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SeaTrack—Ground Station Orbit Prediction and Planning Software for Sea–Viewing Satellites
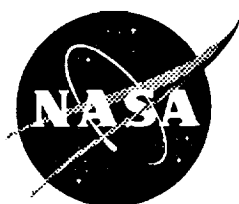
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SeaTrack—Ground Station Orbit Prediction and Planning Software for Sea–Viewing Satellites

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Abstract

An orbit prediction software package (SeaTrack) was designed to assist High Resolution Picture Transmission (HRPT) stations in the acquisition of direct broadcast data from sea-viewing spacecraft. Such spacecraft will be common in the near future, with the launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in 1994, along with the continued Advanced Very High Resolution Radiometer (AVHRR) series on NOAA platforms. The Brouwer-Lyddane model was chosen for orbit prediction because it meets the needs of HRPT tracking accuracies, provided orbital elements can be obtained frequently (up to within 1 week). SeaTrack requires elements from the U.S. Space Command (NORAD Two-Line Elements) for the satellite's initial position. Updated Two-Line Elements are routinely available from many electronic sources (some are listed in the Appendix). SeaTrack is a menu-driven program that allows users to alter input and output formats. The propagation period is entered by a start date and end date with times in either Greenwich Mean Time (GMT) or local time. Antenna pointing information comes in a tabular form and includes azimuth/elevation pointing angles, sub-satellite longitude/latitude, acquisition of signal (AOS), loss of signal (LOS), pass orbit number, and other pertinent pointing information. One version of SeaTrack (non-graphical) allows operation under DOS (for IBM-compatible personal computers) and UNIX (for Sun and Silicon Graphics workstations). A second, graphical, version displays orbit tracks, and azimuth-elevation for IBM-compatible PC's, but requires a VGA card and Microsoft Fortran.

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1.0 INTRODUCTION

Direct broadcast of remote sensing data by satellites and acquisition by High Resolution Picture Transmission (HRPT) stations is a growing field. For many years, scientists interested in sea-surface temperature data have successfully used data from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellite series (NOAA-9,10,11,12). Sometimes the data are acquired and used in real-time, which is a major advantage of such HRPT stations. The upcoming launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on Orbital Sciences Corporation's SeaStar satellite will increase opportunities for scientists to observe ocean behavior by providing ocean color data.

An orbit determination and tracking program is extremely useful for HRPT station operators to plan for and acquire AVHRR and SeaWiFS data to further these ocean remote sensing scientific, and even commercial, applications. Thus, we present here the orbit prediction model SeaTrack, so that the HRPT stations can capture the real-time broadcasting LAC data when the spacecraft is in view. The motivation for development of a new program for this purpose is: to provide specific, user-selectable options for input and output that are specifically geared to the needs of the HRPT stations; and to provide source code so users can perform additional customization as desired. The program is not satellite or location specific, and therefore can be used to track satellites other than the NOAA series or SeaStar/SeaWiFS. SeaTrack will be available to HRPT stations via the anonymous File Transfer Protocol (FTP) on Internet at manua.gsfc.nasa.gov (128.183.121.18). (login as "anonymous" and enter node name as password, then type "cd pub/mission-ops"). It is also available from COSMIC:

> COSMIC
> Computer Software Management and Information Center
> The University of Georgia
> 382 East Broad Street
> Athens, GA 30602-4272
> phone = (706) 542-3265 fax = (706) 542-4807
> E-Mail: service@cossack.cosmic.uga.edu

This report will describe SeaTrack's prediction model and supporting routines. A user's guide will also be provided to explain how the program is to be used to track satellites.

2.0 SeaTrack DESCRIPTION

The Brouwer-Lyddane model was chosen as the prediction model for SeaTrack. The Brouwer-Lyddane routines were developed by Hoisington for the Data Capture Facility/GSFC using the original publications of Brouwer (1959) and Lyddane (1963) in addition to the Goddard Trajectory Determination System (GTDS) (Cappellari et al., 1976). Brouwer-Lyddane is a general perturbations model that yields an analytical solution. The Brouwer-Lyddane model does not take into account atmospheric drag, which gradually moves the satellite into a lower orbit and consequently increases its velocity. Therefore, Brouwer-Lyddane predictions degrade over time, with predicted satellite positions occurring later in the orbit than the actual position. However, a detailed study by Patt et al. (1993) showed that predictions of the NOAA-12 satellite

degraded only 2 seconds in 1 week. Similar results are expected for SeaStar, based on analyses of orbit predictions for Landsat-5, which is in a similar orbit (see Patt *et al.*, 1993). Assuming that NORAD elements will be updated frequently (within one week), Brouwer-Lyddane is a suitable model for HRPT satellite tracking.

The purpose of the SeaTrack model is to allow input of commonly available orbital elements into the Brouwer-Lyddane model, compute satellite positions and velocities, and convert these output positions and velocities into convenient and meaningful quantities for satellite tracking. Specifically, SeaTrack reads NORAD Two-Line orbital elements as inputs, converts these to mean Brouwer elements for use in the Brouwer-Lyddane model, propagates forward in time using the model, determines overpass times and positions for a given ground (HRPT) station, and computes azimuth/elevation, longitude/latitude, and Acquisition of Signal (AOS)/Loss of Signal (LOS) times that station operators require for data acquisition. It also provides graphical display of the output quantities. The remainder of this section describes how SeaTrack performs these functions.

2.1 Elements

Orbital elements are used to describe a satellite's orbit. The U.S. Space Command (formerly NORAD) provides elements in a two-line form (called NORAD Two-Line Elements). An example Two-Line Element set for NOAA-12 follows with explanations about the terms that are used in SeaTrack. (A column number bar is given above the elements to aid in the explanation.)

```
          1         2         3         4         5         6
1234567890123456789012345678901234567890123456789012345678901234567890123456789

1 21263U 91 32  B 93231.76315203  .00000177  00000-0  88271-4 0  6491
2 21263  98.6545 260.6933 0013797  33.2603 326.9449 14.22300920117899
```

The pertinent items in the element set are as follows.

- Satellite Number = 21263 (line 1 columns 3-7)
  every spacecraft receives a distinct identification number (the number for SeaStar is not yet known).

- Launch Year = 91 (line 1 columns 10-11)
  the year in which the spacecraft was launched (actually 1991).

- Epoch Year = 93   (line 1 columns 19-20)
  the year the elements were obtained (actually 1993).

- Epoch day = 231.76315203 (line 1 columns 21-32)
  the epoch day of year in GMT (1 < = epoch day < 367).

- Inclination = 98.6545 degrees (line 2 columns 9-16)
  the angle at which the orbit plane crosses the equatorial plane, measured counter-clockwise from east.

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- Right Ascension of Ascending Node = 260.6933 degrees (line 2 columns 18-25)
  the angle on the equatorial plane from the vernal equinox eastward to the orbit ascending node, the point where the satellite crosses the Equator on an ascending pass. The vernal equinox is the ascending node of the Earth's orbit around the Sun.

- Eccentricity = .0013797 (line 2 columns 27-33)
  the shape of the orbit where zero defines a circular orbit and higher values indicate a more elliptical orbit (0 < = eccentricity < 1 for Earth orbit).

- Argument of Perigee = 33.2603 degrees (line 2 columns 35-42)
  the angle in the orbital plane from the ascending node to the point of perigee in the direction of the satellite's motion. Perigee is the point in the orbit closest to the Earth's center for an elliptical orbit.

- Mean Anomaly = 326.9449 degrees (line 2 columns 44-51)
  the angle on the orbital plane from the point of perigee to the position of the satellite in the direction of the satellite's motion.

- Mean Motion = 14.22300920 (line 2 columns 53-63)
  the mean number of orbits per day.

- Orbit number = 11789 (line 2 columns 64-68)
  the current revolution number. The value is incremented when a satellite crosses the equator on an ascending pass.

The Brouwer-Lyddane routine in SeaTrack (BRWLYD) uses Brouwer mean orbital elements (average values of an orbit) as input. The Brouwer mean elements are as follows:

1. Semi-Major Axis (α)
2. Eccentricity (ϵ)
3. Inclination (i)
4. Right Ascension of Ascending Node (Ω)
5. Argument of Perigee (ω)
6. Mean Anomaly (M)

All of these values except the semi-major axis can be obtained from the Two-Line Elements. The semi-major axis is computed in the subroutine RNORAD by utilizing Earth constants and values from the NORAD elements (Patt *et al.*, 1993). First, the mean motion is converted from revolutions per day (N) to radians per minute (Xno):

$$Xno = 2\pi N/1440 \tag{1}$$

The calculation of the semi-major axis uses the gravitational constant in units of Earth radii

($R_e^{1.5}$) per minute), and also the J_2 perturbation term. The Earth radius (R_e), gravitational constant (G_e), and J_2 are defined as:

$$R_e = 6378.137 \text{ km}$$
$$G_e = 398600.5 \text{ km}^2/\text{sec}^{-2}$$
$$J_2 = 0.00108263$$

(Astronomical Almanac, 1983).

The revised value of the gravitational constant (Xke) is:

$$Xke = 60(G_e R_e^{-3})^{1/2}$$

$$= 0.0743668531 \tag{2}$$

where Xke is in units of Earth radii$^{1.5}$ ($R_e^{1.5}$) per minute. The initial (classical) estimate of the semi-major axis is:

$$A_1 = (Xke/Xno)^{2/3} \tag{3}$$

where A_1 is in units of Earth radii.

The perturbation corrections to the semi-major axis use the inclination (i), the eccentricity (ϵ), and J_2 as follows:

$$\text{Temp} = 0.75 \, J_2(3 \, COS^2(i) - 1)/(1 - \epsilon^2)^{1.5} \tag{4}$$
$$\text{Del}_1 = \text{Temp}/A_1^2 \tag{5}$$
$$A_O = A_1\{1 - \text{Del}_1[1/3 + \text{Del}_1(1 + 134 \, \text{Del}_1/81)]\} \tag{6}$$
$$\text{Del}_O = \text{Temp}/A_O^2 \tag{7}$$
$$A_{ODP} = A_O R_e/(1 - \text{Del}_O) \tag{8}$$

where A_{ODP} is the mean semi-major axis in kilometers. This value represents the first element of the Brouwer element array.

2.2 Calling Sequence

The routine BRWLYD propagates the Brouwer mean elements to the desired time and converts them into Keplerian osculating elements (instantaneous values of an orbit). The model uses the Earth's radius (R_e), the gravitational constant (G_e), and a fourth-order gravity field (J_2, J_3, and J_4 terms) as constants. These values are set in SeaTrack's NEWCDATA routine, and follow the International Astronomical Union (IAU) 1976 conventions (Astronomical Almanac, 1983). The output Keplerian elements represent the same terms and units as the Brouwer elements.

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CALL BRWLYD(Brw,Ier,Del,Os)

This call initiates and runs the Brouwer-Lyddane model. Brw is a six-element input array of double precision real values that contains the Brouwer mean elements. Ier is an output integer completion code (1 = success, 2 = invalid input parameter). The output osculating elements (Os) are formulated as a six-element array of double precision real values. Del is an input double precision real value which represents the time difference in seconds between the epoch (the time at which the Brouwer mean elements were calculated) and the prediction time (also known as the propagation time).

Predicted positions in the form of Keplerian osculating elements are not directly useful for scheduling. SeaTrack converts these elements first to vectors and then to longitude/latitude and azimuth/elevation which are much easier to understand.

2.3 Propagation

Propagation start and end times are input as date and 24-hour time in either GMT or local time). These values are then converted to seconds since January 1, 2000 12:00 GMT by the routine DATSEC2000, thereby enforcing the J2000 time reference system. Negative times do not affect computation. The following equations derive seconds from epoch to the start time, seconds from epoch to the end time, and the period (seconds) of propagation:

$$\text{Start} = \text{Stsec} - \text{Epsec} + \text{Timeadj} \tag{9}$$
$$\text{End} = \text{Endsec} - \text{Epsec} + \text{Timeadj} \tag{10}$$
$$\text{Period} = \text{Endsec} - \text{Stsec} \tag{11}$$

where Stsec is the start time of the requested propagation, Epsec is the epoch time of the element set, Timeadj is a time adjustment factor, and Endsec is the end time of the requested propagation. If the start and end times are entered in local time then the time adjustment factor (Timeadj) needs to be added to Start and End, as noted above. This occurs because the epoch time and date given from the NORAD elements are in GMT. Timeadj can be set to zero for GMT mode because time adjustment then is ignored. Period does not need to be adjusted because it is just the time difference between two events which are in the same time mode.

The number of seconds between each propagation point is given by the integer Delta, which is also input by the user. The total number of propagation intervals is determined from the start and end times and the Delta time. Now that the propagation points, start and end times are known, a loop can be used to call BRWLYD. The result is a collection of predicted satellite positions in Keplerian osculating elements spanning the propagation period.

2.4 Calculation of SeaTrack Outputs

The standard output from the Brouwer-Lyddane model is a description of the predicted orbit, given in Keplerian osculating elements. In order for HRPT station operators to perform planning operations, point antennas, and actually acquire data from SeaStar, they require more convenient and useful expressions of the orbit position. These are typically azimuth/elevation

measured from given station coordinates, longitude/latitude of the spacecraft, AOS/LOS times at the station, and maximum elevation of the spacecraft during an overpass.

2.4.1 Osculating Elements to Earth-Centered Inertial Vectors

The first step in the computation of the desired output quantities is the conversion of osculating elements to vectors in the Earth-Centered Inertial (ECI) coordinate system. The Cartesian (XYZ) form of the ECI system fixes the X axis as the vector from the center of the Earth towards the direction of the vernal equinox (Figure 1). The routine KEPXYZ2 converts osculating elements into ECI vectors.

CALL KEPXYZ2(Os,Pv,Vv)

Os is an array of double precision real values that contains the six input osculating elements defined earlier. Pv and Vv are each a three-element array of double precision real values that contain the position (m) and velocity (m/s) vectors of the spacecraft, respectively, in the ECI coordinate system. These vectors are computed from the osculating elements as follows.

The mean anomaly does not accurately relate the satellite position to a given time. Kepler's second law states that satellites must move faster at perigee than apogee to preserve the equal areas principle. The true anomaly takes this into account. The eccentric anomaly (E) relates the mean anomaly (M) to the true anomaly (F). The eccentric anomaly is related to the mean anomaly by Kepler's equation:

$$M = E - \epsilon SIN(E) \tag{12}$$

The eccentric anomaly is not directly solvable from this equation. The following algorithm gives a good approximation for small eccentricities:

$$E_0 = M \tag{13}$$
$$E_n = M + \epsilon SIN(E_{n-1}) \tag{14}$$

The algorithm is iterated until the absolute value of the difference of two consecutive E values is less than 1×10^{-15}, up to 13 iterations.

The true anomaly (F) can then be determined:

$$F = TAN^{-1} [Xp_0 SIN(E) / (COS(E) - \epsilon)] \tag{15}$$

(Wertz, 1978) where

$$Xp_0 = (1 - \epsilon^2)^{1/2} \tag{16}$$

Since the true anomaly relates the satellite position to time, the ascending node-to-spacecraft position angle can now be found:

$$\omega' = \omega + F \tag{17}$$

The position and velocity vectors are now computed using the following equations (Wertz, 1978). First the unit vectors are computed:

$$\mathbf{A} = \begin{bmatrix} COS(\Omega)COS(\omega') - SIN(\Omega)COS(i)SIN(\omega') \\ COS(\Omega)SIN(\omega')COS(i) + SIN(\Omega)COS(\omega') \\ SIN(i)SIN(\omega') \end{bmatrix} \tag{18}$$

$$\mathbf{B} = \begin{bmatrix} -SIN(\Omega)COS(i)COS(\omega') - COS(\Omega)SIN(\omega') \\ COS(\Omega)COS(i)COS(\omega') - SIN(\Omega)SIN(\omega') \\ SIN(i)COS(\omega') \end{bmatrix} \tag{19}$$

The ECI position vector (**Pv**) and velocity vector (**Vv**) can now be computed:

$$\begin{bmatrix} Pv_x \\ Pv_y \\ Pv_z \end{bmatrix} = Rsp\ \mathbf{A} \tag{20}$$

$$\begin{bmatrix} Vv_x \\ Vv_y \\ Vv_z \end{bmatrix} = Xp_3\ \mathbf{A} + Xp_2\ \mathbf{B} \tag{21}$$

where

$$Rsp = \alpha[1-\epsilon COS(E)] \tag{22}$$
$$Xp_1 = (\alpha G_e)^{1/2}/\ Rsp \tag{23}$$
$$Xp_2 = Xp_0\ Xp_1 \tag{24}$$
$$Xp_3 = \epsilon SIN(E)Xp_1 \tag{25}$$

and G_e has already been defined.

2.4.2. Earth-Centered Inertial to Earth-Fixed Vectors

In order to obtain satellite longitude/latitude at nadir and azimuth/elevation, an Earth-fixed coordinate system must be established. A Cartesian (or XYZ) coordinate system with the origin fixed at the center of the Earth is an optimal system. This is termed the Earth-Centered Earth-Fixed (ECEF) coordinate system (Figure 2). The X axis represents the vector from the origin to the point where the equator intersects the Prime Meridian. The Z axis represents the vector from the origin to the North Pole.

The routine ECEF converts the ECI vectors into ECEF vectors by using the Greenwich Hour Angle (Gha) as the rotation angle. The following calls complete the transition:

```
CALL GHA2000(Del+Epsec,Gha)    * obtain Greenwich Hour Angle
CALL ECEF(Pv,Vv,Pve,Vve,Gha)   * convert ECI coordinates to ECEF
```

Del is the difference in seconds between the epoch and prediction time. Epsec represents the total number of seconds that have passed between the epoch and January 1, 2000 12:00 GMT. An exact starting date was chosen so there could be consistency with time calculations. Epsec was found by calling the routine DATSEC2000. The day (real value), month, and year are input and the total number of seconds since the year 2000 is returned. The routine GHA2000 computes the Greenwich Hour Angle (Gha) in degrees using an algorithm described in the next section. Pve and Vve are each a three-element array of double precision real values that contain the position (m) and velocity (m/s) vectors of the spacecraft, respectively, in the ECEF coordinate system.

Pve and Vve can be calculated (as in the routine ECEF) by the following:

$$Pve_x = Pv_x COS(Gha) + Pv_y SIN(Gha) \tag{26}$$
$$Pve_y = Pv_y COS(Gha) - Pv_x SIN(Gha) \tag{27}$$
$$Pve_z = Pv_z \tag{28}$$
$$Vve_x = Vv_x COS(Gha) + Vv_y SIN(Gha) + \Omega_E Pve_y \tag{29}$$
$$Vve_y = Vv_y COS(Gha) - Vv_x SIN(Gha) - \Omega_E Pve_x \tag{30}$$
$$Vve_z = Vv_z \tag{31}$$

where

$$\Omega_E = .0000729211585494 \text{ (Earth rotation rate in rad/sec)}$$

This represents a rotation of the inertial vectors by the angle Gha about the North pole; the additional terms in Ω_E are needed to correct the ECEF velocity for the Earth's rotation rate.

2.4.3 Greenwich Hour Angle

The Greenwich Hour Angle (Gha) is found by supplying seconds since January 1, 2000 12:00 GMT to the routine GHA2000. The output Gha is in degrees and takes into account nutation as well as precession (Astronomical Almanac, 1983). Ephemeris parameters are used to compute the nutation in longitude and obliquity. These parameters are declared in the routine EPHPARMS. The equations are shown in the following, with all units are in degrees:

$$\text{Sun mean longitude (Xls)} = 280.46592 + 0.9856473516 \text{ T} \tag{32}$$

where T represents the number of days since the year 2000.

$$\text{Sun mean anomaly (Gs)} = 357.52772 + 0.9856002831 \text{ T} \tag{33}$$

$$\text{Moon mean longitude (Xlm)} = 218.31643 + 13.17639648 \text{ T} \tag{34}$$

$$\text{Moon mean orbit ascending node (Omega)} = 125.04452 - 0.0529537648 \text{ T} \tag{35}$$

The nutation in longitude (Dpsi) and obliquity of the ecliptic (Eps) are computed in the routine NUTATE:

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$$Dpsi = [-17.1996 \text{ SIN(Omega)} + 0.2062 \text{ SIN(2Omega)} - 1.3187 \text{ SIN(2Xls)}$$
$$+ 0.1426 \text{ SIN(Gs)} - 0.2274 \text{ SIN(2Xlm)}] / 3600 \tag{36}$$

Eps is the sum of the mean obliquity (Epsm) and the nutation in obliquity (Deps):

$$Epsm = 23.439291 - 3.560 \times 10^{-7} \text{ T} \tag{37}$$

$$Deps = [9.2025 \text{ COS(Omega)} + 0.573 \text{ COS(2Xls)}] / 3600 \tag{38}$$

$$Eps = Epsm + Deps \tag{39}$$

The Greenwich mean sidereal time (Gmst) needs to be computed in order to determine Gha:

$$Gmst = 100.4606184 + 0.9856473663 \text{ T} + 2.908 \times 10^{-13} \text{ T}^2 \tag{40}$$

The Greenwich Hour Angle can now be computed as follows:

$$Gha = Gmst + Dpsi \text{ COS(Eps)} + Fday/360 \tag{41}$$

where Fday represents the fractional part of the day in seconds.

2.4.4 Spacecraft Elevation

The spacecraft elevation is the angle from the horizon at a given station location to the spacecraft (positive if it is above the horizon and negative if it is below). The zenith angle is the angle from the zenith, 90 degrees above the horizon, to the spacecraft. SeaTrack first calculates the zenith angle and subtracts this value from 90 to obtain the elevation angle.

In order to obtain accurate azimuth and elevation angles, the ellipsoidal shape of the Earth must be taken into account. The routines GETZEN and GETAZM use ellipsoidal model methods (Patt and Gregg, 1993). The routine GETZEN determines the geocentric ECEF position vector (Pos) of the station and the geodetic ECEF local vertical vector (Geod) from the station's longitude/latitude coordinates.

$$\text{TAN(Slat}_c) = (1-F)^2 \text{ TAN(Slat}_g) \tag{42a}$$
$$\text{Slon}_c = \text{Slon}_g \tag{42b}$$
$$\text{Pos}_x = R_L \text{ COS(Slat}_c) \text{ COS(Slon}_c) \tag{42c}$$
$$\text{Pos}_y = R_L \text{ COS(Slat}_c) \text{ SIN(Slon}_c) \tag{42d}$$
$$\text{Pos}_z = R_L \text{ SIN(Slat}_c) \tag{42e}$$

where Slon_g and Slat_g are the station's geodetic longitude and latitude, Slon_c and Slat_c are the station's geocentric longitude and latitude, and R_L is the magnitude of the Earth center-to-station vector, computed as

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$$R_L = R_E (1-F) / [1 - (2F - F^2)COS^2(Slat)]^{1/2} \qquad (43)$$

(Wertz, 1978). F is the Earth reference ellipsoid flattening factor, defined to be 1/298.257 (Astronomical Almanac, 1983).

Geod is normalized when it is computed and is found by:

$$Geod_x = \frac{(1-F)^2 Pos_x}{[Pos_z^2 + (1-F)^4(Pos_x^2 + Pos_y^2)]^{1/2}} \qquad (44a)$$

$$Geod_y = \frac{(1-F)^2 Pos_y}{[Pos_z^2 + (1-F)^4(Pos_x^2 + Pos_y^2)]^{1/2}} \qquad (44b)$$

$$Geod_z = \frac{Pos_z}{[Pos_z^2 + (1-F)^4(Pos_x^2 + Pos_y^2)]^{1/2}} \qquad (44c)$$

The vector between the ECEF station position vector (**Pos**) and the satellite position vector (**Pve**) is computed as:

$$\mathbf{Dvw} = \mathbf{Pve} - \mathbf{Pos} \qquad (45)$$

The dot product of **Dvw** and **Geod** is related to the zenith angle by:

$$\mathbf{Dvw} \bullet \mathbf{Geod} = |\mathbf{Dvw}| \, |\mathbf{Geod}| \, COS(Zen) \qquad (46)$$

Therefore,

$$COS(Zen) = \frac{\mathbf{Dvw} \bullet \mathbf{Geod}}{|\mathbf{Dvw}| |\mathbf{Geod}|} \qquad (47)$$

$|\mathbf{Geod}|$ cancels out because **Geod** is already a normalized vector. The final equation for the elevation angle (assuming Zen is in degrees) becomes:

$$Zen = COS^{-1}(\mathbf{Dvw} \bullet \mathbf{Geod}/|\mathbf{Dvw}|) \qquad (48)$$
$$Elev = 90 - Zen \qquad (49)$$

2.4.5 Spacecraft Azimuth

Spacecraft azimuth is defined as the angle from local North to the spacecraft as viewed from the station, measured clockwise. It is obtained from knowledge of the components of the spacecraft in the local East and North vectors. The East vector from zenith is the normalized cross product of a unit vector **Z** (in the direction of the z axis) and the geodetic station position

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vector **Geod** (from Eq. 44). The East vector E is computed as:

$$E = \frac{Z \times Geod}{|Z \times Geod|}$$

(50)

which is equivalent to

$$E_x = -Geod_y / (Geod_x^2 + Geod_y^2)^{1/2}$$

(50a)

$$E_y = Geod_x / (Geod_x^2 + Geod_y^2)^{1/2}$$

(50b)

$$E_z = 0$$

(50c)

The North vector **N** is simply the cross product of **Geod** and **E**.

$$N = Geod \times E$$

(51)

The components of the satellite direction vector **Dvw** in the direction of North, and East are given by

$$Dvw_N = Dvw \bullet N$$

(52)

$$Dvw_E = Dvw \bullet E$$

(53)

From this the azimuth angle can be found:

$$Azim = TAN^{-1}(Dvw_E/Dvw_N)$$

(54)

The arctangent function is evaluated over the range of 0 to 360 degrees by consideration of the signs of Dvw_E and Dvw_N; most Fortran compilers provide an intrinsic function for this purpose (i.e., the function ATAN2). If the elevation is near 90 degrees then the routine GETAZM sets the azimuth to zero.

2.4.6 Longitude/Latitude

Geodetic longitude and latitude of the sub-satellite point are found by using an ellipsoidal method (Patt and Gregg, 1993). The algorithm from the routine LATLON approximates these values with high accuracy. Approximations for the SeaStar orbit (705 km) were found to be accurate to 0.3 arcseconds; the maximum error is 0.6 arcseconds for an altitude of 300 km.

The spacecraft nadir vector **D** in the ECEF coordinate system is needed to calculate longitude/latitude and can be represented by subtracting the spacecraft position vector Pve from the nadir point's position vector **G** (which is not initially known):

$$D = G - Pve$$

(55)

The desired geodetic longitude/latitude corresponds to the point on the ellipsoidal Earth's

nearest to the spacecraft. This point occurs where the ellipsoid is normal to the nadir vector D.

The approximation for determining G is as follows. A flattening factor can be found for an Earth-centered ellipsoid which contains the point P but is above the surface of the Earth. This ellipsoid would also be normal to vector D, but would have a different flattening factor (called F_p) than for the Earth's surface. In routine LATLON the variable OMF2P represents $(1-F_p)^2$. This value can be obtained from:

$$(1-F_p)^2 = \frac{G_x(1-F)^2 - D_x}{G_x - D_x} \tag{56}$$

By substitution,

$$(1-F_p)^2 = \frac{G_x(1-F)^2 - G_x + Pve_x}{Pve_x} \tag{57}$$

G_x and Pve_x have approximately the same relative magnitudes as $|G|$ and $|Pve|$. F and Pve are known. A good approximation comes from the fact that $|G|$ can be represented by the mean radius of the Earth (6371 km). The final equation becomes:

$$(1-F_p)^2 = \frac{6371(1-F)^2 + |Pve| - 6371}{|Pve|} \tag{58}$$

Now that this flattening value is known, equations similar to Equations 44 can be used to calculate the zenith vector Zv at the spacecraft, which is a unit vector antiparallel to the nadir vector D:

$$Zv_x = \frac{(1-F_p)^2 Pve_x}{[Pve_z^2 + (1-F_p)^4(Pve_x^2 + Pve_y^2)]^{1/2}} \tag{59a}$$

$$Zv_y = \frac{(1-F_p)^2 Pve_y}{[Pve_z^2 + (1-F_p)^4(Pve_x^2 + Pve_y^2)]^{1/2}} \tag{59b}$$

$$Zv_z = \frac{Pve_z}{[Pve_z^2 + (1-F_p)^4(Pve_x^2 + Pve_y^2)]^{1/2}} \tag{59c}$$

The longitude and latitude of the sub-satellite point can now be determined from the zenith vector:

$$Lat = SIN^{-1}(Zv_z) \tag{60}$$

$$\text{Lon} = \text{TAN}^{-1}(Zv_y/Zv_x) \tag{61}$$

The value of the longitude is determined over the range -180 to 180 degrees by consideration of the signs of Zv_y and Zv_x and the use of the Fortran ATAN2 function.

2.4.7 Acquisition of Signal

Acquisition of Signal (AOS) represents the time when a satellite first becomes observable in a pass. This occurs when the elevation is approximately equal to the station's minimum elevation angle. Mountains or other obstacles may prevent the signal from being visible at an elevation of zero degrees. The computation of AOS begins when either of the following occurs:

1) the current propagation point (at time Proptm) is within a pass and the preceding point (at time Proptm - Delta) did not occur in a pass (start of a pass).
2) a propagation starts within the pass (the first propagation point is within a pass at time Proptm).

The algorithm requires two times and two elevations (one greater and one less than the minimum elevation) to initiate the search for AOS. Time is measured in seconds since the epoch. Elevations are checked in Delta decrements from Proptm until the satellite is no longer in view (this occurs at time Prptmp when the satellite's elevation is less than the minimum elevation angle). If this process iterates 300 times, then the loop stops and the AOS is not found (AOS would be represented as Proptm in this case). This can occur with geostationary or slowly moving satellites within a viewing pass. The following variables are set and then the routine FINDAOS is called:

    CALL FINDAOS(Aostme,Elevat,Aost1,Rt1,Aost2,Rt2)

    Aost1 = Prptmp
    Aost2 = Proptm
    Rt1 is the elevation at Prptmp
    Rt2 is the elevation at Proptm
    Aostme = Proptm - (Proptm-Prptmp)/2 (midpoint time)
    Elevat is the elevation at Aostme

If Elevat is greater than the minimum elevation angle, then the current midpoint becomes the new upper bound:

    Rt2 = Elevat
    Aost2 = Aostme

Otherwise, if Elevat is less than or equal to the minimum elevation angle, then the current midpoint becomes the new lower bound:

Rt1 = Elevat
Aost1 = Aostme

The new midpoint time is calculated by:

$$Aostme = Aost2 - (Aost2 - Aost1)/2 \tag{62}$$

Elevat and all elevations are derived from a call to the routine GETZEN. The routine FINDAOS is repeatedly called until the midpoint's elevation (absolute value) is approximately equal to the minimum elevation angle (within 0.001 degrees). The time at which this occurs is AOS.

2.4.8 Loss of Signal

Loss of Signal (LOS) is the time when a satellite progresses over the horizon directly after a pass (or when the satellite descends under the minimum elevation angle). The LOS is computed when either of the following occurs:

1) the current propagation point (at time Proptm) is not in a viewing pass and the preceding point (at time Proptm - Delta) was in a viewing pass (end of a pass).
2) a propagation ends within a pass (the last propagation point is within a pass at time Proptm).

The algorithm for determining LOS is similar to the AOS algorithm in that times and elevations (one greater and one less than the minimum elevation angle) are used to initiate the LOS search. The only difference is how the initial elevations are computed. In case 1 the current time corresponds to Lost2, and in case 2 the current time corresponds to Lost1 (these values are the upper and lower bounds). The current times in the AOS algorithm both correspond to Aost2 so one search could find the initial values for both cases.

Since it is known in case 1 that the current point occurs in a pass, the initial variables can be set:

Lost1 = Proptm - Delta
Lost2 = Proptm
Rt1 is the elevation at Proptm - Delta
Rt2 is the elevation at Proptm
Lostme = Lost2 - Delta/2
Elevat is the elevation at Lostme

In case 2 the propagation ends within a pass, so a search is needed to progress the orbit until the satellite descends under the minimum elevation angle. Elevations are checked in Delta increments until this occurs. If this process iterates 300 times, then the loop stops and the LOS is not found (LOS would then be represented by Proptm). This can occur with geostationary

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or slow moving satellites within a viewing pass. If an elevation less than the minimum elevation is found (at time Prptmp) then the following initial variables can be set:

Lost1 = Proptm
Lost2 = Prptmp
Rt1 is the elevation at Proptm
Rt2 is the elevation at Prptmp
Lostme = Proptm + (Proptm - Prptmp)/2
Elevat is the elevation at Lostme

Now that the initial variables are set, the routine FINDLOS can be called:

CALL FINDLOS(Lostme,Elevat,Lost1,Rt1,Lost2,Rt2)

If Elevat is greater than the minimum elevation angle, then the current midpoint becomes the new lower bound:

Rt1 = Elevat
Lost1 = Lostme

Otherwise, if Elevat is less than or equal to the minimum elevation angle, then the current midpoint becomes the upper bound:

Rt2 = Elevat
Lost2 = Lostme

The new midpoint time is calculated by:

$$Lostme = Lost2 - (Lost2-Lost1)/2 \tag{63}$$

Elevat and all elevations are derived from a call to the routine GETZEN. The routine FINDLOS is repeatedly called until the midpoint's elevation (absolute value) is approximately equal to the minimum elevation angle (within 0.001 degrees). The time at which this occurs is LOS.

2.4.9 Maximum Elevation and Satellite Height

A satellite's maximum elevation is the highest elevation for a single pass which may occur on or between propagation points. This is found in SeaTrack's PROP routine. Every propagation point in a pass is compared to find the highest elevation. This occurs at time Timemx. Thus, the time at which the actual maximum occurs must be between Timemx-Delta and Timemx+Delta where Delta is the propagation time interval. The elevations at these times are Preve and Enext. All elevations are found by calling the routine GETZEN.

A search routine similar to FINDAOS and FINDLOS is used to find the maximum elevation

(termed FINDMAX). Maximum elevation occurs between Timemx and Timemx+Delta or between Timemx and Timemx-Delta. Preve and Enext are compared to find the initial variables for the call to FINDMAX. If Preve > Enext then maximum elevation occurs between Timemx and Timemx-Delta:

T1 = Timemx - Delta
E1 = Preve
T2 = Timemx
E2 = elevation at T2

If Enext > = Preve then maximum elevation occurs between Timemx and Timemx+Delta:

T1 = Timemx
E1 = elevation at T1
T2 = Timemx+Delta
E2 = Enext

E1 and T1 represent the lower bound values. E2 and T2 represent the upper bound values. The midpoint variables are:

$$Tm = T2 - (T2 - T1)/2 \qquad (64)$$
$$Em = \text{elevation at } Tm$$

The call to FINDMAX is:

CALL FINDMAX(Tm,Em,T1,E1,T2,E2)

Within FINDMAX, the midpoint is either set to an upper or lower bound depending on the values of E1 and E2. If E1 > E2, then the maximum elevation must occur between T1 and Tm, thus the upper bound values (E2 and T2) are set to the midpoint values. Otherwise, the lower bound values (E1 and T1) are set to the midpoint values. FINDMAX continues to compare the E1 and E2 elevations until they are within 0.0001 degrees of each other. This is the maximum elevation.

The computation of the satellite height (km) is an approximation which is only used in the graphics routines to plot the viewing range of the station. The height is the difference of the satellite's ECEF position magnitude $|Pve|$ and the Earth's geodetic radius (R_L) at the sub-satellite latitude (Lat), computed using Equation 43. Then

$$He = |Pve| - R_L \qquad * \text{ height above the Earth (km)} \qquad (65)$$

2.4.10 Starting Orbit Number

The orbit number refers to the number of revolutions the satellite has traveled around the Earth since launch. Every time the satellite crosses the equator on an ascending pass (when a

negative latitude is followed by a positive latitude in the direction of the orbit), this number is incremented. The NORAD Two-Line Elements give orbit numbers at epoch in integer form. This means that the satellite must have just crossed the ascending node. SeaTrack uses a simple method to calculate the orbit number for the start of the propagation. Latitudes are calculated in 20 minute intervals (Delta = 1200 seconds) from epoch to the propagation start time. Every time the satellite crosses the equator on an ascending pass, the orbit number is incremented.

Since SeaTrack uses the Brouwer-Lyddane model, accuracy can only be obtained by updating NORAD elements frequently (preferably every couple of days). From this observation, calculation of the starting orbit number would be an inexpensive computation since the start of the propagation would be close to the epoch.

Assuming a maximum mean motion of 17.00 revolutions per day (upper limit for a satellite in Earth orbit), an orbit would take approximately 85 minutes. For a period less 42.5 minutes, a satellite would not be able to cross the equator (descending or ascending) more than once. If the interval was greater than 42.5 minutes (assuming the mean motion specified above), the equator could be crossed between two propagation points with positive elevations. Taking this into account, the 20 minute interval was arbitrarily chosen based on the fact that the equator crossing would always occur between a negative and positive elevation (in that order).

2.4.11 Day/Night and Ascending/Descending Flags

The day/night flag for a pass is set on the first propagation point after AOS from the station. This means that the flag is set at the beginning of every pass. The satellite could be in night and the station in day (and vice versa). Solar zenith angles greater than 90 degrees represent night, while angles between 0 and 90 degrees represent day. Even if the Sun rises above or falls below the horizon during a pass, the flag is still determined at the beginning of the pass.

The routine SUN2000 contains a model (Van Flandern and Pulkkinen, 1979) which calculates the ECI Sun vector. Perturbations for the Moon, Mars, Venus, and Jupiter are taken into account in addition to corrections for nutation of the Earth's pole and for the Earth orbit velocity. The routine SUNANGS converts this vector (represented by Sun_i) into a solar zenith angle. First, the Sun vector must be converted into the ECEF coordinate system. This can be accomplished by Equations 26 through 28 by substituting the Sun vector for the orbit position, where Sun_g represents the Sun vector in the ECEF coordinate system and Sun_i represents the Sun vector in the ECI coordinate system.

The components of the station to Sun vector in the vertical, North, and East directions are computed using the vectors **Geod**, **N** and **E** from Sections 2.4.4. and 2.4.5:

$$Sun_V = Sun_g \bullet Geod \qquad (66)$$
$$Sun_N = Sun_g \bullet N \qquad (67)$$
$$Sun_E = Sun_g \bullet E \qquad (68)$$

The solar zenith angle (Sunz) can now be determined:

$$Sunz = TAN^{-1}[(Sun_N^2 + Sun_E^2)^{1/2}/ Sun_V] \qquad (69)$$

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The ascending/descending flag is set at the first propagation point after AOS for each pass and consequently the satellite can change from ascending to descending (or vice versa) during a pass. This can be computed simply by checking the satellite ECEF velocity vector (Vve). If the z component is less than zero then the satellite is descending, otherwise it is ascending. The sign of this value represents the direction of the satellite's orbit with respect to the ECEF z axis (the North pole).

Since SeaWiFS HRPT operators will only acquire data during daylight, an option in the SeaTrack package enables output of overpasses to include only daylight. The user may also select night only, or both (default).

3.0 VALIDATION

Validation of the SeaTrack package was performed by comparison with three other general perturbations models: the Satellite General Perturbations Model 4 (SGP4), from the U.S. Space Command, a Brouwer-Lyddane model from NOAA (Kidwell, 1991), and Traksat, a shareware model available from Paul Traufler (111 Emerald Dr., Harvest, Alabama, 35749). All three have been used extensively for satellite tracking. All three produce sub-satellite latitude and longitude coordinates, which were compared to the SeaTrack output. In addition, Traksat produces azimuth and elevation at a given ground site, which was used to compare to those produced by SeaTrack. Another independent calculation of azimuth and elevation was not available.

. All model comparisons were performed for a 10-day propagation period, to emphasize the validity of SeaTrack for weekly or less propagation times from recent element sets. NOAA-11 was chosen as the test spacecraft, which is in a similar orbit to SeaStar. The results of the comparison are shown in Table 1.

Table 1. Comparison of SeaTrack output with three general perturbations models widely in use for satellite tracking: SGP4, NOAA Brouwer-Lyddane, and Traksat. Shown are maximum errors for a 10-day propagation from epoch. All comparisons used the NOAA-11 satellite.

Model	Longitude (deg.)	Latitude (deg.)	Displacement (km)
SGP4	0.017	0.029	3.5
NOAA B-L	0.0009	0.016	1.8
Traksat	0.01	0.02	2.4

	Azimuth (deg).	Elevation (deg.)
Traksat	0.14	0.05

Analysis of pointing requirements for HRPT stations showed that, even for an 8-ft antenna (the maximum size expected to be used by stations), a 3.31° accuracy was sufficient for the SeaWiFS mission (Patt *et al.*, 1993). As shown by the comparison of azimuth and elevation with Traksat, clearly SeaTrack meets this requirement, even for a 10-day propagation (Table 1). This pointing requirement translates to approximately 40.7 km error along-track at the SeaStar altitude (Patt *et al.*, 1993). Again, clearly SeaTrack meets this requirement as compared to SGP4, NOAA Brouwer-Lyddane, and Traksat (Table 1).

4.0 USER'S GUIDE

SeaTrack was written on a 486DX2/50 Personal Computer (PC) in Microsoft Fortran 5.1, using DOS 5.0, and on Silicon Graphics, Inc.'s (SGI) Iris Indigo XS-24 in Fortran/77, using SGI's UNIX operating system, IRIX 4.0.5. The package has also been successfully tested on a Sun SPARCstation 2 (operating system SunOs 4.1.2). A graphics version provides graphics support on a PC, using Microsoft Fortran's graphics library.

The non-graphics version of SeaTrack contains the following files:

```
filename                  format  contents
------------              ------  ----------------
seatrk.for                ASCII   source code for all routines
seatrk.exe                BINARY  executable file for PC only
norad.dat                 ASCII   sample NORAD 2-line element file
```

The program will create the files pos.dat and opt.dat for default settings if they are not available. The user may then change the settings.

The graphical version of SeaTrack requires a 386 or higher PC with VGA graphics capability, and Microsoft Fortran Version 5.0 or higher. Two additional files are included with the graphical version to complement visual displays:

```
filename                  format  contents
------------              ------  ----------------
cstlne.dat                ASCII   low resolution coastline data
coast.dat                 ASCII   high resolution coastline data
```

An executable version is not available with the standard distribution. Thus the program must be compiled and linked to create the executable. This can be accomplished in Microsoft Fortran by the following command for a standard installation (refer to your Fortran manual for more information, especially for compilation instructions for specific installations):

c: > fl seatrkg.for graphics.lib

It is recommended that all related files be put into a newly created directory on a hard disk. Output files and additional NORAD files can also be placed in this directory. To run SeaTrack, simply type in the executable filename at the command prompt:

```
DOS  > seatrk  (or seatrkg, if you are using the graphical version)
UNIX  %a.out (or other user-defined executable name)
```

The following main menu should appear:

```
                - SeaTrack -
==================================
(1) Propagate
(2) Options
(3) Local position and time
(4) View specified NORAD element file
(5) View text file
(6) Graphics displays
(7) Quit
==================================
Select:
```

Note: In the graphical version of SeaTrack (seatrkg), Choice 6 enables visual display, and Choice 7 quits the program.

In order to correctly run SeaTrack, output and input setup options must be run. These are accessed by Options 3 (input options) and 2 (output options). These setup options are discussed first before proceeding to orbit propagation and graphics display.

4.1 Local Position and Time Information

Once SeaTrack is installed the first thing a user should do is set the station position and time. This can be accomplished by selecting 3 from the main menu. This information is stored in the file POS.DAT and can be changed whenever needed. The position menu is as follows:

```
Position and time
-----------------
a. Station name = GSFC HRPT Station
b. Longitude =    -76.851100
c. Latitude =      38.995800
d. Minimum elevation angle = 5.0
e. Time mode (local/gmt) = local
f. Hours from GMT = -4
g. Save and exit
h. Exit without saving
>>> Change?
```

(Enter the appropriate letter).

a> The station name is an array of thirty characters. It is used during report generation.

b> The station's longitude is represented by the values -180.00 degrees West to 180.00 degrees East.

c> The station's latitude is represented by the values 90 degrees North to -90 degrees South.

d> Mountains and other obstructions can prevent satellite information from reaching the

station. The minimum elevation angle can be set so that contact reports ignore satellite positions that lie behind obstructions. A minimum elevation angle of zero means there are no obstructions and visibility extends to the horizon.

e> The time mode can be set to either local time or Greenwich Mean Time (GMT). All subsequent input and output times will correspond to this time mode.

f> Hours from GMT signify the time zone for the station. Entries should range from -12 to +12 hours. Eastern Standard Time (for example) is -5 hours from GMT. Daylight Savings Time must be taken into account (e.g. Eastern Daylight Time is -4 hours from GMT).

g> This option must be selected to save the position and time information. The station name, longitude, latitude, minimum elevation angle, time mode, and hours from GMT (in that order) are stored in the file POS.DAT with one entry per line. Once the values are saved, the program reverts back to the main menu.

h> This option will abort any changes made to the position data. The program then reverts back to the main menu.

4.2 Options

The options menu allows a user to change information concerning output files and propagation input. The NORAD data file, output filenames, propagation interval, and satellite number are saved in the file OPT.DAT with one entry per line. The options menu is as follows:

```
a. NORAD element data file = norad.dat
b. Output coordinate file = auto
c. Schedule pointing file = auto
d. Viewing file = auto
e. Propagation interval (sec) = 60
f. Satellite number = 21263
g. Print Day passes only, Night only, or Both = b
h. Number of lines to scroll when viewing = 20
i. Save and exit
j. Exit without saving
>>> Change?
```

a> SeaTrack uses NORAD Two-Line Element files to obtain satellite position information. The Two-Line Element format is described in section 2.3. A sample NORAD element file called NORAD.DAT is included with the program. Element files should be updated every 1-3 days to maintain accuracy. These files can be found on electronic bulletin boards and FTP sites (see Appendix for partial listing). SeaWiFS Mission Operations will provide SeaStar elements every 1-3 days on Omnet in a bulletin board named "seawifs" (see Appendix). Once the element file is specified, option 4 from the main menu can be used to view the element file.

b,c,d> The filenames of the three output files must be 12 characters or less (including the extension, ".out"). SeaTrack has an auto-naming option which can be initiated by using "auto"

as the filename (see menu above). Auto-named files have a similar format:

```
schedule file   = scMMDDYY.out
coordinate file = cdMMDDYY.out
viewing file    = vwMMDDYY.out
```

MMDDYY represents the month (1-12), the day of month (1-31), and year (last two digits) for the start of a propagation. If the option "auto" is selected for all three files, every file will have the same MMDDYY value for a given propagation. Some examples for different propagations are:

```
sc010193.out - a schedule file for January 1, 1993
cd020194.out - a coordinate file for February 1, 1994
vw123195.out - a viewing file for December 31, 1995
```

All three output files have a nine-line header which includes file format, filename, station name and position, propagation start and end times, satellite number, time mode, and interval time. The information in all of these files is stored in ASCII format and can be viewed with the View File (option 5) on the main menu. The contents of these files will be discussed later.

e > The interval between propagation points is an integer value that represents how often the satellite's position should be predicted, in units of seconds. Propagation intervals of 60 seconds or less are recommended.

f > Satellite numbers are integers (of no more than 5 numbers) that correspond to the unique satellite identification number found in the NORAD Two-Line Element file. Many NORAD element files include the name of the satellite before each Two-Line Element.

g > This option tells SeaTrack whether the operator is interested in all overpasses, daytime overpasses only, or nighttime passes only. SeaWiFS operators will be interested only in daytime passes, since the transmitter is only on during daylight.

h > This option allows the user to view the schedule files while on line in SeaTrack, by stopping the scrolling of important information after a specified number of lines. It also applies for the main menu option to view the NORAD Two-Line Element files. Entering "m" at the prompt will return the user to the main menu.

i > This option saves the NORAD element filename, output filenames, propagation interval, and satellite number to the file OPT.DAT. The program then returns to the main menu.

j > This option aborts any changes to the options, and then the program returns to the main menu.

4.3 Propagation

Once the position information and options are set, a satellite orbit can be predicted by selecting the Propagate option on the main menu (choice number 1). SeaTrack will scan the specified NORAD element file for the satellite number given in options menu. If the satellite is not found, an error message will be displayed. If this occurs then the NORAD element file should be viewed to see if the satellite is present and in the proper Two-Line Element format.

If the satellite is found in the file, then orbital information is displayed. This includes the satellite ID number, launch year, epoch information, number of orbits per day, and the Brouwer mean elements. The epoch represents the date and time of the mean elements. Orbit number, year, day of year, and Gregorian date and time all pertain to the epoch. The Gregorian date and time correspond to the time mode selected in options menu. An example shows the display format of this information:

```
Searching for satellite 21263 in file NORAD.DAT
Satellite found in file...

ID No. = 21263            Launched 1991
Epoch Year = 1993         Epoch Day (gmt) = 231.76315203
Orbit No. = 11768         Orbits/day =  14.22

Starting Mean Brouwer Elements
      semi-major axis a     =      7192.867530319787000 km
      eccentricity e        =      1.379700000000000E-003 dimensionless
      inclination i         =        98.654500000000000 degrees
      right ascension O     =       260.693300000000000 degrees
      argument of perigee w =        33.260300000000000 degrees
      mean anomaly M        =       326.944900000000000 degrees

Epoch date = 19 AUG 1993
Epoch time = 14:18:56 PM
```

Now that the epoch Keplerian mean elements are known, the propagation starting and ending dates must be entered. The proper time mode is displayed to remind the user. The format is month, day, year, hour, minutes, and seconds. Each must be separated by a space, and all times must be in 24-hour format. Input years from 50 to 99 correspond to the years between and including 1950 and 1999. Input years from 0 to 49 correspond to the years between and including 2000 and 2049. An example follows:

```
***Enter times in 24 hour local time****

Enter starting date (Mo Dy Yr Hr Mi Se):
8 19 93 15 0 0

Enter ending date (Mo Dy Yr Hr Mi Se):
8 21 93 0 0 0
```

The starting date in this example represents August 19, 1993 3:00:00 PM. The ending date is August 21, 1993 12:00:00 AM. The input values must be within the following bounds:

```
Input  Bounds
-------------
1 < = Mo < = 12      * month
1 < = Dy < = 31      * day
0 < = Yr < = 99      * year
0 < = Hr < = 23      * hour
0 < = Mi < = 59      * minutes
0 < = Se < = 59      * seconds
```

SeaTrack only allows forward propagation. Thus if a starting date is entered that precedes the epoch, the starting date will be changed to the epoch.

Recall that the starting propagation date is included in output filenames when auto-naming is used. Now that this date is known, the filenames listed in the options menu are checked to see if files with the same names already exist in the current directory. Each file is checked individually, and if a file already exists, then a prompt informs the user. The user can overwrite the files by entering "y" or "Y" (without the quotes). Any other input will send the user back to the main menu. The user can then change filenames from the options menu.

4.4 Output Files

The propagation of a satellite results in one output file (schedule). Since the file is stored as ASCII text, it can be viewed from the main menu (by selecting choice 5). The file is created during propagation. In addition to being saved, the schedule file is output to the screen. Two additional files are created by the graphical version (coordinate and viewing files). All three files have a similar nine-line header.

4.4.1 Schedule Files

The schedule file contains information used for HRPT antenna pointing in text format, as a series of tables. Every pass is numbered and represented in a tabular format. Each entry in the table represents a different contact which includes Gregorian date, time, azimuth, elevation, longitude, and latitude (all angle units are degrees). The longitude and latitude are the coordinates for the sub-satellite position. The first contact in a table corresponds to AOS and the last corresponds to LOS. All times are represented in AM/PM format and correspond to the time mode specified in the options menu.

The table header contains the orbit number of the contact directly after AOS, the AOS date and time, a day/night flag, and an ascending/descending node flag. The day/night flag is set when the sun is above or below the station at AOS with respect to the station position at the start of the pass. The ascending/descending node flag is also set at AOS and represents whether the satellite is travelling in a Northerly or Southerly direction.

The table footer includes the orbit number of the contact directly before LOS, the LOS date and time, and the duration of the pass in minutes. Durations over 9999.9 minutes do not fit into the table and thus asterisks would fill in the gap. This would only occur with geostationary or

slow moving satellites. The orbit number in the header and footer need not always be the same. A sample pass table from a schedule file looks like:

```
SCHEDULE FILE: sc081993.out
Station: GSFC HRPT Station                Location: ( -76.85,  39.00)

Start:   8-19-93  3: 0: 0 PM
  End:   8-21-93 12: 0: 0 AM
 Sat#:   21263
 Time:   local
 Intv:      60 sec

                              Pass:     1
       -----------------------------------------------------------------
       | Orbit:   11771| AOS: 19 AUG 1993  7:28:23 PM |  day / ascend  |
       -----------------------------------------------------------------
       | Date    |      | Time    |      | Azim/Elev |     | Long/Lat  |
       ----------        ---------        -----------       -----------
       19 AUG 1993       7:28:23 PM       143.39 /  5.00    -62.61 / 19.65
       19 AUG 1993       7:29: 0 PM       141.61 /  7.66    -63.14 / 21.80
       19 AUG 1993       7:30: 0 PM       137.78 / 12.66    -64.03 / 25.33
       19 AUG 1993       7:31: 0 PM       132.15 / 18.74    -64.95 / 28.86
       19 AUG 1993       7:32: 0 PM       123.28 / 26.23    -65.93 / 32.39
       19 AUG 1993       7:33: 0 PM       108.36 / 34.84    -66.96 / 35.90
       19 AUG 1993       7:34: 0 PM        83.75 / 41.72    -68.06 / 39.41
       19 AUG 1993       7:35: 0 PM        53.33 / 41.22    -69.26 / 42.91
       19 AUG 1993       7:36: 0 PM        29.96 / 33.89    -70.56 / 46.40
       19 AUG 1993       7:37: 0 PM        16.00 / 25.38    -72.01 / 49.87
       19 AUG 1993       7:38: 0 PM         7.68 / 18.09    -73.65 / 53.33
       19 AUG 1993       7:39: 0 PM         2.38 / 12.18    -75.53 / 56.77
       19 AUG 1993       7:40: 0 PM       358.79 /  7.29    -77.73 / 60.18
       19 AUG 1993       7:40:32 PM       357.31 /  5.00    -79.08 / 61.98
       -----------------------------------------------------------------
       | Orbit:   11771| LOS: 19 AUG 1993  7:40:32 PM | Dur =  12.15 min|
       -----------------------------------------------------------------
```

At the end of the schedule file is a summary of the passes. Each entry in this table includes important information for each pass including orbit number, AOS, LOS, duration in minutes, maximum elevation, and the day/night flag. The orbit number corresponds to the orbit number listed in the pass table footer. The maximum elevation represents the highest elevation the satellite reaches for a given pass. This table should be used as a quick reference to choose viewing times that satisfy the user's needs. A summary of seven passes follows (note that the first pass corresponds to the sample pass table above):

```
                       Summary of Contacts
-------------------------------------------------------------------------
Orbit Num  Acquisition of Signal      Loss of Signal      Duration MaxElev DN
---------  ---------------------      --------------      -------- ------- --
   11771   19 AUG 1993  7:28:23 PM  19 AUG 1993  7:40:32 PM  12.15   42.63  D
   11772   19 AUG 1993  9: 9:14 PM  19 AUG 1993  9:20: 3 PM  10.82   22.23  N
   11778   20 AUG 1993  7:46:50 AM  20 AUG 1993  7:57:10 AM  10.33   18.71  D
   11779   20 AUG 1993  9:26: 2 AM  20 AUG 1993  9:38:34 AM  12.53   51.80  D
   11780   20 AUG 1993 11: 9:39 AM  20 AUG 1993 11:12:35 AM   2.93    5.73  D
   11785   20 AUG 1993  7: 7:29 PM  20 AUG 1993  7:18:45 PM  11.26   27.66  D
   11786   20 AUG 1993  8:47: 1 PM  20 AUG 1993  8:58:58 PM  11.96   35.12  N
-------------------------------------------------------------------------
```

4.4.2 Coordinate Files

Coordinate files contain the longitude/latitude coordinate for every sub-satellite point over the specified propagation period. The default is one-minute intervals. The files contain only one longitude/latitude pair per line. The graphics routines use the files to display orbit tracks over the given propagation period on a world map.

4.4.3 Viewing Files

Viewing files contain pass information when the satellite is within view of the station. These are internal files used for plotting of azimuth/elevation over the local station location. The information saved in the file for a single pass includes sub-satellite longitude/latitude coordinates and azimuth/elevation pointing information at AOS, LOS, and every propagation point within the pass. Passes are separated by a flag represented by longitude/latitude values of 400 and azimuth/elevation of 0.

The station longitude/latitude coordinate and the satellite's maximum height during the propagation are also stored in the viewing file. This information is used to graphically display the station's viewing window for a particular satellite. The size of the viewing window is dependent on the satellite height, and thus higher satellites create larger viewing windows.

4.5 Graphics

SeaTrack runs on at least three distinct platforms (PC, SGI, and Sun), but only has graphics capability on the PC. The programs are identical otherwise. The graphical version contains several graphics routines which utilize Microsoft Fortran's graphics library (GRAPHICS.LIB). SeaTrack provides the following graphics plots:

* orbit for specified propagation period on global projection
* orbit for specified propagation period within station's view
* polar plot for a graphical display of azimuth and elevation

The graphics routines are accessed by selecting Graphic displays (choice 6) on the main menu. SeaTrack's graphics routines use the data from coordinate and viewing files. The user must enter either the five digit number representing the day of year/year when auto-naming is used or the actual filenames.

Coastline longitude/latitude coordinates are contained in a 7561 line file (CSTLNE.DAT) and a 50,107 line file (COAST.DAT). In order to speed up plotting, the smaller file is used for the global projection. The larger file is used for zooming into a station's viewing window for a given satellite. Both files continue to connect coastline positions until a move flag is found. Each coordinate line in CSTLNE.DAT contains longitude, latitude, and flag. A flag value of zero signifies not to connect the current position to the next. COAST.DAT, on the other hand, uses a latitude and longitude values of 999.99 to represent a move to another position without connecting points.

The first display (Figure 3) shows a satellite's orbit over a propagation period. The satellite

is NOAA-12, and all parameters correspond to the examples shown earlier. All of the longitude/latitude positions in the coordinate file are connected with lines to produce a single orbit path. The viewing file contains the information which allows the station viewing window to be displayed. This size of the window depends on the satellite height above the Earth. SeaTrack maintains a maximum height (km) for each propagation. This is the value used to determine the size of the viewing window. Every longitude/latitude coordinate is mapped to a pixel on the screen and then plotted.

The second display (Figure 4) is a zoomed image of the first display centered about the station. In addition to the propagation points, AOS and LOS points are displayed. Pass numbers are given at the beginning of each pass. These numbers correspond to the passes listed in schedule files. The projection of the Earth is clipped by comparing the latitude/longitude values from COAST.DAT to predetermined minimum and maximum values. These minimum and maximum longitude/latitude values are the same as the minimum and maximum values of the longitude/latitude coordinates of the viewing window. All coordinates from the coastline file that fall outside these values are not plotted.

The graphical version of SeaTrack includes a polar plot (Figure 5) which displays passes by azimuth and elevation. The degrees of the circle (starting at the top) represent the azimuth angles. The center of the circle represents zenith at 90 degrees elevation and the outer circle represents the horizon at 0 degrees elevation. All points are connected with a straight line, producing shorter time intervals between propagation points produce better images.

Acknowledgments

References

The Astronomical Almanac for the Year 1984, 1983. U.S. Government Printing Office, Washington, DC.

Brouwer, D., 1959. Solution of the problem of artificial satellite theory without drag, *Astron. J.*, 64: 378-397.

Cappellari, J.O., Velez, C.E., and Fuchs, A.J., 1976. Mathematical Theory of the Goddard Trajectory Determination System, *GSFC Report X-582-76-77*, 596 pp.

Kidwell, K.B., 1991. NOAA Polar Orbiter User's Guide, NOAA/NESDIS (NCDC/SDSD), Washington, DC, 279 pp.

Lyddane, R.H., 1963. Small eccentricities or inclinations in the Brouwer theory of the artificial satellite, *Astron. J.*, 68: 555-558.

Patt, F.S. and Gregg, W.W., 1993. Exact closed-form geolocation algorithm for Earth survey sensors, *International Journal of Remote Sensing*, accepted for publication.

Patt, F.S., Hoisington, C.M., Gregg, W.W., and Coronado, P.L., 1993. Analysis of Selected Orbit Propagation Models for the SeaWiFS Mission, *NASA Technical Memorandum 104566, Vol. 11*, 16 pp.

Van Flandern, T.C. and Pulkkinen, I.F., 1979. Low-precision formulae for planetary positions, *The Astrophysical Journal Supplement Series*, 41: 391-411.

Wertz, J.R. (editor), 1978. *Spacecraft Attitude Determination and Control*, D. Reidel, Dordrecht, Holland, 858 pp.

APPENDIX

Instructions for Obtaining Updated Two-Line Elements

Orbital elements in NORAD Two-Line Element format are available from a number of electronic sites. Several are provided here for user convenience.

1)   Omnet Bulletin Board. The SeaWiFS Mission Operations Team will provide 1-3 day updated NORAD Two-Line Elements (TLE) for SeaStar/SeaWiFS after launch on an electronic bulletin board called "seawifs" maintained by Omnet. Access requires an Omnet account. This can be arranged by calling 617-265-9230 (Telex: 7400497 OMNT UC; Electronic Mail: OMNET.SERVICE). After logging in, merely type "check seawifs" to obtain a list of items in the bulletin board, some of which are recent element sets. The Omnet service requires a service charge. Requirements are a computer and a modem.

2)   RBBS. The Reports and Information Dissemination (RAID) Bulletin Board System (RBBS) is operated by the Orbital Information Group at NASA/GSFC. The Board contains recent NASA TLE's (same format as NORAD) for a large number of satellites. Access is free and requirements are only a computer and a modem. Authorization and information about accessing the system may be obtained by sending a FAX to 301-805-3916, containing name, address, and phone number.

3)   SeaWiFS Anonymous FTP Site. The SeaWiFS Project maintains an anonymous FTP site containing updated TLE's for SeaWiFS only, as well as other Project-related information. The only hardware requirement is Internet access. Access may be obtained by using the command sequence: "ftp manua.gsfc.nasa.gov" (or 128.183.121.18), login as "anonymous" and enter node name as password, then type "cd pub/mission-ops", then type "get seatrk.for".

4)   Celestial BBS. The most recent orbital elements from the NASA Prediction Bulletins are carried on the Celestial BBS, 513-427-0674 which may be accessed 24 hours/day at 300, 1200, or 2400 baud using 8 data bits, 1 stop bit, no parity.

5)   Updated elements can also be obtained at the following anonymous FTP sites:

archive.afit.af.mil (129.92.1.66)	dir:pub/space
ftp.funet.fi (128.214.6.100)	dir:pub/astro/pc/satel
kilroy.jpl.nasa.gov (128.149.63.2)	dir:pub/space/elements/nasa
	dir:pub/space/elements/satelem

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FIGURE CAPTIONS

Figure 1. Earth-Centered Inertial (ECI) coordinate system (from Patt and Gregg, 1993)

Figure 2. Earth-Centered Earth-Fixed (ECEF) coordinate system (from Patt and Gregg, 1993)

Figure 3. Graphical display of orbit tracks on a world map for NOAA-12, showing the visibility mask for the ground station (in this case, NASA/Goddard Space Flight Center in Greenbelt, Maryland).

Figure 4. Graphical display of station's view of overpasses, corresponding to the orbits shown in Figure 3.

Figure 5. Polar plot of satellite azimuth/elevation, where elevation is the radius. This view corresponds to the plots shown in Figures 3 and 4.
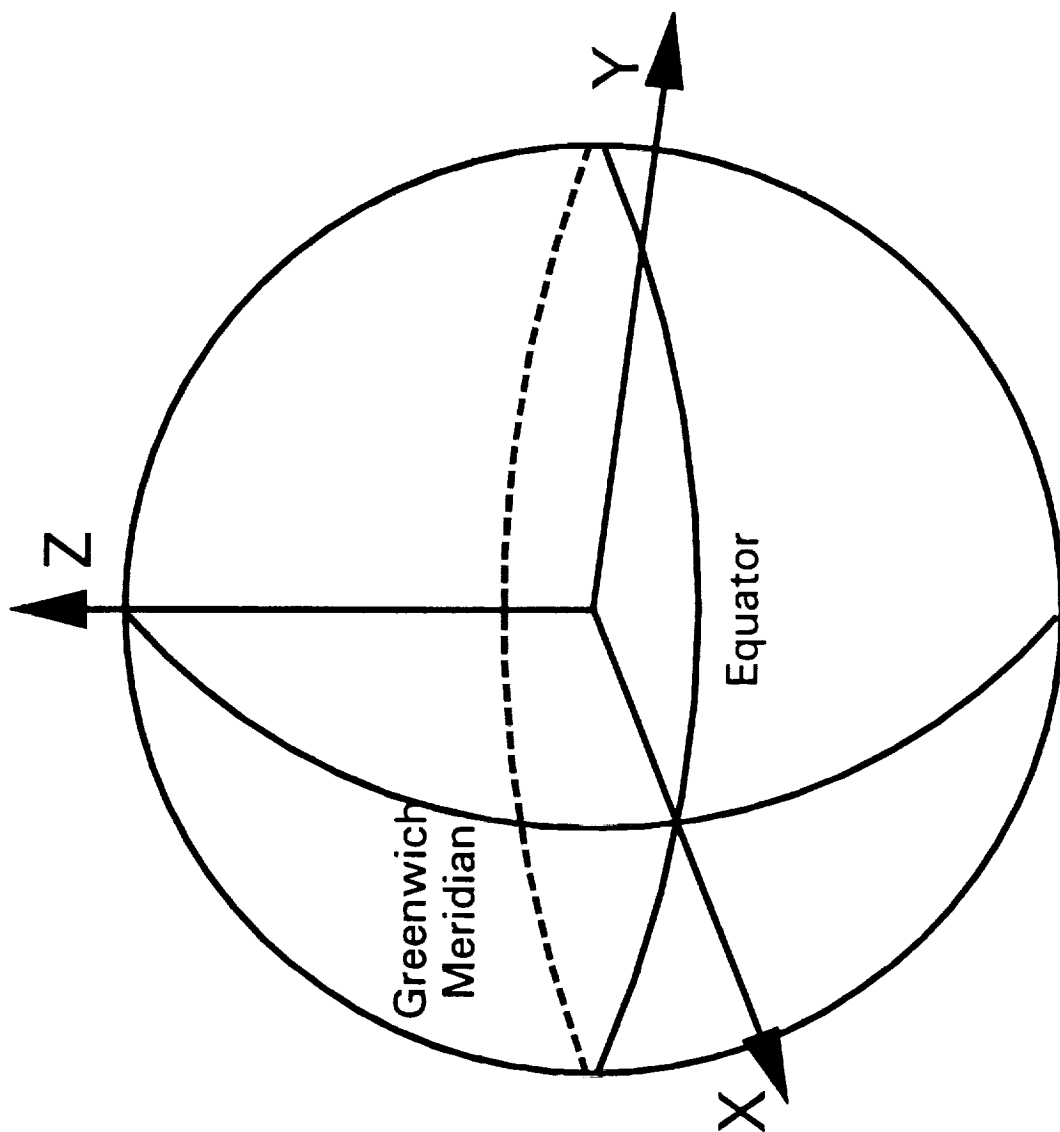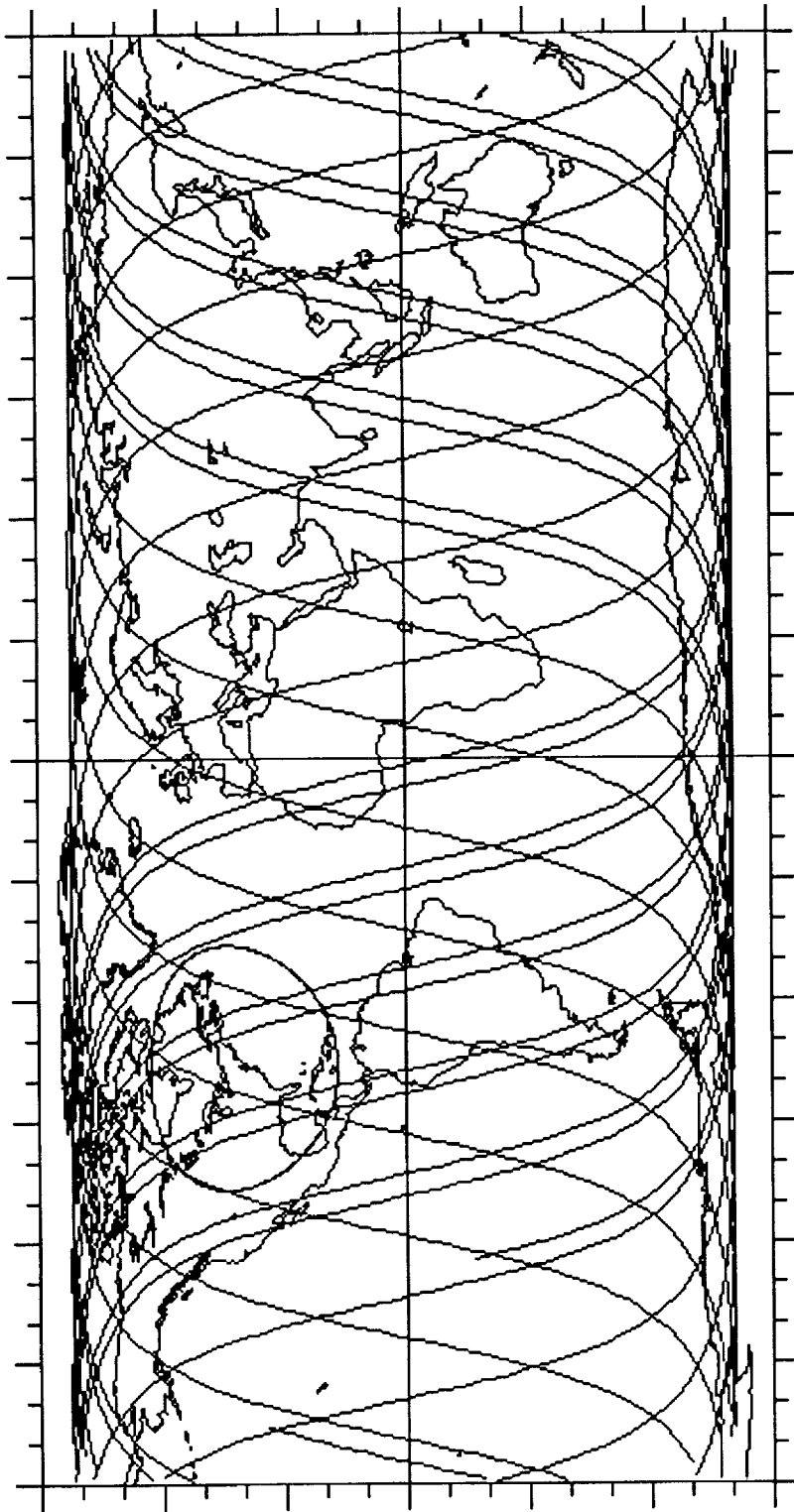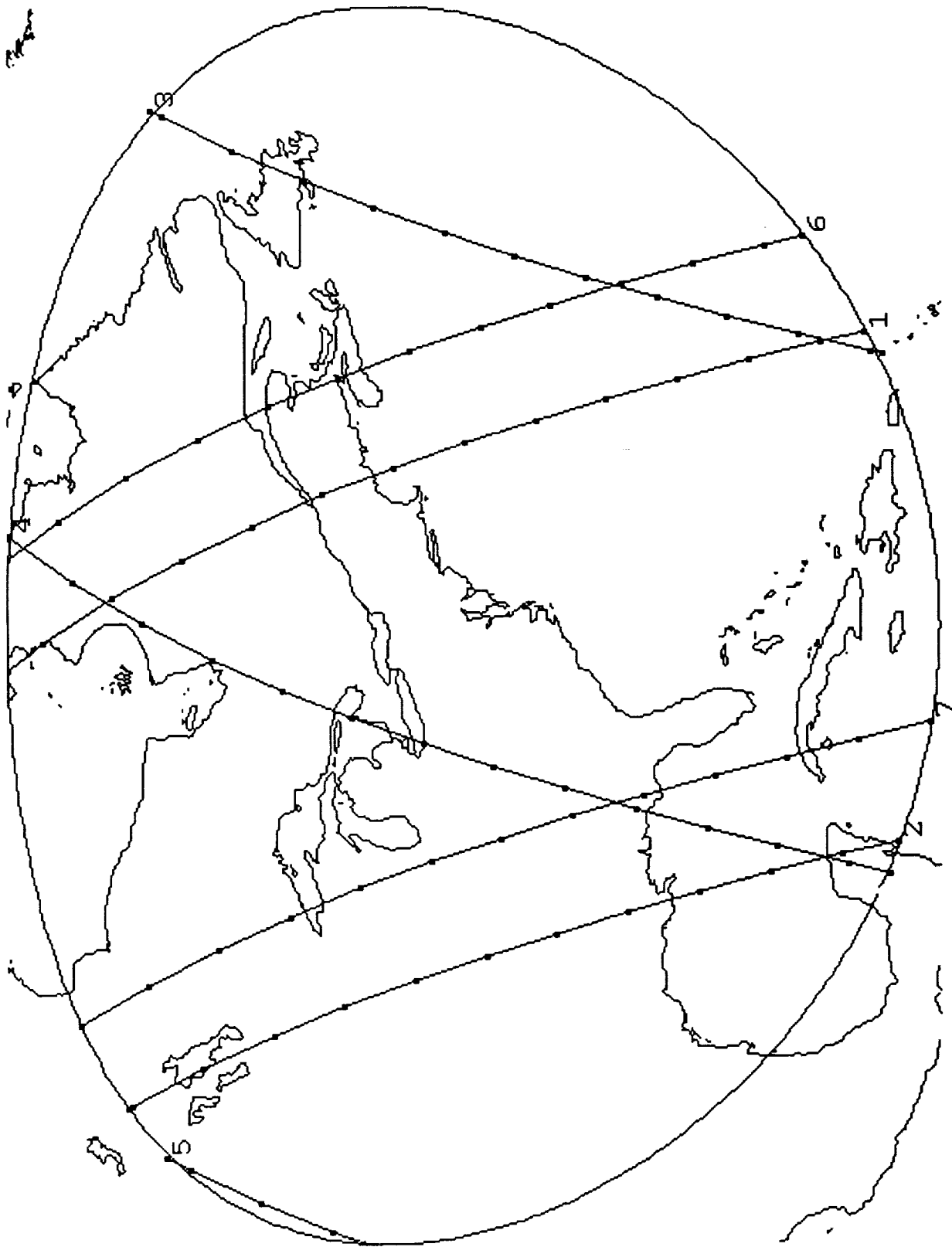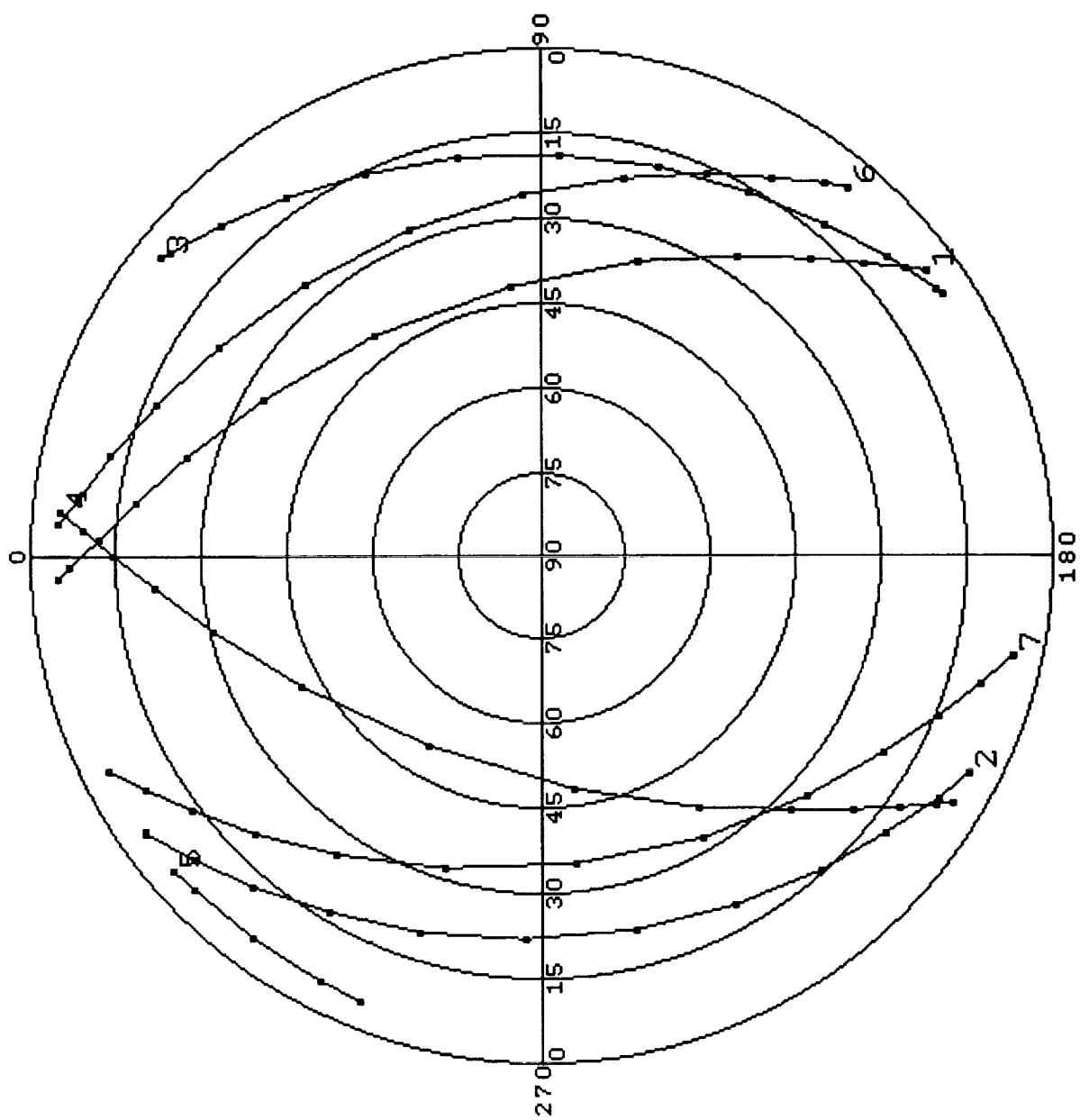
Figure 1.

Figure 2.

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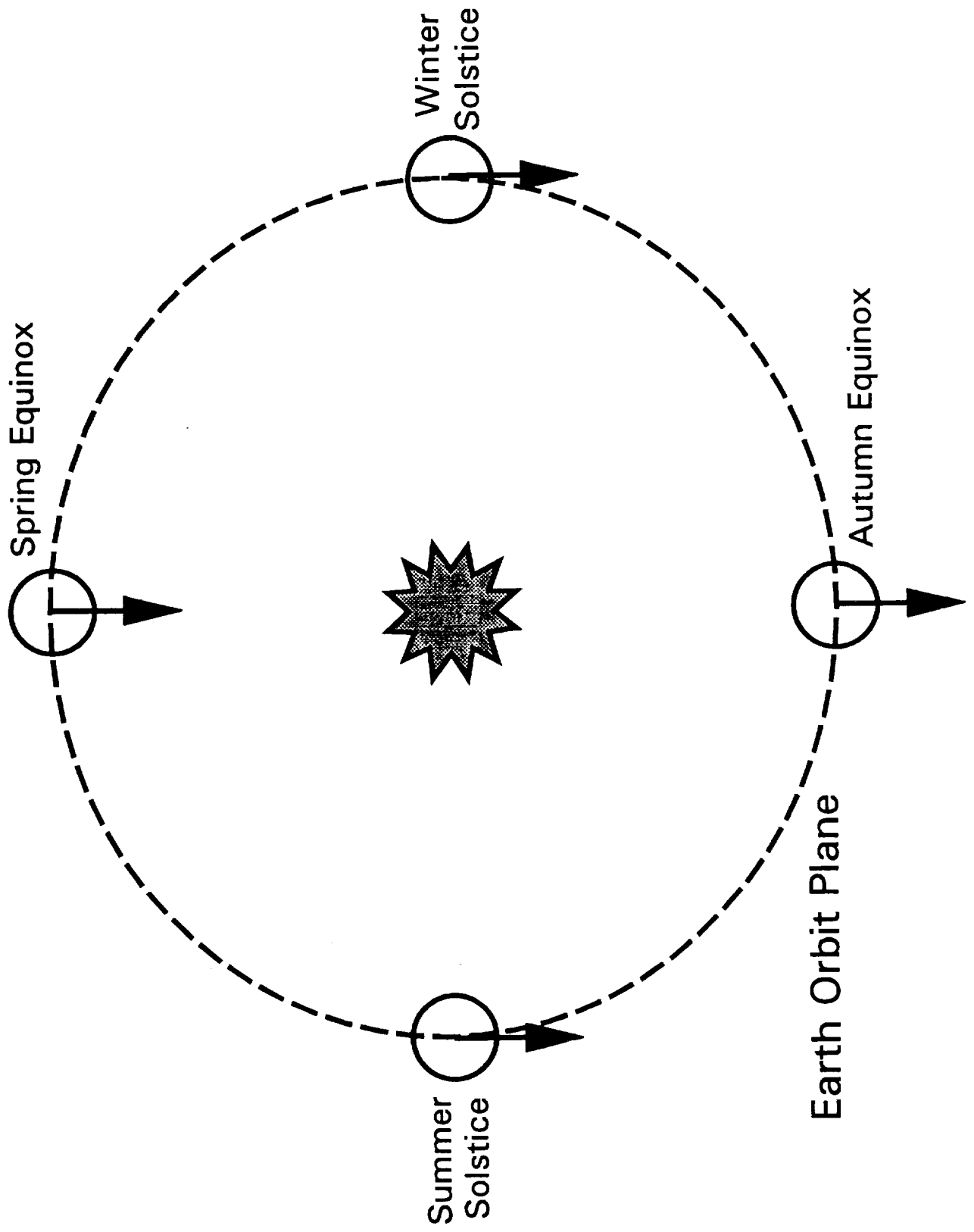
Figure 3.

Figure 4.

Figure 5.

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13. ABSTRACT (Maximum 200 words)

An orbit prediction software package (SeaTrack) was designed to assist High Resolution Picture Transmission (HRPT) stations in the acquisition of direct broadcast data from sea–viewing spacecraft. Such spacecraft will be common in the near future, with the launch of the Sea–viewing Wide Field–of–view Sensor (SeaWiFS) in 1994, along with the continued Advanced Very High Resolution Radiometer (AVHRR) series on NOAA platforms. The Brouwer–Lyddane model was chosen for orbit prediction because it meets the needs of HRPT tracking accuracies, provided orbital elements can be obtained frequently (up to within 1 week). SeaTrack requires elements from the U.S. Space Command (NORAD Two–Line Elements) for the satellite's initial position. Updated Two–Line Elements are routinely available from many elecronic sources (some are listed in the Appendix). SeaTrack is a menu–driven program that allows users to alter input and output formats. The propagation period is entered by a start date and an end date, with times in either Greenwich Mean Time (GMT) or local time. Antenna pointing information comes in tabular form and includes azimuth/elevation pointing angles, sub–satellite longitude/latitude, acquisition of signal (AOS), loss of signal (LOS), pass orbit number, and other pertinent pointing information. One version of SeaTrack (non–graphical) allows operation under DOS (for IBM–compatible personal computers) and UNIX (for Sun and Silicon Graphics workstations). A second (graphical) version displays orbit tracks, and azimuth–elevation for IBM–compatible PCs, but requires a VGA card and Microsoft Fortran.

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