               00000720
      RI=I                                           00000730
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GOCENTER TO SATELLITE J AND 00000740
C THE ANGLE MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE 00000750
C AND EQUATORIAL PLANE.                             00000760
      CALL ELLIP(PI,F(J),WP(J),TP(J),A(J),TAU,FSP,R) 00000770
C SUBROUTINE PRIME COMPUTES THE INERTIAL CARTESIAN COORDINATES OF THE 00000780
C SATELLITE J (WITH GOCENTER AS THE ORIGIN).         00000790
      CALL PRIME(FSP,W(J),XI(J),R,9.,XS,YS,ZS)        00000800
C FS IS THE SATELLITE LONGITUDE IN DEGREES.         00000810
      FS=(ATAN(YS/XS)-WPAD*PI)*RTD                  00000820
      IF(XS.LT.0.)FS=FS+P*RTD                       00000830
C TS IS THE SATELLITE COLATITUDE IN DEGREES.        00000840
      TS=RTD*ARCOS(ZS/R)                            00000850
      F=G*WRAD*RI                                    00000860
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K. 00000870
      X=R*F*SIN(T)*COS(F)                           00000880
      Y=R*F*SIN(T)*SIN(F)                           00000890
      Z=R*F*COS(T)                                   00000900
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE 00000910
C CENTER OF THE EARTH.                             00000920
C RGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL 00000930
C MILES.                                             00000940
      ACC=ARCOS((X*XS+Y*YS+Z*ZS)/(R*F))              00000950
      RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5         00000960
      ARG=SIN(ACC)*R/PGF                             00000970
      IF(ARG.GT.1.0000000) ARG=1.0000000           00000980
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO 00000990
C SATELLITE J.                                     00001000
      D=(ARSIN(ARG)-P/2.)*PTD                       00001010
      RT=SQRT(R*R-R*RE*RE)                          00001020
      IF(RGE.LE.RT) D=-D                             00001030
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY. 00001040
      CALL DOPE(R,F(J),A(J),TAU,FSP,WP(J),W(J),XI(J),XV,YV,ZV) 00001050
C (XT,YT) ARE THE COMPONENTS OF THE RELATIVE VELOCITY OF GROUND 00001060
C STATION K.                                         00001070
      XT=-WPAD*RE*SIN(T)*SIN(F)/3600.              00001080
      YT=WPAD*RE*SIN(T)*COS(F)/3600.               00001090
      DOT=(XV-XT)*(XS-X)+(YV-YT)*(YS-Y)+ZV*(ZS-Z) 00001100
      DOT=-DOT/RGE                                    00001110
C UPDOP IS THE UPLINK DOPPLER SHIFT IN HZ.         00001120
C DNDOP IS THE DOWNLINK DOPPLER SHIFT IN HZ.       00001130
      UPDOP=DOT*PP/CL                               00001140
      DNDOP=DOT*PP1/CL                              00001150
      WRITE(6,20)J,RI,PGF,D,UPDOP,DNDOP,FS,TS,K    00001160
20    FORMAT(1H,'I3,P8.1,'17.3,F14.3,'17.3,F17.3,F13.3,F13.3,I10) 00001170
500    CONTINUE                                       00001180
      WRITE(6,25)                                     00001190
25    FORMAT(1H, '//)                               00001200
700    CONTINUE                                       00001210
900    CONTINUE                                       00001220

```



```

30      WRITE(6,30)
      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,'HFS',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(P1,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.
      R12=(TC1**2+TC2**2+TC3**2)**.5
      CALL UNPPIM(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) P1,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)
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)	00001840
A22=-	SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)	00001850
A31=	SIN(XIS)*SIN(FSP)	00001860
A32=	SIN(XIS)*COS(FSP)	00001870
XS=	A11*XPS+A12*YPS	00001880
YS=	A21*XPS+A22*YPS	00001890
ZS=	A31*XPS+A32*YPS	00001900
RETURN		00001910
END		00001920
SUBROUTINE	ELLIP(T,E,WP,TP,A,TAU,FSP,P)	00001930
P=	3.1415926	00001940
Z=	2.*P*(T-TP)/TAU	00001950
P2=	2.*P	00001960
2	IF(Z.GT.P2)Z=Z-P2	00001970
	IF(Z.GT.P2)GO TO 2	00001980
	E1=Z+E*SIN(Z)	00001990
	E2=(Z+E*(SIN(E1))-(E*COS(E1))*E1)/(1.-E*COS(E1))	00002000
	Q=0.	00002010
4	E3=(Z+E*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))	00002020
	Q=Q+1.	00002030
	DE=E3-E2	00002040
	DE2=DE**2	00002050
	E2=E3	00002060
	IF(DE2.GT..00000001)GO TO 4	00002070
	TH=ARCOS((COS(E2)-E)/(1.-E*COS(E2)))	00002080
	IF(Z.GT.P)TH=2.*P-TH	00002090
	FSP=WP+TH	00002100
	R=(A*(1.-E**2))/(1.+E*COS(FSP-WP))	00002110
	RETURN	00002120
	END	00002130
SUBROUTINE	DOPE(R,E,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)	00002140
P=	3.1415926	00002150
T=	FSP-WP	00002160
PD=	(A**2.*P/(TAU*(1.-E**2)**.5))*SIN(T)	00002170
TD=	(2.*P/TAU)*((1.-E**2)**(-1.5))*((1.+E*COS(T))**2)	00002180
XPC=	RD*COS(FSP)-P*TD*SIN(FSP)	00002190
XPC=	XPC/3600.	00002200
YPC=	PD*SIN(FSP)+R*TD*COS(FSP)	00002210
YPC=	YPC/3600.	00002220
CALL	PRIMP(C.,WS,XIS,XPC,YPC,XD,YD,ZD)	00002230
RETURN		00002240
END		00002250
SUBROUTINE	UNPRIM(TC1,TC2,TC3,FSP,WS,XIS,R12,FU12,TU12)	00002260
A11=	COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)	00002270
A12=-	SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)	00002280
A21=	COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)	00002290
A22=-	SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)	00002300
A31=	SIN(XIS)*SIN(FSP)	00002310
A32=	SIN(XIS)*COS(FSP)	00002320
A13=	SIN(XIS)*SIN(WS)	00002330
A23=-	SIN(XIS)*COS(WS)	00002340
A33=	COS(XIS)	00002350
Z1=	A11*TC1+A21*TC2+A31*TC3	00002360
X1=	A12*TC1+A22*TC2+A32*TC3	00002370
Y1=	A13*TC1+A23*TC2+A33*TC3	00002380
XU=	X1	00002390
YU=	-Y1	00002400
ZU=	-Z1	00002410
RTD=	57.29577951	00002420
P=	3.14159265	00002430

```

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=APCOS(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*PAR)*((COS(TE*PAR))**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*PAR)
V7=SIN(XI)
IF(V7.EQ.0.) V7=.000000001
ANG=TE/V7
IF(ANG.GT.P2) ANG=P2
DAH=360.*(WREL*ANG/P**2)*((DVP**2)*A**2)/MUE
C5=DAH
DAY=9760.*DAH
AB=A*(C5*T)/2.
RHO=RM
C6=P*(1./81.)*(1./RHO)**3
C7=2.77218*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)
PATIO=-C9/C10
C11=-(15./4.)*S2I+AR2*((315./128.)-(315./16.)*C2I+(2205./128.)*C4I)
1 I)
WPS=0.
IF(PATIO.LT.0.) GO TO 50
IF(PATIO.GT.1.) GO TO 50
WPS=ARSIN(SQRT(PATIO))
E1=E0*EXP(-C6*(AB**1.5)*(SIN(2.*WPS))*(C11/C7)*T)
GO TO 100
50 WPC=(P/4.)*.001
C8=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=E0*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

```

```

u ))
DWH=DW/(C7*AB**1.5)
W=W7+DWH*T
ABIG=A+(C5*T)
V50=A*(1.+EC)
V5=ABIG*(1.+E1)/V50
RETURN
END

```

```

00003040
00003050
00003060
00003070
00003080
00003090
00003100
00003110

```

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),'EDELMAH 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 LATITUDE 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/200000.,200000.,200000.,200000.,200000.,200000.,200000.,200000.,200000.,200000./ 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

```



```

10      WRITE(6,10)
      FORMAT(1H,'SAT',5X,'HRS',12X,'RANGE',9X,'ANGLF',8X,'UPDOPPLER
11      1',8X,'DNDOPPLR',9X,'SUBL',9X,'SUBC',6X,'STATION',//)
      T=B(K)/RTD
      G=B(K+2)/PTD
C I IS THE HOUR.
      DO 500 I=3,150,3
      RI=I
C SUBROUTINE ELLIP COMPUTES THE RANGE FROM GEOCENTER TO SATELLITE J AND
C THE ANGLF MEASURED IN ORBIT PLANE; REFERRED TO NODE OF ORBIT PLANE
C AND EQUATORIAL PLANE.
      CALL ELLIP(RI,E(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(PSP,W(J),XI(J),R,0.,XS,YS,ZS)
C PS IS THE SUBSATELLITE LONGITUDE IN DEGREES.
      FS=(ATAN(YS/XS)-WRAD*PI)*RTD
      IF(XS.LT.0.) FS=FS+PI*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=RE*SIN(T)*COS(F)
      Y=RE*SIN(T)*SIN(F)
      Z=RE*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)/(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
C D IS THE ELEVATION ANGLE IN DEGREES FROM GROUND STATION K TO
C SATELLITE J.
      D=(ARSIN(ARG)-PI/2.)*RTD
      RT=SQRT(R*R-RE*RE)
      IF(PGE.LE.RT) D=-D
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
      CALL DOPE(R,E(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=-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
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,RI,RGE,D,UPDOP,DNDOP,FS,TS,K
20      FORMAT(1H,I3,F8.1,F17.3,F14.3,F17.3,F17.3,F13.3,F13.3,I10)
500      CONTINUE
      WRITE(6,26)
26      FORMAT(1H,/)
700      CONTINUE
900      CONTINUE
      WRITE(6,30)
30      FORMAT(1H,////)
      L=WUMS-1
      IF(L.EQ.0) GO TO 350

```

```

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,E(M1),WP(M1),TP(M1),A(M1),TAU,FSP,R)                 00001400
  CALL ELLIP(RI,E(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,FU12,TU12)           00001500
  F12=RTD*ATAN(TC2/TC1)                                                00001510
  IF(TC1.LT.0.) F12=F12+P*RTD                                          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=ARCOS(VIZ)                                                        00001560
  DELM=ARSIN(RE/F)                                                     00001570
  IF(DELM.LT.DELM) NOVIZ=0                                             00001580
  TR3=TC3/R12                                                           00001590
  IF(TR3.GE.1.) TR3=.99999999                                          00001600
  IF(TR3.LE.-1.) TR3=-.99999999                                        00001610
  T12=ARCOS(TR3)*P*RTD                                                 00001620
  CALL DOPE(R,E(M1),A(M1),TAU,FSP,WP(M1),W(M1),XI(M1),XV,YV,ZV)      00001630
  CALL DOPE(R,E(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,FU12,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

```

	XS=A11*XPS+A12*YPS	00001840
	YS=A21*XPS+A22*YPS	00001850
	ZS=A31*XPS+A32*YPS	00001860
	RTURN	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+E*SIN (Z)	00001950
	E2=(Z+E*(SIN (E1))-(E*COS (E1))*E1)/(1.-E*COS (E1))	00001960
	Q=0.	00001970
4	F3=(Z+E*(SIN (E2))-(E*COS (E2))*E2)/(1.-E*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=ARCCOS ((COS (F2)-E)/(1.-E*COS (E2)))	00002040
	IF (Z.GT.P) TH=2.*P-TH	00002050
	FSP=WP+TH	00002060
	R=(A*(1.-E**2))/(1.+E*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=FSP-WP	00002120
	PD=(A*E**2.*P/(TAU*(1.-E**2)**.5))*SIN (T)	00002130
	TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*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 PRINS (C.,WS,XIS,XPC,YPC,XD,YD,ZD)	00002190
	RTURN	00002200
	END	00002210
	SUBROUTINE UNPRIN (TC1,TC2,TC3,FSP,WS,XIS,P12,FU12,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
	FU12=PTD*ATAN (YU/XU)	00002400
	IF (XU.LT.0.) FU12=FU12+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,AO,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
RTD=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**A0**1.5
V=(24./TAU)*10.
V=V*V6
V50=A0*(1.+EO)
CALL ARGPER(A0,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, A0 IS REALLY THE NEW 'A' AS COMPUTED BY THE PREVIOUS ITERATION.
C SO FOR THE SECOND ITERATION A0 REALLY EQUALS A1, FOR THE THIRD
C A2 AND SO ON. THUS THE LOGIC STATEMENT IS REQUIRED.
IF(I.GT.1)A0=A
CALL MOON(A0,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=((-135./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+A2*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=.	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
1+(2205./64.)*(COS(V4))**4)	00003190
RAT2=NUM/DEN	00003200
IF(RAT2.LT.0.) RETURN	00003210
IF(RAT2.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
MUF=.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*PAR))**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=.000000001	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

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.,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.,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=57.29577951
      WPAD=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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00000010
00000020
00000030
00000040
00000045
00000050
00000060
00000070
00000080
00000090
00000100
00000110
00000120
00000130
00000140
00000150
00000160
00000170
00000180
00000190
00000200
00000210
00000220
00000230
00000240
00000250
00000260
00000270
00000280
00000290
00000300
00000302
00000304
00000306
00000310
00000320
00000330
00000340
00000350
00000360
00000370
00000380
00000390
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00000410
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00000430
00000440
00000450
00000460
00000470
00000480
00000490
00000500
00000510
00000520
00000530
00000540
00000550
00000560
00000570

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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, FSP, P)
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) - WRAD*RI) * RTD
      IF (XS.LT.0.) FS = FS + P*RTD
11  IF (FS.LT.-360.) FS = FS + 360.
      IF (FS.LT.-360.) GO TO 11
C TS IS THE SUBSATELLITE CLATITUDE IN DEGREES.
      TS = RTD*ARCOS (ZS/P)
      F = G + WRAD*RI
C (X,Y,Z) ARE THE INERTIAL CARTESIAN COORDINATES OF GROUND STATION K.
      X = RE*SIN(T)*COS(P)
      Y = RE*SIN(T)*SIN(P)
      Z = RE*COS(T)
C ACC IS THE ANGLE BETWEEN GROUND STATION K AND SATELLITE J FROM THE
C CENTER OF THE EARTH.
C PGE IS THE RANGE FROM GROUND STATION K TO SATELLITE J IN NAUTICAL
C MILES.
      ACC = ARCOS ((X*XS + Y*YS + Z*ZS) / (RE*P))
      RGP = ((XS-X)**2 + (YS-Y)**2 + (ZS-Z)**2)**.5
      ARG = SIN(ACC) * P / RGP
      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 = (ARCSIN(ARG) - P/2.) * PTD
      RT = SQRT (R*P - RE*RE)
      IF (PGE.LT.PT) D = -D
C AZIMUT IS THE AZIMUTH ANGLE.
      SLAT = TS/RTD
      SLOW = FS/RTD
      ARG = G - SLOW
      ALPHA = (SLAT - T) / 2.0
      BETA = (SLAT + T) / 2.0
      GAMMA = ABS(ARG) / 2.0
      IF (GAMMA.GT.P12.AND.GAMMA.LT.P) GAMMA = P - GAMMA
      SINA = SIN(ALPHA)
      SINB = SIN(BETA)
      COSA = COS(ALPHA)
      COSB = COS(BETA)
      COTG = COTAN(GAMMA)
      U1 = SINA*COTG/SINB
      ALPHA = ATAN(U1)
      U2 = COSA*COTG/COSB
      BETA = ATAN(U2)
      IF (BETA.GT.P12.AND.BETA.LT.P2) BETA = BETA + P
      IF (BETA.GT.-P12.AND.BETA.LT.0.) BETA = BETA + P
      AZIMUT = (ALPHA + BETA) * RTD
      ARG = SIN(ARG)
      IF (ARG.GT.0.0) AZIMUT = 360.0 - AZIMUT
C SUBROUTINE DOPE COMPUTES THE COMPONENTS OF SATELLITE VELOCITY.
      CALL DOPE (R, E(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*PE*SIN(T)*SIN(P)/3600.
      YT = WRAD*PE*SIN(T)*COS(P)/3600.
      DOT = (XV-XT)*(XS-X) + (YV-YT)*(YS-Y) + (ZV)*(ZS-Z)
      DOT = -DOT/PGE

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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.FQ.0) GO TO 350 00001260
C FR IS THE CROSSLINK FREQUENCY IN HZ. 00001270
  FR=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,'PANGF',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(PI,E(M1),WP(M1),TP(M1),A(M1),TAU,FSP,R) 00001440
      CALL ELLIP(RI,F(M2),WP(M2),TP(M2),A(M2),TAU2,F2P,P2) 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=ACOS(VIZ) 00001580
      DELM=ARSIN(RE/R) 00001590
      IF(DEL.LE.DELM) NOVIZ=0 00001600
      T12=ACOS(TC3/R12)*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/R12 00001650
C DOP12 IS THE CROSSLINK DOPPLER SHIFT IN HZ. 00001660
      DOP12=-DOT*FP/CL 00001670
50  WRITE(6,50) RI,F12,T12,DOP12,NOVIZ,M1,M2 00001680
      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 ,//)	00001720
250	CONTINUE	00001730
350	CONTINUE	00001740
	END	00001750
	SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)	00001760
	A11=COS(FSP)*COS(WS)-COS(XIS)*SIN(WS)*SIN(FSP)	00001770
	A12=-SIN(FSP)*COS(WS)-COS(XIS)*SIN(WS)*COS(FSP)	00001780
	A21=COS(FSP)*SIN(WS)+COS(XIS)*COS(WS)*SIN(FSP)	00001790
	A22=-SIN(FSP)*SIN(WS)+COS(XIS)*COS(WS)*COS(FSP)	00001800
	A31=SIN(XIS)*SIN(FSP)	00001810
	A32=SIN(XIS)*COS(FSP)	00001820
	XS=A11*XPS+A12*YPS	00001830
	YS=A21*XPS+A22*YPS	00001840
	ZS=A31*XPS+A32*YPS	00001850
	RETURN	00001860
	END	00001870
	SUBROUTINE ELLIP(T,P,WP,TP,A,TAU,FSP,R)	00001880
	P=3.1415926	00001890
	Z=2.*P*(T-TP)/TAU	00001900
	P2=2.*P	00001910
2	IF(Z.GT.P2) Z=Z-P2	00001920
	IF(Z.GT.P2) GO TO 2	00001930
	E1=Z+P*SIN(Z)	00001940
	E2=(Z+E*(SIN(E1))-(Z*COS(E1))*E1)/(1.-E*COS(E1))	00001950
	Q=0.	00001960
4	E3=(Z+E*(SIN(E2))-(E*COS(E2))*E2)/(1.-E*COS(E2))	00001970
	Q=Q+1.	00001980
	DE=E3-E2	00001990
	DE2=DE**2	00002000
	E2=E3	00002010
	IF(DE2.GT..00000001) GO TO 4	00002020
	TH=ARCCOS((COS(E2)-E)/(1.-E*COS(E2)))	00002030
	IF(Z.GT.P) TH=2.*P-TH	00002040
	FSP=WP+TH	00002050
	P=(A*(1.-E**2))/(1.+E*COS(FSP-WP))	00002060
	RETURN	00002070
	END	00002080
	SUBROUTINE DODE(P,P,A,TAU,FSP,WP,WS,XIS,XD,YD,ZD)	00002090
	P=3.1415926	00002100
	T=FSP-WP	00002110
	RD=(A*E*2.*P/(TAU*(1.-E**2)**.5))*SIN(T)	00002120
	TD=(2.*P/TAU)*((1.-E**2)**(-1.5))*(1.+E*COS(T))**2	00002130
	XPC=RD*COS(FSP)-R*TD*SIN(FSP)	00002140
	XPC=XPC/3600.	00002150
	YPC=RD*SIN(FSP)+R*TD*COS(FSP)	00002160
	YPC=YPC/3600.	00002170
	CALL PRIME(0.,WS,XIS,XPC,YPC,XD,YD,ZD)	00002180
	RETURN	00002190
	END	00002200

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)	00000010
	DATA A/14342.,14342.,22767.,22767.,22767.,22767.,	00000020
3	57369.,57369.,57369.,57369./	00000025
	DATA E/.725.,.725,0.,0.,0.,0.,0.,0.,0.,0./	00000030
	DATA W/0.,270.,0.,0.,0.,0.,0.,0.,0.,0./	00000040
	DATA WP/-90.,-90.,0.,0.,0.,0.,0.,0.,0.,0./	00000050
	DATA TP/0.,-6.,-3.,-9.,-15.,-21.,	00000060
1	0.,-24.,-48.,-72./	00000065
	DATA XI/63.435,63.435,0.,0.,0.,0.,90.,90.,90.,90./	00000070
	WRITE(6,7)	00000100
7	FORMAT(1H,5X,'T1',8X,'P1',13X,'NO.',13X,'T',/)	00000110
	RTD=57.2957795	00000120
	DO 11 M=1,10	00000130
	W(M)=W(M)/RTD	00000140
	WP(M)=WP(M)/RTD	00000150
	XI(M)=XI(M)/RTD	00000160
11	CONTINUE	00000170
	P=3.1415926	00000180
	PE=3440.	00000190
	WRAD=15./RTD	00000200
	RM=35.	00000210
	DO 600 I=1,6	00000220
	RI=T-1.	00000230
	DO 500 J=1,13	00000240
	RJ=J	00000250
	T=(RJ-1.)*15./PTD	00000260
	DO 400 K=1,25	00000270
	RK=K	00000280
	FIN=((RK-1.)*15./PTD)+RI*WRAD	00000290
	F=FIN-RI*WRAD	00000300
	CON=6.987*10.**(-6)	00000310
	SATNO=0.	00000320
	DO 300 L=1,10	00000330
	RL=L	00000340
	TAU=CON*A(L)**1.5	00000350
	CALL ELLIP(RI,P(L),WP(L),TP(L),A(L),TAU,PSP,R)	00000360
	CALL PRIME(PSP,W(L),VI(L),P,0.,XS,YS,ZS)	00000370
	Y=PE*SIN(T)*COS(FIN)	00000380
	Y=RE*SIN(T)*SIN(FIN)	00000390
	Z=RE*COS(T)	00000400
	ACC=ARCCOS((X*XS+Y*YS+Z*ZS)/(RE*P))	00000410
	RGE=((XS-X)**2+(YS-Y)**2+(ZS-Z)**2)**.5	00000420
	ARG=SIN(ACC)*R/RGE	00000430
	IF(ARG.GT..9999999)ARG=.9999999	00000440
	D=(ARSIN(ARG)-P/2.)*PTD	00000450
	RT=SQRT(R*P-RE*RE)	00000460
	IF(PGE.LE.RT)D=-D	00000470
	IF(D.GT.EM)SATNO=SATNO+1.	00000480
	IF(SATNO.GT.1)GO TO 400	00000490
	IF(PL.LT.9.9)GO TO 300	00000500
	T1=T*PTD	00000510
	P1=P*RTD	00000520
	WRITE(6,20)T1,P1,SATNO,RI	00000530
20	FORMAT(1H,4F12.3)	00000540
300	CONTINUE	00000550
	IF(RJ.LE.1.)GO TO 500	00000560
	IF(RJ.GT.12.)GO TO 500	00000570
400	CONTINUE	00000580
500	CONTINUE	00000590
600	CONTINUE	00000600
	END	00000610

	SUBROUTINE PRIME(FSP,WS,XIS,XPS,YPS,XS,YS,ZS)	00000620
	A11=cos(FSP)*cos(WS)-cos(XIS)*sin(WS)*sin(FSP)	00000630
	A12=-sin(FSP)*cos(WS)-cos(XIS)*sin(WS)*cos(FSP)	00000640
	A21=cos(FSP)*sin(WS)+cos(XIS)*cos(WS)*sin(FSP)	00000650
	A22=-sin(FSP)*sin(WS)+cos(XIS)*cos(WS)*cos(FSP)	00000660
	A31=sin(XIS)*sin(FSP)	00000670
	A32=sin(XIS)*cos(FSP)	00000680
	XS=A11*XPS+A12*YPS	00000690
	YS=A21*XPS+A22*YPS	00000700
	ZS=A31*XPS+A32*YPS	00000710
	RETURN	00000720
	END	00000730
	SUBROUTINE FLIP(T,E,WP,TP,A,TAU,FSP,R)	00000740
	P=3.1415926	00000750
	Z=2.*P*(T-TP)/TAU	00000760
	P2=2.*P	00000770
2	IF(Z.GT.P2) Z=Z-P2	00000780
	IF(Z.GT.P2) GO TO 2	00000790
	E1=Z+P*sin(Z)	00000800
	E2=(Z+E*(sin(E1)-(E*cos(E1))*E1)/(1.-E*cos(E1))	00000810
	Q=0.	00000820
4	E3=(Z+E*(sin(E2)-(E*cos(E2))*E2)/(1.-E*cos(E2))	00000830
	Q=Q+1.	00000840
	DE=E3-E2	00000850
	DE2=DE**2	00000852
	E2=E3	00000860
	IF(DE2.GT..0000001) GO TO 4	00000870
	TH=ARCOS((cos(E2)-E)/(1.-E*cos(E2)))	00000880
	IF(Z.GT.P) TH=2.*P-TH	00000890
	FSP=WP+TH	00000900
	P=(A*(1.-E**2))/(1.+E*cos(FSP-WP))	00000910
	RETURN	00000920
	END	00000930
