PREFACE

In order to make our extensive series of technical reports more readily available, we have scanned the old master copies and produced electronic versions in Portable Document Format. The quality of the images varies depending on the quality of the originals. The images have not been converted to searchable text.
ABSTRACT

The two dimensional, real time navigational accuracy available from NAVSTAR/GPS is investigated, with emphasis on GPS performance during the partially implemented phase (1980 to 1987), and on the ocean areas surrounding Canada.

The mathematical models used in this study to compute NAVSTAR satellite positions, check for satellite visibility, and compute the covariance matrix of two dimensional position are described. The length of the semi major axis of the standard error ellipse represented by this covariance matrix is used as the GPS performance indicator. A computer program implementing these models is listed.

Results based on four error models are presented. These error models are P-code ranging only (with 4 metre range errors), C/A-code ranging only (16 metre range errors), P-code assisted by Loran-G and C/A-code assisted by Loran-C. For this analysis Loran-G ranges to Cape Race, Angissoq and Sandur were assumed to have standard deviations of 140 m. In all cases it was assumed that the user's clock could be kept synchronized to GPS time independently from the GPS measurements, to within 0.3 microseconds. Based on these assumptions, it was found that in the Davis Strait area, combined P-code GPS and Loran-C should provide 150 metre positioning about 11 hours per day, with the present (1980) orbital configuration of six GPS satellites.

GPS performance with only six satellites is also a function of both latitude and longitude. In general high latitudes (60° and above) have poorer performance. The performance at low and middle latitudes depends on the relationship between the observer's meridian and the meridians travelled by the GPS satellite subtracks. Plots of the variation in the length of the GPS error ellipse semi major axis over a 24 hour period are presented for 14 different locations. Complete output listings are presented for three locations and several error models.
A full GPS constellation of 24 satellites was simulated. The two dimensional, P-code positioning accuracy in Davis Strait, using all visible satellites was uniformly of the order of five metres.

It is concluded that it is feasible to use GPS in its present limited deployment as an operational survey positioning system in the eastern Canadian arctic, provided the requirements of the survey are met by 150 metres or better positioning for about 11 hours per day.
ACKNOWLEDGEMENT

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1. Introduction

The purpose of this study is to analyze the performance of the Navigation Satellite Timing and Ranging (NAVSTAR) system, also known as the Global Positioning System (GPS), for the purposes of positioning at sea, during the partially implemented phase of NAVSTAR development (the period 1980 to 1987). The combination of NAVSTAR and passive ranging Loran-C is also investigated.

1.1 NAVSTAR status

NAVSTAR/GPS is presently under development by the United States Department of Defense. Phase one (concept validation) of this development has been completed. Phase two (full scale development) began during 1979. Phase three (production/development) is scheduled for the period 1983 to 1987 (Eckhardt, 1980).

Six prototype NAVSTAR satellites are now in orbit. This constellation will be maintained until operational satellites are placed in orbit, using the Space Shuttle, during the period 1985 to 1987. Once the full constellation of 18 or 24 NAVSTAR satellites are in place, continuous coverage from four or more satellites will be available anywhere on earth. This permits an instantaneous solution for four parameters - normally a three dimensional (3D) position and a time synchronization. Until 1985 at least, however, the six prototype satellites will provide coverage at any location on earth varying from no satellites up to all six satellites. This coverage is a function of time, as well as position, with a main period of twelve hours (NAVSTAR satellite orbital period).
1.2 Passive ranging

NAVSTAR positioning depends on passive ranging measurements, also known as pseudo-ranging and as "rho-rho" measurements. Atomic clocks in each NAVSTAR satellite are kept accurately synchronized with each other. Timing signals (using the technique of pseudo-random-noise or PRN data modulation on a carrier) are thus transmitted "simultaneously" from all satellites. The user measures the time of arrival of these signals, as compared to his own clock. Since his own clock will not in general be synchronized to the NAVSTAR satellite clocks, this synchronization must somehow be determined. There are two possibilities. Either an extra NAVSTAR passive ranging measurement can be used (self synchronization), or else some external method of synchronization can be used. In the latter case, an atomic clock is required by the user.

Passive ranging has been in use for some time with the Loran-C radionavigation system (Grant, 1976). In this case as well, synchronization can be accomplished internally (using an extra Loran-C range), or externally (using position fixes from some other system to "calibrate" the clock).

1.3 Study outline.

There are five ways in which NAVSTAR ranges can be used:

i) 3D fix with self-synchronization (requires four or more satellites).

ii) 3D fix with external synchronization (requiring three or more satellites).

iii) 2D fix with self-synchronization (requires three or more satellites).

iv) 2D fix with external synchronization (requires two or more satellites).

v) fix from combination of NAVSTAR with some other system (requires one or more satellites).

In this study we confine our interest to the last three possibilities.
In section 2 we develop the mathematical models required to compute a 2D error ellipse, given NAVSTAR satellite almanacs, user's position, and a passive ranging error model.

In section 3 we consider a selection of error models for passive ranging NAVSTAR, Loran-C, and user's clock synchronization.

In section 4 we present results of our analysis of NAVSTAR performance as a function of time, as a function of position (considering locations off Canada's east, north and west coasts, and in the north Atlantic), as a function of error model (isolating the effect of various factors in the error model), and in combination with Loran-C.

Details of these results, plotted and in tabular form, are contained in the appendices, as are the program listings used.
2. Mathematical models

2.1 NAVSTAR Satellite Positions.

The GPS user continuously receives navigation information from the GPS satellites in the form of data bits modulated on the received signals. This information includes the satellite's time, its clock correction and ephemeris parameters, almanacs and health for all GPS satellites (Van Dierendonck et al, 1978).

The satellite ephemeris presentation model is characterized by a set of parameters that is an extension of Keplerian elements plus secular drift terms and harmonic coefficients (ibid). The definitions of these parameters are given on Table 1. The mathematical models necessary for the determination of satellite positions into earth-fixed cartesian coordinates at specific transmission epochs are presented in a step by step fashion in Table 2.

2.2 Satellite Visibility Check

Because of the very high frequency of the GPS signals, visibility of GPS satellites is limited to the line of sight reception. To test for satellite visibility it is necessary to consider the coordinates of the satellite with respect to the observer's position on the surface of the earth.

The relative position of a satellite at $X_{S_i} = (x_{S_i}, y_{S_i}, z_{S_i})^T$ with respect to an observer given by $(\phi_{obs}, \lambda_{obs}, h_{obs})$ or by $X_{obs} = (x_{obs}, y_{obs}, z_{obs})^T$ is given by (Krakiwsky and Wells, 1971)

$$x_{AT} = x_{S_i} - x_{AT_{obs}}$$

(1)

where the superscript AT denotes the Average Terrestrial Coordinate System. After transformation to the observer's topocentric (local geodetic) system we have
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>Mean Anomaly at reference time.</td>
</tr>
<tr>
<td>( \Delta n )</td>
<td>Mean Motion difference from computed value.</td>
</tr>
<tr>
<td>e</td>
<td>Eccentricity.</td>
</tr>
<tr>
<td>( \sqrt{a} )</td>
<td>Square root of semi-major axis.</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>Right Ascension at reference time.</td>
</tr>
<tr>
<td>( i )</td>
<td>Inclination Angle at reference time.</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Argument of the Perigee.</td>
</tr>
<tr>
<td>( \dot{\Omega} )</td>
<td>Rate of Right Ascension.</td>
</tr>
<tr>
<td>( C_{uc}, C_{us} )</td>
<td>Cosine and Sine harmonic correction terms to the argument of latitude.</td>
</tr>
<tr>
<td>( C_{rc}, C_{rs} )</td>
<td>Cosine and sine harmonic correction terms to the orbit radius.</td>
</tr>
<tr>
<td>( C_{ic}, C_{is} )</td>
<td>Cosine and sine harmonic correction terms to the inclination.</td>
</tr>
<tr>
<td>( t_{oe} )</td>
<td>Ephemeris reference time.</td>
</tr>
</tbody>
</table>
TABLE 2

GPS satellite positions computation from broadcast ephemeris

\[
\begin{align*}
\nu &= 3.986000 \cdot 10^{14} \, \text{m}^3/\text{sec}^2 \quad \text{Universal Gravitational Constant (WGS 72)} \\
\omega_e &= 7.292115147 \cdot 10^{-5} \, \text{rad/sec} \quad \text{Earth's rotation rate (WGS 72)} \\
a &= \left(\frac{\nu}{a^3}\right) \quad \text{Semi-major axis.} \\
\eta_0 &= \sqrt[3]{\frac{\nu}{a^3}} \quad \text{Computed Mean Motion} \\
t_k &= t - t_{oe} \quad \text{Time from reference epoch} \\
\eta &= \eta_0 + \Delta n \quad \text{Corrected Mean Motion} \\
M_k &= M_0 + nt_k \quad \text{Mean Anomaly} \\
M_k &= E_k - e \sin E_k \quad \text{Kepler's equation for eccentric anomaly.} \\
COSV_k &= (\cos E_k - e)/(1 - e \cos E_k) \quad \text{True Anomaly} \\
SINV_k &= \sqrt{1-e^2} \sin E_k/(1-e \cos E_k) \\
\phi_k &= V_k + \omega \quad \text{Argument of latitude.} \\
\delta u_k &= C_{uc} \cos 2\phi_k + C_{us} \sin 2\phi_k \quad \text{Correction to the argument of latitude} \\
\delta r_k &= C_{rc} \cos 2\phi_k + C_{rs} \sin 2\phi_k \quad \text{Correction to the orbit radius} \\
\delta i_k &= C_{ic} \cos 2\phi_k + C_{is} \sin 2\phi_k \quad \text{Correction to the inclination angle} \\
u_k &= \phi_k + \delta u_k \quad \text{Corrected argument of latitude} \\
r_k &= a(1-e \cos E_k) + \delta r_k \quad \text{Corrected orbit radius} \\
i_k &= i_0 + \delta i_k \quad \text{Corrected inclination} \\
x_k &= r_k \cos u_k \quad \text{Position in orbital plane} \\
y_k &= r_k \sin u_k \\
\Omega_k &= \Omega_0 + \left(\Omega - \omega_e\right)t_k - \omega_e t_{oe} \quad \text{Corrected longitude of ascending node} \\
x_k &= x_k \cos \Omega_k - y_k \cos i_k \sin \Omega_k \quad \text{Earth fixed coordinates} \\
y_k &= x_k \sin \Omega_k + y_k \cos i_k \cos \Omega_k \quad \text{Earth fixed coordinates} \\
z_k &= y_k \sin i_k
\end{align*}
\]
where $P_z$ represents a reflection on the $y$-axis, and $R_2, R_3$ represent rotations about the $y$ and $z$ axes respectively.

Once the position vector $x_{i}^{\text{Topo}}$ is computed, visibility is only possible if

$$z_{i}^{\text{Topo}} \geq 0$$

(3)

The azimuth of a visible satellite is then given by

$$A = \tan^{-1} \frac{y}{x}$$

(4)

and its elevation angle is given by

$$E = \tan^{-1} \frac{z}{(x^2 + y^2)^{1/2}}$$

(5)

2.3 Positioning Design Matrix

As already stated earlier NAVSTAR positioning depends on passive ranging measurements, also known as pseudo-range measurements. These are defined as the transit times of the satellite generated signals as observed by the user and scaled by the speed of light $c$. For a given observation, the true slant range $R$ is represented by the equation

$$R = C(t_R - t_T) + e$$

(6)

Where $t_R$ is the GPS received time, $t_T$ is the GPS transmission time and $e$ is the measurement error due to atmospheric delay, measurement noise and other user errors. The corresponding pseudo-range measurement is described as

$$\tilde{R} = R + C(\Delta t_u - \Delta t_s) + e$$

(7)

where $\Delta t_s$ and $\Delta t_u$ are the satellite's and user's clock offsets from the GPS reference time. The range $R$ may be expressed in terms of the navigator's coordinates and the satellite position, so that the equation
summarizes the information from n satellites which is required for the
computation of user position and user clock bias. The n equations
represented by eqn. (8) can be linearized on the usual way using a first
order Taylor series expansion about an approximate user position and clock
bias $X^o$. The linearized equations can then be written in expanded
matrix form as

$$A\delta + BV + W = 0 \quad (9)$$

where $\delta$ is a vector of corrections to the user's position and clock bias,
$V$ is the vector of residuals, $W$ is the misclosure vector and $A$ and $B$
are design matrices with

$$B = I \quad (10a)$$

and

$$A = \frac{\partial F}{\partial X} \bigg|_{X^o} \quad (10b)$$

In the 2-D case we consider here the design matrix $A$ has rows
having three elements such that

$$A_t = \left[ \frac{\partial F}{\partial \phi} \frac{\partial F}{\partial \lambda} \frac{\partial F}{\partial \Delta t_u} \right]_t \quad (11)$$

where $t$ denotes time epoch and

$$\frac{\partial F}{\partial \phi} = \left[ \frac{\partial F}{\partial x_t^o} \frac{\partial F}{\partial y_t^o} \frac{\partial F}{\partial z_t^o} \right] \frac{\partial}{\partial \phi} \left[ \begin{array}{c}
  x_t^o \\
  y_t^o \\
  z_t^o 
\end{array} \right] \quad (12a)$$
\[
\frac{\partial F}{\partial \lambda} = \begin{bmatrix} \frac{\partial F}{\partial x_t} & \frac{\partial F}{\partial y_t} & \frac{\partial F}{\partial z_t} \end{bmatrix} \frac{\partial}{\partial \lambda} \begin{bmatrix} x_t^\circ \\ y_t^\circ \\ z_t^\circ \end{bmatrix} 
\]

(12b)

\[
\frac{\partial F}{\partial \Delta t_u} = c
\]

(12c)

where the partial derivatives involved are given in Krakiwsky and Wells (1971) and McCaskill et al (1978) as

\[
\frac{\partial F}{\partial X} = - \frac{X_s - X_0^{\text{obs}}}{R^0} 
\]

(13a)

\[
\frac{\partial F}{\partial Y} = - \frac{Y_s - Y_0^{\text{obs}}}{R^0} 
\]

(13b)

\[
\frac{\partial F}{\partial Z} = - \frac{Z_s - Z_0^{\text{obs}}}{R^0} 
\]

(13c)

\[
\frac{\partial X}{\partial \phi} = \left[ \frac{a}{(1-e^2 \sin^2 \phi)^{3/2}} + h \right] \sin \phi \cos \lambda + \frac{ae^2 \sin \phi \cos^2 \phi \cos \lambda}{(1-e^2 \sin^2 \phi)^{3/2}} 
\]

(14a)

\[
\frac{\partial Y}{\partial \phi} = - \left[ \frac{a}{(1-e^2 \sin^2 \phi)^{3/2}} + h \right] \sin \phi \sin \lambda + \frac{ae^2 \sin \phi \cos^2 \phi \sin \lambda}{(1-e^2 \sin^2 \phi)^{3/2}} 
\]

(14b)

\[
\frac{\partial Z}{\partial \phi} = \left[ \frac{a}{(1-e^2 \sin^2 \phi)^{3/2}} + h - \frac{ae^2}{(1-e^2 \sin^2 \phi)^{3/2}} \right] \cos \phi + \frac{ae^2 (1-e^2) \sin^2 \phi \cos \phi}{(1-e^2 \sin^2 \phi)^{3/2}} 
\]

(14c)

\[
\frac{\partial X}{\partial \lambda} = \left[ \frac{a}{(1-e^2 \sin^2 \phi)^{3/2}} + h \right] \cos \phi \sin \lambda 
\]

(14d)
\[
\frac{\partial Y^o}{\partial \lambda} = \left[ \frac{a}{(1-e^2 \sin^2 \phi)^{\frac{3}{2}}} + h \right] \cos \phi \cos \lambda
\]  

(14e)

\[
\frac{\partial Z^o}{\partial \lambda} = 0
\]  

(14f)

### 2.4 Covariance Matrix of Position

Assuming that a weight matrix \( P \) is given for the errors corresponding to the \( n \) simultaneous (or near simultaneous) pseudo-range measurements to the \( n \) satellites, the estimate of \( \delta \) is given by

\[
\hat{\delta} = (A^T P A)^{-1} A^T P W
\]  

(15)

and the covariance of the corresponding error in the estimate of \( \delta \) is given by

\[
\Sigma^o = (A^T P A)^{-1}
\]  

(16)

which is also the covariance of the adjusted solution vector

\[
\hat{X} = X^o + \delta
\]

Once the covariance matrix of position matrix of position has been computed from eqn.(16) corresponding error ellipses can be computed in the usual manner whereby the semi-major (\( \alpha \)) and semi-minor (\( \beta \)) axes are given by

\[
\alpha = \left[ \frac{\sigma_\delta^2 + \sigma_\lambda^2}{2} + \sqrt{\left( \frac{\sigma_\phi^2}{4} \right)^2 + \frac{\sigma_{\phi \lambda}^2}{4}} \right]
\]
\[ \beta = \left[ \frac{\sigma_\phi + \sigma_\lambda}{2} - \sqrt{\frac{(\sigma_\lambda - \sigma_\phi)^2}{4} + \frac{\sigma_{\phi\lambda}^2}{2}} \right] \]

and the orientation of the error ellipse is given by

\[ \theta = \frac{1}{2} \tan^{-1} \left( \frac{2\sigma_{\phi\lambda}}{\sigma_\lambda - \sigma_\phi} \right) \]
3. Error models

3.1 NAVSTAR Error Models

The level of navigation performance with the GPS is a direct result of the waveform characteristics of the GPS satellite signals. Operation with either the P or C/A code to a large extent establishes the navigation accuracy level which can be achieved by the user. The environmental medium and propagation link in which the signals are transmitted and received are also significant performance constraints on GPS. The basic NAVSTAR error models and the term which may be employed in a performance analysis have been discussed by Martin (1978), and also by Gilbert (1979). A summary of this error budget, which was also used for the present analysis, is given in table 3.

3.2 LORAN-C Error Models

Examining the combined performance of GPS with LORAN-C associated standard deviations for the LORAN ranges were computed using the empirical relationship (pers.comm. Grant)

\[ \sigma_L = \frac{100}{\sqrt{\text{SNR}}} \text{ (m)} \]

where SNR is the signal-to-noise ratio of the measured ranges which can typically be 0.5 for a weak signal or 10.0 for a strong signal. From recent operations on Davis Strait the accuracy of LORAN ranging to Saglek, Cape Race and Angissog was of the order of 100 to 280 m, from table 4. For the present analysis LORAN ranging to Cape Race, Angissoq and Sandur was assumed with obtainable accuracies of \( \approx 140 \) m, i.e. \( \text{SNR} = 0.5 \).
TABLE 3.

GPS Error Budget expressed as uncorrelated equivalent range errors (m)

<table>
<thead>
<tr>
<th></th>
<th>P-Code</th>
<th>C/A-Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Ephemeris</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Satellite Clock Delay</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Pseudorange Noise</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Range Quantization</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Mechanization</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Ionospheric Dual Frequency</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Compensation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncompensated ionospheric delay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime</td>
<td>5.0 to 15.0</td>
<td>0.5 to 1.5</td>
</tr>
<tr>
<td>Nightime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric Delay</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Multipath</td>
<td>1.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Rms</td>
<td>4.0 m</td>
<td>16 to 21 m</td>
</tr>
</tbody>
</table>
TABLE 4

Loran Measurements in Davis Strait*  
(*)  \( \phi = 66^\circ 45' \)

<table>
<thead>
<tr>
<th>To</th>
<th>Noise N</th>
<th>S/N = 128/N</th>
<th>( \sigma_L = 100/\sqrt{S/N} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saglek</td>
<td>1000</td>
<td>0.13</td>
<td>280 m</td>
</tr>
<tr>
<td>Cape Race</td>
<td>377</td>
<td>0.34</td>
<td>170 m</td>
</tr>
<tr>
<td>Angissoq</td>
<td>135</td>
<td>0.95</td>
<td>100 m</td>
</tr>
</tbody>
</table>

* After Grant (October 1980, personal communication).
3.3 Clock synchronization Error

To further enhance the analysis of the NAVSTAR navigation performance it was assumed that clock synchronization can be retained within 0.3 $\mu$sec ($\approx$ 100 m in equivalent range) and that the navigator knows his position within $10^\circ$ in $\phi$ and $\lambda$.

This information was incorporated into the model by treating $\phi$, $\lambda$ and $\Delta t_u$ as "pseudo-observables" with weight matrix $P_x$, and rewriting equation (16) as

$$ C_0 = (A^T P A + P_x)^{-1} $$
4. Results

Some aspects of the nature of GPS orbits and the combination of their lines of position are discussed in section 4.1.

For the purposes of this report, GPS performance was measured by the length of the semi-major axis of the error ellipse computed as described in section 2.4. This performance was evaluated as a function of time, as a function of position, and as a function of error model, both alone and in combination with LORAN-C. Results are given in Sections 4.2, 4.3 and 4.4.

For the purposes of this report, LORAN-C transmitters were treated as "stationary" GPS satellites, located on the surface of the earth. That is rho-rho LORAN-C was treated as measuring chord distances through the earth, rather than geodesic distances over the surface of the earth. This introduces a spurious dip of up to 10° below the horizon for the range vector, but this will propagate only weakly into the determination of the two-dimensional horizontal design matrix in equation 16.

4.1 GPS orbit geometry

Because of their high altitude (20,000 km) GPS spacecraft are visible at spherical distances of up to 76°.

Due to their twelve hour orbital period and the small precession of their orbit planes, GPS satellites ground tracks repeat from day to day nearly exactly.

Due to their 63° orbit plane inclination and twelve hour period, the GPS ground tracks plot almost like a square wave on a mercator plot. In contrast to Transit satellite ground tracks, GPS ground tracks move from west to east. Figures 1 and 2 show GPS ground tracks plotted on a polar
Figure 1.
SUBTRACKS OF SIX GPS SPACE VEHICLES IN ORBIT AS OF 1 OCTOBER 1980. SHOWING VISIBLE SVS FROM 65°N, 60°W, AS OF 0019 UT
Figure 2.
SUBTRACKS OF SIX GPS SPACE VEHICLES IN ORBIT
AS OF 1 OCTOBER, 1980.
SHOWING VISIBLE SVS FROM
65°N, 60°W, AS OF 0024 UT
stereographic projection.

The combination of lines of position from GPS satellites at a given tracking station changes with time as satellites rise and set over the horizon, and change position relative to each other and to the tracking station. In particular, if a satellite providing a particularly strong geometry sets, the combined positional accuracy may change dramatically. Figures 1 and 2 illustrate an example of this. Figure 1 shows the five GPS satellites visible from Davis Strait (65°N, 60°W) as of 0019 hours on 1 October 1980. Note that satellites 7, 5, 4 and 8 are almost collinear with Davis Strait, but satellite 9 is not. Figure 2 shows the situation five minutes later. Satellite 9 has set and the remaining satellites are even more collinear with Davis Strait. The error ellipse semi major axes at Davis Strait corresponding to Figures 1 and 2 respectively are 31 and 414 metres.

Figure 3 shows a 36 hour record of this semi major axis at Davis Strait. Each of the discontinuities corresponds to the rise or set of a satellite which significantly changes the strength of the geometry.
FIGURE 3.

SEMI-MAJOR AXIS OF ERROR ELLIPSE USING GPS ALONE (IF MORE THAN 3 SATELLITES) AND IN COMBINATION WITH LORAN-C (IF FEWER)
FOR DAVIS STRAIT (65°N, 60°W) USING P-CODE

HOURS FROM 0000 HOURS UT OCTOBER 1, 1980
4.2 GPS performance as a function of time

There are three aspects to this analysis. Most important is the variation in GPS performance during a 24 hour cycle. Second is the variation from day to day, and third is the variation from year to year.

The present constellation of six satellites was assumed throughout. The performance during a 24 hour cycle is characterized by periods of no satellites, periods of excellent multisatellite geometry, and periods in between these extremes. Performance characteristics were computed at five minute intervals for 24 hour time spans. Appendix C contains the results.

The performance characteristics used are the combined error ellipse semi-major axis, semi-minor axis, and orientation; the number of satellites visible; and the elevation, azimuth, and subtrack latitude and longitude for each visible satellite.

A typical plot of the error ellipse semi-major axis is shown in figure 3. A full set of plots is contained in Appendix B.

Plots of the portion of each day for which GPS provides a specified accuracy (as measured by the error ellipse semi-major axis) are shown in figures 4, 5, 6 and 7, 8 and 9.

Analysis of the variation from day to day and year to year is limited by the fact that only one set of GPS almanacs was available, and these almanacs accurately represent actual GPS orbits only at the time of transmission. According to van Dierendonk (1978) the almanac error is 1 km after 1 day and 20 km after 5 weeks. A time series of almanacs would be required for a more detailed analysis.

From the 36 hour results listed in Appendix B, it can be seen that the orbit periods differ by a few minutes from exactly 24 hours. This is equivalent to an along track precession of several hundred kilometers (at
Figure 4

GPS performance as a function of position

Hours per day for which the GPS P-code ranging error ellipse semi-major axis is below a specified value.
Figure 5.
GPS performance as a function of error model for Davis Strait. Hours per day for which the GPS/loran error ellipse semi-major axis is below a specified value.
GPS performance as a function of error model for Labrador sea. Hours per day for which GPS/LORAN error ellipse semi-major axis is below a specified value.
GPS Performance as a function of error model for Baffin Bay. Hours per day for which GPS/LORAN error ellipse semi-major axis is below a specified value.
Figure 8

GPS performance along meridian $\lambda=25^\circ W$.

Hours per day for which GPS (P-code) error ellipse semi-major axis is below a specified value.
Figure 9

GPS performance along meridian $\lambda=70^\circ W$.
Hours per day for which GPS (P-code) error ellipse semi-major axis is below a specified value.
orbit altitude) per day. This appears to be outside the error of the almanacs, and hence probably represents a real (but slight) change in the orbit configurations from day to day.

A special run was made, using the same almanacs, for 1 October, 1981, and compared with the 1980 results. This indicated that the orbit planes precess by a few degrees per year. This is likely within the error of the almanacs, and no firm conclusion should be drawn.

4.3 GPS performance as a function of position

Three tracking station positions were selected for analysis. They are Labrador (55°N, 65°W), Davis Strait (65°N, 60°W) and Baffin Bay (70°N, 68°W). The results are contained in Appendix B.

Figure 4 compares GPS performance at each of these three positions, expressed in terms of the number of hours per day that GPS accuracy measured by the error ellipse semi-major axis) was below a specified value. For example, from this preliminary analysis GPS accuracy is predicted to be 150 metres or better for 11.5, 11.0 and 10.75 hours per day at Labrador, Davis Strait and Baffin Bay respectively.
4.4 GPS performance as a function of error model

Two simple error models were chosen for GPS ranges, using the data of Table 3. P-code ranging was assumed to have a standard deviation of 4 metres, and C/A-code ranging standard deviation to be 16 metres.

Rho-Rho LORAN-C ranging from Angissoq and Cape Race were both assumed to have standard deviations of 140 metres at all tracking stations. According to the data of Table 4 this was probably a reasonable choice for Davis Strait. It is probably too pessimistic for Labrador. Baffin Bay is probably beyond the groundwave range for Angissoq and Cape Race.

A priori standard deviations of 10° in latitude and longitude were assigned to the tracking station coordinates. An a priori standard deviation of the tracking station clock synchronization, expressed in terms of equivalent range, of 100 metres was assumed.

In the absence of these a priori standard deviations (weighted constants) the C/A code error ellipses are exactly four times the size of the P-code error ellipses. However when the weighted constraints are included this is no longer true.

The algorithm chosen for the combination of GPS and LORAN-C was; a) if four or more GPS satellites were visible, a GPS-only error ellipse was computed; b) if one to three GPS satellites were visible a combined GPS-LORAN error ellipse was computed; c) if no GPS satellites were visible, no error ellipse was computed.
Runs were made at each of the three tracking stations for each of three conditions:

a) P-code ranging without LORAN
b) C/A-code ranging without LORAN
c) C/A-code ranging with LORAN

The results are summarized in Figures 5, 6 and 7. Figure 5 alone shows results from P-code ranging with LORAN. Figure 5 indicates that 150 metre or better positioning is predicted for 8.5, 10.0, 11.0 and 11.75 hours per day at Davis Strait, using C/A only, C/A + LORAN, P only and P with LORAN respectively.

The weighted constraint of 100 metres equivalent range (or 0.33 microseconds) on the clock synchronization implies the use of an atomic frequency standard, and of some external method of maintaining synchronization (for example Transit fixes to check GPS range measurements). However, as long as there are three or more GPS satellites with good geometry, the GPS-only solution for synchronization overwhelms the influence of this weighted constraint. From two special runs at Davis Strait with this constraint removed, 150 metre or better positioning is predicted for 11.0 and 11.3 hours per day using P code only and P code with LORAN. This is essentially unchanged from the previous results. On the other hand a priori knowledge of the clock synchronization as represented by this weighted constraint does mean that GPS fixes are possible with only two satellites.
4.5 Fully implemented GPS performance

The performance of a full GPS constellation of 24 satellites was simulated by generating almanacs for satellites spaced 45° apart in mean anomaly $M_0$, in each of three orbit planes separated in right ascension by 120° and inclined at 63°.

For this analysis, all visible satellites were used in a two dimensional position fix, with the clock synchronization constrained as above. This of course differs from the usually proposed mode of four parameter fixes (three dimensions plus clock synchronization) using only the best four of the available satellites.

Using P-code only, the results shown in Figure 10 indicate continuous coverage, with the standard error ellipse semi major axis at about 5 metres.
Figure 10.
Full satellite constellation.
DAVIS SATELLITE (60°N, 60°W) using P-code.

NNAVIAL(0) PERFORMANCE
SEMI-MAJOR AXIS OF ERROR ELLIPSE
UNITS IN METRES

HOURS

0 10 20 30 40 50 60
5. Conclusions

During the present phase of GPS development, during which only limited GPS coverage is available, the variation in GPS performance has a predominant 24 hour cycle. The nature of this cycle is strongly dependent on the number and relative positions of the GPS satellites, and were weakly dependent on the receiver position.

The 24 hour cycle evolves slightly from day to day as the satellites precess, however more information on the variation of GPS satellite almanac parameters with time is required before firm conclusions can be drawn on the nature of this evolution.

The results presented here predict that the present six-satellite GPS configuration will provide 150 metre or better positioning about 11 hours per day for the area studied (Labrador to Baffin Bay). This coverage degrades slightly as latitude of the tracking station increases, and is worse for C/A-code GPS ranging unaided by LORAN-C.

The main objective of this study was to assess the feasibility of using GPS in its present limited deployment as an operational survey positioning system in the eastern Canadian arctic. Consistant with this objective the mathematical models and error models used, while reasonably realistic, are simple and contain several approximations identified in this report. The principal conclusion of this report then is:

It is feasible to use GPS if 150 metres or better positioning for about 11 hours per day meets the requirements of an operational survey.

It is deemed that the approximations used in this analysis will not affect this principal conclusion.
REFERENCES


APPENDIX A PREANALYSIS SOFTWARE

This Appendix contains a listing of the software used to generate the results in this report. It consists of a main routine and eleven subroutines.

MAIN PROGRAM A-2
FUNCTION MODUL 0 A-5
SUBROUTINE HHMMSS A-5
SUBROUTINE ROTREF A-6
SUBROUTINE PLHXYZ A-7
SUBROUTINE XYZPLH A-7
SUBROUTINE DERIV A-8
SUBROUTINE SAIVEC A-9
SUBROUTINE MAPMPH A-10
SUBROUTINE ELIPS A-10
SUBROUTINE PLINIT A-11
SUBROUTINE PLOT A-11
IMPLICIT REAL*8(A-H,O-Z)
REAL *8 MD, INC, NO, MK
INTEGER ELEV, AZIM, SLAT, SLGN, EA, EB, PHI
C
DIMENSION SLAT(6), SLON(6)
DIMENSION SIGR(3), SIGLRN(2), PRN(2), XLAT(3), XLON(3)
DIMENSION MD(6), DN(6), E(6), A(6), CW(6), INC(6),
# W(6), CWD(6), TOE(6), ISAT(6), NO(6)
# JD(6), TJD(6), IH(6), IM(6), IS(6)
DIMENSION ELEV(6), AZIM(6), EPOCH(6), XS(3)
DIMENSION DA(6,3), ATPA(3,3), IW1(3), IW2(3)
DIMENSION PX(3)
C
COMMON /PLOTS/ XMIN, XMAX
COMMON /ALIMAC/ A, MD, NO, E, W, INC, CW, CWD,
# TOE, EPOCH, ISAT
C
XMIN=0.D0
XMAX=600.D0
CALL PLINIT(8,120)
RHO = PI/180.D0
C
DATA ICR /5/ , IPR/6/ , PRN /8HPRECISE , 8H C/A /
C
REFERENCE ELLIPSOID PARAMETERS
C
DATA GM /3.986008014/ , WE /7.2921151470-5/
DATA AE /6378135.00/ , BE /6356750.500/ ,
DATA XLAT /46.7756055600 , 59.9881305500 , 64.9073833300/
DATA XLON /306.825511100 , 314.825702800 , 336.077291700/
C
(UNCORRELATED) RANGE ERROR SCHEDULES
MCOOE = 1 , PRECISE MODE , SIGRG = 4.00 M
2 , C/A MODE , SIGRG = 16.00 M
3 , SIGRG = 1.00 (IDENTITY WEIGHT MATRIX)
C
SIGRG(1) = 4.00D0
SIGRG(2) = 16.00D0
SIGRG(3) = 1.000D0
C
PX(1) = 1./100.D0
PX(2) = 1./100.D0
PX(3) = 1./100.D0
C
LORAN RANGE ERROR SCHEDULES
C
MLOR = 1 , WEAK SIGNAL(S/N RATIO SNR=0.5)
2 , STRONG SIGNAL(S/N RATIO SNR=10.0)
C
SIGLRN(1) = 100. / DSQRT(0.5D0)
SIGLRN(2) = 130. / DSQRT(10.0D0)
C
DO 20 I = 1,3
XLAT(I) = XLAT(I) * RHO
20 XLON(I) = XLON(I) * RHO
C
READ(ICR,1001) CLAT, OLONG, HT, DAY1, ELMIN, NSAT, MCODE, MLOR, LORAN
IF(OLONG.LT.0.00) OLONG = OLONG + 360.00
C
SNR = 0.5
IF(MLOR,N0,2) SNR = 10.
WRITE(IPR,2016) CLAT, OLONG, PRN(MCODE), SIGRG(MCODE), SNR
READ SATELLITE ALMANAC

ISAT - SATELLITE NUMBER
TOE - ALMANAC REFERENCE TIME: TIME OF THE WEEK (SEC)
A - SQUARE ROOT OF THE SEMI-MAJOR AXIS
MO - MEAN ANOMALY AT REFERENCE TIME (RAD)
E - ECCENTRICITY
W - ARGUMENT OF THE PERIGEE (RAD)
INC - INCLINATION ANGLE AT REFERENCE TIME (RAD)
CW - RIGHT ASCENSION AT REFERENCE TIME (RAD)
CWD - RATE OF RIGHT ASCENSION (RAD/SEC)
JD - ALMANAC REFERENCE TIME; JULIAN DAY OF YEAR
TJD - TIME OF JULIAN DAY

DO 10 I = 1, NSAT
READ(ICR,1000) ISAT(I), TOE(I), A(I), MO(I), E(I), W(I), INC(I),
CW(I), CWD(I), JD(I), TJD(I)
# N0(I) = DSORT(GM)/(A(I)**3)
A(I) = A(I)**2
EPOCH(I) = DFLOAT(JD(I)) + TJD(I)/86400.
TOJD = TJD(I)
CALL HHMMSS (TOJD, IH(I), IM(I), IS(I))
10 CONTINUE
I1 = 1
I2 = I1 + 5
IF(I2.GT.NSAT) I2 = NSAT
WRITE(IPR,2001) (ISAT(I), I=I1, I2)
WRITE(IPR,2002) (TOE(I), I=I1, I2)
WRITE(IPR,2011) (JD(I), I=I1, I2)
WRITE(IPR,2003) (A(I), I=I1, I2)
WRITE(IPR,2004) (MO(I), I=I1, I2)
WRITE(IPR,2005) (E(I), I=I1, I2)
WRITE(IPR,2006) (W(I), I=I1, I2)
WRITE(IPR,2007) (INC(I), I=I1, I2)
WRITE(IPR,2008) (CW(I), I=I1, I2)
WRITE(IPR,2009) (CWD(I), I=I1, I2)
WRITE(IPR,2010) (JD(I), I=I1, I2)
IF(I2.EQ.NSAT) GO TO 12
I1 = 12 + 1
GO TO 13
12 CONTINUE
WRITE(IPR,2014)
WRITE(IPR,2012) ISAT
WRITE(IPR,2015)

HOUR = 0.0
FSTDAY = DAY1
14 DAY1 = FSTDAY + HOUR/24.0

NN = 0
DO 11 I = 1, NSAT

CALL SATVEC(I, DAY1, XS)
CALL XYZPLH(XS(1), XS(2), XS(3), PLAT, PLON, HSAT)

CALL COMPUTE SATELLITE (EARTH FIXED) COORDINATES

CALL SATVEC(I, DAY1, XS)
CALL XYZPLH(XS(1), XS(2), XS(3), PLAT, PLON, HSAT)

CALL COMPUTE LAT AND LON OF SATELLITE SUBPOINT

SLAT(I) = DINT(PLAT/RHO)
SLON(I) = DINT(PLON/RHO)
COMPUTE SATELLITE AZIMUTH, ELEVATION ANGLE, SLANT RANGE AND ITS DERIVATIVE WITH RESPECT TO LAT AND LONG

CALL DERIV (IPR, AE, BE, OLAT, OLONG, HT, XS, S, DSDP, DSDL, EL, AZ, IER)

ELEV(I) = DINT(EL)
AZIM(I) = DINT(AZ)

DAY = DAY1
TOD = HOUR*3600.DO
CALL HHMMSS (TOD, IHR, MIN, SEC)
IHR = MOD(IHR, 24)
T = DFLOAT(IHR) + MIN/60.DO

CALL DERIV (IPR, AE, BE, OLAT, OLONG, HT, XS, S, DSDP, DSDL, EL, AZ, IER)

IF (EL.LT. ELMIN) GO TO 17
NN = NN + 1

FORM DESIGN MATRIX

WGTRG = 1.DO/SIGLRN(MCODE)
DA(NN,1) = DSDP * WGTRG
DA(NN,2) = DSDL * WGTRG
DA(NN,3) = 1.DO * WGTRG

GO TO 11

17 ELEV(I) = 0
AZIM(I) = 0
EA = 0
EB = 0
PHI = 0
ESA = 0.

11 CONTINUE
NPR = NN
LRN = 0
IF (NN.GT. 3) GO TO 18
IF (NN.LT. 2) GO TO 16
IF (LRAN.EQ.0) GO TO 18

IF LESS THAN 3 PSEUDO-RANGES AVAILABLE TRY COMBINED PERFORMANCE WITH LORAN RANGES

DO 19 L = 1,3
CALL PLHXYZ(XLAT(L), XLON(L), 0.DO, 0.DO, 0.DO, 0.DO, AE, BE, XX, YY, ZZ)
XS(I) = XX
XS(2) = YY
XS(3) = ZZ
CALL DERIV (IPR, AE, BE, OLAT, OLONG, HT, XS, S, DSDP, DSDL, EL, AZ, IER)
LRN = LRN + 1
NN = NPR + LRN

WGTRG = 1./SIGLRN(MLRNR)
DA(NN,1) = DSDP * WGTRG
DA(NN,2) = DSDL * WGTRG
DA(NN,3) = 1.DO * WGTRG

19 CONTINUE

18 CONTINUE
CALL MATMPY(DA, DA, ATPA, 3, NN, 3, 6, 6, 3, 2)
DO 30 II = 1,3
30 ATPA(II, II) = ATPA(II, II) + PX(II)
CALL MINVD(ATPA, 3, 3, DETA, IW1, IW2)
COMPUTE STANDARD ERROR ELLIPSE

CALL ELIPS(ATPA(1,1),ATPA(2,1),ATPA(2,2),EEA,EEB,1,00,FI)

EA = DINT(EEA*6371.0 D3*RH0)
EB = DINT(EEB*6371.0 D3*RH0)
PHI = DINT(F1/RH0)
EEA = EEA * 6371.0 D3 * RH0

PHI = DINT(F1/RH0)

WRITE(IPR,2013) IDAY,THR,IMIN,(ELEV(I),AZIM(I),
# SLAT(I),SLON(I),I=1,NSAT),EA,EB,PHI,NPR,LRN

CALL PLOT(8,120,EEA,T1

HOUR = HOUR + 5./60.

IF(HOUR.LT.24.0D0) GO TO 14

1000 FORMAT(I4,F8.0,4D16.12,4X,I4,F8.0)

1001 FORMAT(4X,5X,REF. TIME - TIME OF WEEK (SEC)$,I4,4D16.8)

2002 FORMAT(4X,5X,SATELLITE NO.$,I4,6I16)

2003 FORMAT(4X,5X,SEMI - MAJOR AXIS (M)$,6D16.8)

2004 FORMAT(4X,5X,MEAN ANOMALY @ TREF (RADIANS)$,6D16.8)

2005 FORMAT(4X,5X,ECCENTRICITY$,19X,6D16.8)

2006 FORMAT(4X,5X,ARG OF PERIGEE (RADIANS)$,6X,6D16.8)

2007 FORMAT(4X,5X,INCLINATION (RADIANS)$,9X,6D16.8)

2008 FORMAT(4X,5X,RIGHT ASCENSION (RADIANS)$,5X,6D16.8)

2009 FORMAT(4X,5X,RATE OF RA (RADIANS/SEC)$,6X,6D16.8)

2010 FORMAT(4X,5X,MEAN MOTION (RADIANS/SEC)$,5X,6D16.8)

2011 FORMAT(4X,5X,JULIAN DATE (DDD HH MM SS)$,4X,6(4X,4I3))

2012 FORMAT(I1X,6(5X,*SAT #$,*I2,4X),2X,*ERROR ELLIPSE$/)

2013 FORMAT(I5,2I13,6(I3,2I14,15,I3),I6,2I14,2I13)

2014 FORMAT(4X)

2015 FORMAT(2X,*DAY HH MM$,* EL AZ LAT LONG$),3X,*AA$,*2X,*BS$,*2

*PHI$,*$/

2016 FORMAT(4X,*GPS PERFORMANCE PRE-ANALYSIS$,*40X,*LATITUDE =*,
# F9.4,10X,*LONGITUDE =*,F8.4,*20X,*OPTIONS USED FOR THIS R
# $*40X,*CODE : "*A8,"*40X,*SIGMA PSEU:RANGE = ,F6.2,
# *5X,*(M)$,*40X,*SIGMA LORAN-RANGE = 100/SQRT(*,F4.1{* (M)*/

STOP

END

FUNCTION MODULO(I,J)
MODULO = I - (I-1)/J*K
RETURN
END

SUBROUTINE HHMMSS (TJD,TH,IH,IM,IS)
IMPLICIT REAL*8(A-H,0-Z)

IH = TJD / 36.02
IM = ((TJD/36.02) - IH)*60.
IS = TJD - IH*3600. - IM*60.
RETURN
END
SUBROUTINE ROTREF(NUM,NAXIS,ANGLE,ROT)

C******************************************************************************
C* COMPUTE PRODUCT MATRIX OF SEQUENCE OF ROTATIONS AND REFLECTIONS
C******************************************************************************
C* INPUTS
C* NUM = NUMBER OF ROTATIONS AND REFLECTIONS IN SEQUENCE
C* NAXIS = SEQUENCE OF ROTATION AND REFLECTION AXES
C* FOR ROTATIONS USE 1, 2, OR 3
C* FOR REFLECTIONS USE -1, -2, OR -3
C* ANGLE = SEQUENCE OF ROTATION ANGLES IN RADIANS
C* FOR REFLECTIONS THIS ANGLE IS IGNORED (ASSUMED ZERO)
C* OUTPUT
C* ROT = 3X3 PRODUCT MATRIX
C******************************************************************************
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION ROT(3,3),R1(3,3),R2(3),ANGLE(NUM),NAXIS(NUM)
EPS = 10.15

C--- INITIALIZE (SET *ROT* = IDENTITY MATRIX)
DO 10 I=1,3
  DO 10 J=1,3
    ROT(I,J)=0.
    IF(I.EQ.J) ROT(I,J)=1.
    CONTINUE
10

C--- PROCESS SEQUENCE OF ROTATIONS AND REFLECTIONS ONE AT A TIME
DO 100 N=1,NUM
  DO 100 J=1,3
    R1(N,J)=1.
    IF(NAXIS(N).LT.0.) R1(N,J)=-1.
  CONTINUE
100

C--- DEFINE 3 AXES FOR CURRENT ROTATION OR REFLECTION
N1=IABS(NAXIS(N))
N2=N1+1
IF(N2.GT.3) N2=N2-3
N3=N2+1
IF(N3.GT.3) N3=N3-3

C--- DEFINE DIAGONAL ELEMENTS
R1(N1,N1) = 1.
  IF(NAXIS(N).LT.0.) R1(N1,N1)=-1.
  R1(N2,N2) = DCOS(ANGLE(N))
  IF(NAXIS(N).LT.0.) R1(N2,N2)=-1.
  R1(N3,N3) = R1(N2,N2)

C--- DEFINE NONZERO OFF-DIAGONAL ELEMENTS
R1(N2,N3) = DSIN(ANGLE(N))
  IF(NAXIS(N).LT.0.) R1(N2,N3)=0.
  R1(N3,N2) = -R1(N2,N3)

C--- DEFINE ZERO OFF-DIAGONAL ELEMENTS
R1(N1,N2) = 0.
  R1(N1,N3) = 0.
  R1(N2,N1) = 0.
  R1(N3,N1) = 0.

C--- FORM PRODUCT (SET *ROT* = *R1* * *ROT*)
DO 100 J=1,3
  DO 100 I=1,3
    R2(I)=0.
  CONTINUE
30
  R2(I)=R2(I) + R1(I,K)*ROT(K,J)
  CONTINUE
100

RETURN
END
SUBROUTINE PLHXYZ(PHI, RLAM, H, XO, YO, ZO, A, B, X, Y, Z)

C C
This routine computes the Cartesian coordinates X, Y, Z given the ellipsoidal coordinates PHI, RLAM, H.

C INPUT:
PHI - ELLIPSOIDAL LATITUDE IN RADIANS.
RLAM - ELLIPSOIDAL LONGITUDE IN RADIANS. (POSITIVE EAST OF GREENWICH)
H - ELLIPSOIDAL HEIGHT IN METRES.
XO, YO, ZO - TRANSLATION COMPONENTS FROM THE ORIGIN OF THE CARTESIAN COORDINATE SYSTEM (X, Y, Z) TO THE CENTER OF THE REFERENCE ELLIPSOID. (IN METRES.)
A, B - SEMI-MAJOR AND SEMI-MINOR AXES OF THE REFERENCE ELLIPSOID IN METRES.

C OUTPUT:
X, Y, Z - CARTESIAN COORDINATES OF THE POINT IN METRES.

C C
IMPLICIT REAL*8(A-Z)

E2 = (A*A - B*B) / (A*A)
SP = DSIN(PHI)
CP = DCOS(PHI)
N = A / DSQRT(1.0D0 - E2*SP**2)
X = XO + (N + H) * CP * DCOS(RLAM)
Y = YO + (N + H) * CP * DSIN(RLAM)
Z = ZO + (N*(1.0D0 - E2) + H) * SP
RETURN
END

SUBROUTINE XYZPLH(X, Y, Z, PHI, RLAM, H)

C C
This routine computes the ellipsoidal coordinates PHI, RLAM, H given the Cartesian coordinates X, Y, Z.

C INPUT:
X, Y, Z - CARTESIAN COORDINATES OF THE POINT IN METRES.
XO, YO, ZO - TRANSLATION COMPONENTS FROM THE ORIGIN OF THE CARTESIAN COORDINATE SYSTEM (X, Y, Z) TO THE CENTER OF THE REFERENCE ELLIPSOID. (IN METRES.)
A, B - SEMI-MAJOR AND SEMI-MINOR AXES OF THE REFERENCE ELLIPSOID IN METRES.

C OUTPUT:
PHI - ELLIPSOIDAL LATITUDE IN RADIANS.
RLAM - ELLIPSOIDAL LONGITUDE IN RADIANS. (POSITIVE EAST OF GREENWICH)
H - ELLIPSOIDAL HEIGHT IN METRES.

C C
IMPLICIT REAL*8(A-Z)

NOTE ADOPTED ELLIPSOID OF REFERENCE *NWL 9D*

DATA A, B, XO, YO, ZO, 6378135.00, 6356750.00, 3*000/
E2 = (A*A - B*B) / (A*A)
XP = X - XO
YP = Y - YO
ZP = Z - ZO
S = DSQRT(XP**2 + YP**2)
RLAM = DATAN2(YP, XP)
ZPS = ZP / S
H = DSQRT(XP**2 + YP**2 + ZP**2) - A
PHI = DATAN(ZPS / (1.0D0 - E2*A/(A + H)))
1 = A/DSQRT(1.0D0 - E2*A/(A + H))
HP = H
PHI0 = PHI
H = S / DCOS(PHI) - N
PHI = DATAN(ZPS / (1.0D0 - E2*/N/(N + H)))
IF (DABS(PHI0 - PHI) .GT. 1.D-11 .OR. DABS(H-P-H) .GT. 1.D-5) GO TO 1
RETURN
END
SUBROUTINE DERIV(LU, AE, BE, XLAT, XLOX, HGT, XS,
          S, DSDP, DSDL, ELEV, AZ, IER)

DOUBLE PRECISION AE, ANE, BO, CL, CP, DATN2, DCOS,
          DEPOK, DROK, DROD, DSDL, DSDP, DSIN, DSGRT, DX,
          ELEV, PI, RM, RN, ROT, S, SEC, SL, SP, HGT, AZ,
          ANG(3), DROD(3), DX(3), NAXIS(3),
          ROT(3, 3), XR(3), XS(3), XT(3)

DIMENSION ANG(3), DROD(3), DX(3), NAXIS(3),
          ROT(3, 3), XR(3), XS(3), XT(3)

DATA NAXIS / 3, 2, -2 /

PURPOSE DERIV COMPUTES SLANT RANGE(S) TO SATELLITE, ITS
DERIVATIVES WITH RESPECT TO LAT (DSDP) AND LONG (DSDL),
AND ELEVATION ANGLE (ELEV)

INPUT ARGUMENTS

LU = LISTING LU

AE = SEMI-MAJOR AXIS OF EARTH ELLIPSOID (M)

BE = SEMI-MINOR AXIS (M) OR RECIPROCAL FLATTENING

XLOX = RECEIVER LATITUDE (DEG)

HGT = RECEIVER ELLIPSOID HEIGHT (M)

INDEX = DOPPLER INTERVAL NUMBER (SINCE LOCKON)

XS(3, 33) = SATELLITE LOCAL TERRESTRIAL COORDS

S = RECEIVER TO SATELLITE SLANT RANGE (M)

DSDP = DERIVATIVE OF S WITH RESPECT TO LATITUDE (M/DEG)

DSDL = DERIVATIVE OF S WITH RESPECT TO LONG (M/DEG)

ELEV = SATELLITE ELEVATION ABOVE HORIZON (DEG)

IER = 0 SUCCESSFUL RETURN

EXTERNALS DATN2, DCOS, DEPOK, DSIN, DSGRT, RORF

IEF = 0

C COMPUTE RECEIVER LOCAL TERRESTRIAL COORDS XR

CP = DCOS(XLAT*PI/180.)

SP = DSIN(XLAT*PI/180.)

CL = DCOS(XLOX*PI/180.)

SL = DSIN(XLOX*PI/180.)

BOA = (AE / BE)**2

IF (BE .LT. 0.6E3) BOA = (1. - 1.*BE)**2

RN = AE / DSQRT(CP**2 + BOA * SP**2)

RM = RN * BOA * (RN/AE)**2

XR(1) = (RN + HGT) * CP + CL

XR(2) = (RN + HGT) * CP - SL

XR(3) = (RN + BOA + HGT) * SP

C COMPUTE DERIVATIVES OF XR WITH RESPECT TO LAT AND LONG

DRDP(1) = -(RN + HGT) * SP * CL / 180.

DRDP(2) = -(RM + HGT) * SP * SL / 180.

DRDP(3) = -(RM + HGT) * CP / 180.

DROD(1) = -XR(2) / PI / 180.

DROD(2) = XR(1) / PI / 180.

DROD(3) = 0.

C WRITE(LU,1001) XR, DROD, DROK

C COMPUTE SLANT RANGE AND ITS DERIVATIVES

DO 10 I = 1, 3

S = DSQRT(DX(1)**2 + DX(2)**2 + DX(3)**2)

DSDP = -(DX(1)*DRDP(1) + DX(2)*DRDP(2) + DX(3)*DRDP(3)) / S

DSDL = -(DX(1)*DROD(1) + DX(2)*DROD(2) + DX(3)*DROD(3)) / S

C COMPUTE ELEVATION ANGLE

ANG(1) = (XLOX - 180.) * PI / 180.

ANG(2) = (XLAT - 90.) * PI / 180.

ANG(3) = 0. DO

CALL RORF(3, NAXIS, ANG, ROT)

DO 20 I = 1, 3

XT(I) = 0.

DO 20 J = 1, 3

XT(I) = XT(I) + ROT(I,J) * DX(J)

ELEV = DATN2(XT(3), DSQRT(DX(1)**2 + DX(2)**2)) * 180. / PI

AZ = DATN2(XT(2), XT(1)) * 180. / PI

C WRITE(LU, 1002) S, DSDP, DSDL, ELEV, AZ

RETURN

1001 FORMAT(* DERIV1*.20X, 3F14.2, 2/(57X, 3F14.2))

1002 FORMAT(* DERIV2*.20X, 3F14.2, 2F6.1)

END
SUBROUTINE SATVEC(I, DAY1, XS)

SAIIVCE COMPUTES SATELLITE (EARTH FIXED) COORDINATES FROM
ORBITAL KEPLERIAN PARAMETERS TRANSMITTED BY THE NAVIGATION MESSAGE

IMPLICIT REAL*8 (A-H, O-Z)
REAL *9 !-10 • NO • INC. WK
DIMENSION M(6), NJ(6), A(6), E(6), W(6), INC(6),
# CW(6), CW0(6), TOE(6), ISAT(6), XS(3)

COMMON /ALMNAC/ A, MO, NO, E, W, INC, CW, CW0,
# TOE, EPOCH, ISAT
WE = 7.2921151479D-5

TIME FROM ALMANAC REFERENCE EPOCH
TK = (DAY1 - EPOCH(I))*864. D2

MEAN ANOMALY (RAD)
MK = MO(I) + NO(I)*TK

SOLVE KEPLER'S EQUATION FOR THE ECCENTRIC ANOMALY
EKO = MK + E(I)*DSIN(WK) + (E(I)**2/2.)*DSIN(2.*WK)
50 FTM = EKO - E(I)*DSIN(EKO)
DFTM = FTM - WK
EKO = EKO - DFTM/(1.-E(I)*DCOS(EKO))
IF(DABS(DFTM) .GT. 1.0D-12) GO TO 50
EK = EKO
15 CONTINUE

TRUE ANOMALY (RAD)
ECOSEK = 1.*DO - E(I)*DCOS(EK)
COSVK = (DCOS(EK) - E(I))/ECOSEK
SINVK = DSQRT(1.9Q-E(I)**2)*DSIN(EK)/ECOSEK
VK = DATAN2(SINVK, COSVK)

ARGUMENT OF LATITUDE
FK = VK + W(I)

COMPUTE SECOND HARMONIC PERTURBATIONS IN
ARGUMENT OF LATITUDE
SATELLITE RADIUS
INCLINATION
(CORRECTIONS NOT IMPLEMENTED YET)
UK = FK
RK = A(I) * (1.0D-E(I)*DCOS(EK))

POSITION IN THE ORBITAL PLANE
XPK = RK * DCOS(UK)
YPK = RK * DSIN(UK)

CORRECTED LATITUDE OF THE ASCENDING NODE
CWK = CW(I) + (CWO(I)-WE)*TK - WE*TOE(I)

EARTH FIXED COORDINATES
XK = XPK*DCOS(CWK) - YPK*DCOS(INC(I))*DSIN(CWK)
YK = XPK*DSIN(CWK) + YPK*DCOS(INC(I))*DCOS(CWK)
ZK = YPK*DSIN(INC(I))

XS(1) = XK
XS(2) = YK
XS(3) = ZK
RETURN
END
SUBROUTINE MATMPY(M1,M2,M3,L,M,N,JL,JM,JN,ICODE)

NAME            MATMPY

PURPOSE          TO COMPUTE THE PRODUCT OF TWO MATRICES IN ANY
ALLOWABLE TRANSPOSE COMBINATION AS FOLLOWS:

OPTION ICODE    PRODUCT M3

1          M1*M2
2          (M1)*M2
3          M1*(M2)
4          (M1)*(M2)

(L,M),(M,N),(L,N) ARE THE DIMENSIONS OF THE PRE- AND POST-MATRICES
AND (JL,JM,JN) ARE CORRESPONDING DECLARED ROW DIMENSIONS AT THE CALLING PROGRAM

REAL *8 M1,M2,M3

DIMENSION M1(JL,1), M2(JM,1), M3(JN,1)

DO 11 I = 1,L
  DO 11 J = 1,N
    M3(I,J) = 0.
    DO 11 K = 1,M
      GO TO (1,2,3,4),ICODE
  11 CONTINUE

C     M3 = M1 * M2
    M3(I,J) = M3(I,J) + M1(I,K)*M2(K,J)
    GO TO 11

C     M3 = M1 TRANSPOSE * M2
    M3(I,J) = M3(I,J) + M1(K,I)*M2(J,K)
    GO TO 11

C     M3 = M1 * M2 TRANSPOSE
    M3(I,J) = M3(I,J) + M1(I,K)*M2(J,K)
    GO TO 11

C     M3 = M1 TRANSPOSE * M2 TRANSPOSE
    M3(I,J) = M3(I,J) + M1(K,I)*M2(J,K)

11 CONTINUE

RETURN
END

SUBROUTINE ELIPS(QXX,QXY,QYY,A,B,C,PHI)

C***********************************************************************
C* ELIPS COMPUTES THE SEMI-MAJOR AND SEMI-MINOR AXES AND THE ORIENTATIC
C* (AZIMUTH OF THE MAJOR AXIS) OF THE ERROR ELLIPSE SPECIFIED BY QXX, Q
C* QXY AND THE FACTOR C.
C* C***********************************************************************

IMPLICIT REAL*8(A-H,O-Z)

PI=(QXX+QYY)/2.D0
P2=DSORT((QXX-QYY)**2/4.0D0+QXY**2)
A=DSORT(P1+P2)*C
B=DSORT(P1-P2)*C
PI=3.141592653589793DO
IF(QXX.LT.1.D0-20.AND.QYY.LT.1.D0-20)PHI=0.D0
IF(QXX.LT.1.D0-20.AND.QYY.LT.1.D0-20)GO TO 1
PHI=-0.5DO*DATAN2(-2.DO*QXY,QYY-QXX)
IF(PHI.LT.0.DO)PHI=PHI+2.DO*PI
1 RETURN
END

C***********************************************************************
C* WRITTEN BY:
C* R.R. STEEVES, APRIL, 1976
C***********************************************************************
SUBROUTINE PLINIT(LU,LPLOT)
C
C INITIALIZE PLCT HORIZONTAL AXIS
C
DOUBLE PRECISION XMIN,XMAX
DIMENSION IPLOT(120)
COMMON /PLOTS/ XMIN,XMAX
DATA IAX/1H+/, IBL/1H+/, IST/1H+/
DO 1 I=1,LPLOT
   IPLOT(I)=IST
   CONTINUE
1 CONTINUE
C
C PLOT AXIS
C
WRITE(LU,1000)(IPLOT(I),I=1,LPLOT)
1000 FORMAT(1HI,LH,120A1)
   DO 2 I=1,LPLOT
      IF(I/20*20.EQ.1) GO TO 2
      IPLOT(I)=IBL
   2 CONTINUE
   WRITE(LU,1001)(IPLOT(I),I=1,LPLOT)
1001 FORMAT(' ',5X,*'+',120A1)
   WRITE(LU,1002)
1002 FORMAT(' ')
RETURN
END

SUBROUTINE PLOT(LU,LPLOT,X,T)
DOUBLE PRECISION XMIN,XMAX,X,T
DIMENSION IPLOT(120)
COMMON /PLOTS/ XMIN,XMAX
DATA IBL/1H+/, IAX/1H+/, IST/1H+/
DO 1 I=1,LPLOT
   IPLOT(I)=IBL
   CONTINUE
IF(X.LE.XMIN) GO TO 2
   K=((X-XMIN)/(XMAX-XMIN))*LPLOT+0.5
   IF(K.LT.1.OR.K.GT.LPLOT) GO TO 2
   IPLOT(K)=IST
   2 WRITE(LU,1001)(IPLOT(I),I=1,LPLOT)
1001 FORMAT(' ',F5.1,2X,*'+',120A1)
   WRITE(LU,1002)
1002 FORMAT(' ',7X,*')
RETURN
END
APPENDIX B

<table>
<thead>
<tr>
<th>Plot Description</th>
<th>Loran Status</th>
</tr>
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<tbody>
<tr>
<td>1. Baffin Bay P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>2. Baffin Bay C/A code</td>
<td>No Loran</td>
</tr>
<tr>
<td>3. Baffin Bay C/A code</td>
<td>With Loran</td>
</tr>
<tr>
<td>4. Davis Strait P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>5. Davis Strait C/A code</td>
<td>No Loran</td>
</tr>
<tr>
<td>6. Davis Strait C/A code</td>
<td>With Loran</td>
</tr>
<tr>
<td>7. Labrador P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>8. Labrador C/A code</td>
<td>No Loran</td>
</tr>
<tr>
<td>9. Labrador C/A code</td>
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<tr>
<td>10. Azores P-code</td>
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<tr>
<td>11. Grand Banks P-code</td>
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<td>12. Hudson Bay P-code</td>
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<td>13. Beaufort Sea P-code</td>
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<tr>
<td>14. Arctic Ocean P-code</td>
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<tr>
<td>15. British Columbia P-code</td>
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<tr>
<td>16. 20°N 25°W P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>17. 40°N 25°W P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>18. 60°N 25°W P-code</td>
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</tr>
<tr>
<td>19. 20°N 70°W P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>20. 40°N 70°W P-code</td>
<td>No Loran</td>
</tr>
<tr>
<td>21. 60°N 70°W P-code</td>
<td>No Loran</td>
</tr>
</tbody>
</table>

NOTES: 1. In all plots the length of the semi-major axis standard error ellipse is plotted against time for the 24 hour period starting at 0000 UT 1 Oct. 1980.
2. All plots are for the present GPS configuration of six satellites.
Baffin Bay (70°N, 68°W) using P-code.
Baffin Bay (70°N, 68°W) using C/A-code in combination with LORAN-C
Davis Strait (65°N, 60°W) using P-code.
Davis Strait (65°N, 60°W) using C/A-code
Davis Strait (65°N, 60°W) using C/A-code in combination with LORAN-C
Labrador (55°N, 65°W) using P-code
Labrador (55°N, 65°W) using C/A code
Labrador (55°N, 65°W) using C/A-code in combination with LORAN-C
Hudson Bay (85°N, 60°W) using P-Code.
Arctic Ocean (85°N, 130°E) using P-code
British Columbia (50°N, 130°W) using P-Code
NAVSTAR/SORS PERFORMANCE
SEMI-MAJOR AXIS OF ERROR ELLIPSE

UNITS IN METRES

HOURS

Latitude 20° N, Longitude 25° W using P-code
Latitude 60° N, longitude 25° W using P-code
Latitude 20° N, longitude 70° W using p-code
NAVSTAR/GRS PERFORMANCE
SEMI-MAJOR AXIS OF ERROR ELLIPSE
UNITS IN METRES

Latitute 40° N, Longitude 70° W using P-code
Latitude 60° N, longitude 70° W using P-code
# Appendix C

## Listings of Results

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Code Type</th>
<th>Loran</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Baffin Bay</td>
<td>P-Code</td>
<td>No Loran</td>
</tr>
<tr>
<td>2.</td>
<td>Baffin Bay</td>
<td>C/A Code</td>
<td>No Loran</td>
</tr>
<tr>
<td>3.</td>
<td>Baffin Bay</td>
<td>C/A Code</td>
<td>With Loran</td>
</tr>
<tr>
<td>4.</td>
<td>Davis Strait</td>
<td>P-Code</td>
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</tr>
<tr>
<td>5.</td>
<td>Davis Strait</td>
<td>C/A Code</td>
<td>No Loran</td>
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<tr>
<td>6.</td>
<td>Davis Strait</td>
<td>C/A Code</td>
<td>With Loran</td>
</tr>
<tr>
<td>7.</td>
<td>Labrador</td>
<td>P-Code</td>
<td>No Loran</td>
</tr>
<tr>
<td>8.</td>
<td>Labrador</td>
<td>C/A Code</td>
<td>No Loran</td>
</tr>
<tr>
<td>9.</td>
<td>Labrador</td>
<td>C/A Code</td>
<td>With Loran</td>
</tr>
</tbody>
</table>

**Column headings for each listing**

- **DAY HH MM**: 1980 day, hour minute
- **EL AZ LAT LONG**: elevation and azimuth of satellite in degrees, as seen from ground station, and latitude and longitude of satellite ground track, in degrees
- **AA BB PHI**: GPS error ellipse semi-major axis (AA), semi-minor axis (BB), and orientation of semi-major axis (clockwise from north). AA, BB in metres, PHI in degrees.
- **no headings**: number of satellites visible
  number of Loran-C ranges combined with GPS
### GPS PERFORMANCE PRE-ANALYSIS

**LATITUDE = 70.0000**

**LONGITUDE = 292.0000**

**OPTIONS USED FOR THIS RUN**

**CODE : PRECISE**

**SIGMA PSEUDO-RANGE = 4.00 (M)**

**SIGMA LORAN-RANGE = 100/SORT(0.5) (M)**

<table>
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<tr>
<th>SATELLITE NO.</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>REF. TIME - TIME OF WEEK (SEC)</td>
<td>0.5557280000+06</td>
<td>0.5557280000+06</td>
<td>0.5557280000+06</td>
<td>0.5557280000+06</td>
<td>0.5557280000+06</td>
<td>0.2252000000+06</td>
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<td>145 18 42 8</td>
<td>145 18 42 8</td>
<td>145 18 42 8</td>
<td>145 18 42 8</td>
<td>145 18 42 8</td>
<td>165 14 34 40</td>
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<tr>
<td>SEMI - MAJOR AXIS (M)</td>
<td>0.2656039900+08</td>
<td>0.2656039900+08</td>
<td>0.2656039900+08</td>
<td>0.2656039900+08</td>
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<td>MEAN ANOMALY @ TREF (RADIANS)</td>
<td>-0.3119568900+01</td>
<td>-0.3119568900+01</td>
<td>-0.3119568900+01</td>
<td>-0.3119568900+01</td>
<td>-0.3119568900+01</td>
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<td>ECCENTRICITY</td>
<td>0.1496789200+02</td>
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<td>INCLINATION (RADIANS)</td>
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<td>RIGHT ASCENSION (RADIANS)</td>
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<td>RATE OF RA (RADIANS/SEC)</td>
<td>-0.6230117100-08</td>
<td>-0.6230117100-08</td>
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<td>MEAN MOTION (RADIANS/SEC)</td>
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### ERROR ELLIPSE

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**BAFFIN BAY P - Code**
### GPS PERFORMANCE PRE-ANALYSIS

**LOCATION**: Baffin Bay

**LATITUDE**: 70.0000  **LONGITUDE**: 292.0000

**SIGMA PSEUDO-RANGE**: 16.00  **SIGMA Loran-Range**: 100/SQRT(0.5) (M)

#### SATELLITE NO.

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**REPLAY TIME - TIME OF WEEK (SEC)**

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**JULIAN DATE (DDD HH MM SS)**

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**ECCENTRICITY**

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**ARG OF PERIGEE (RADIANS)**

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**INCLINATION (RADIANS)**

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**RIGHT ASCENSION (RADIANS)**

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**RATE OF RA (RADIANS/SEC)**

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**MEAN MOTION (RADIANS/SEC)**

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#### ERROR ELLIPSE

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**Options Used for this Run**

- Code: PRECISE
- SIGMA PSEUDO-RANGE = 4.00 (M)
- SIGMA LORAN-RANGE = 100/SQRT(0.5) (M)

**Latitude = 65.0000**
**Longitude = 300.0000**

**Davis Strati**

P - Code
GPS PERFORMANCE PRE-ANALYSIS

LATITUDE = 65.0000
LONGITUDE =300.0000

OPTIONS USED FOR THIS RUN

CODE :  C/A

SIGMA PSEUDO-RANGE = 16.00  (M)
SIGMA LORAN-RANGE = 150/SQRT( 0.5)  (M)

SAT #  1  2  3  4  5  6  7  8  9

SATELLITE NO.

PERF. TIME

TIME OF WEEK (SEC)

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JULIAN DATE (DDD HH MM SS)

145 18 42 8  145 18 42 8  145 18 42 8  145 18 42 8  145 18 42 8  169 14 34 40

SEMI MAJOR AXIS (M)

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MEAN ANOMALY @ TREF (RADIANS) -0.21159856D+01  0.12833930D+01  0.38431182D+00  0.32879860D+00  0.17212573D+01  -0.91869770D+00

ECCENTRICITY

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ARG OF PERIGEE (RADIANS)

0.31187789D+01  0.10636910D+01  0.17242551D+01  0.13419558D+01  0.53818911D+01  0.14604583D+01

INCLINATION (RADIANS)

0.11355150D+01  0.11527150D+01  0.11196860D+01  0.11078800D+01  0.11036630D+01  0.10981785D+01

RIGHT ASCENSION (RADIANS)

-0.57891020D+00  -0.58888780D+00  -0.25814451D+01  -0.26417174D+01  -0.57803953D+00  0.31143453D+01

RATE OF RA (RADIANS/SEC)

-0.62431171D-09  -0.61311560D-08  -0.62059780D-08  -0.63774079D-08  -0.62173999D-08  -0.62288299D-08

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DAY HH MM EL AZ LAT LONG EL AZ LAT LONG EL AZ LAT LONG EL AZ LAT LONG EL AZ LAT LONG

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**Options Used for this Run**

- **Code**: C/A
- **Loran**: C

**Davis Strait**

**GPS Performance Pre-Analysis**

**Latitude**: 65.0330

**Longitude**: 390.3000
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GPS PERFORMANCE PRE-ANALYSIS

LATITUDE = 55.0000
LONGITUDE = 295.0000

OPTIONS USED FOR THIS RUN

CODE : C/A
SIGMA PSEUDO-RANGE = 16.00 (M)
SIGMA LORAN-RANGE = 100/SQRT(0.5) (M)

LABRADOR

C/A - Code
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GPS Performance Pre-Analysis

Lat: 55.0000
Long: 295.0000

Options Used for This Run

Code: C/A

Sigma Pseudo-Range = 16.00 (M)

Sigma Loran-Range = 100/Sqrt(0.5) (M)

Labradur

C/A - Code
Loran - C