General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)
LONG PERIOD PERTURBATIONS OF EARTH SATELLITE ORBITS

ANALYTICAL AND COMPUTATIONAL MATHEMATICS, INC.
LONG PERIOD PERTURBATIONS
OF
EARTH SATELLITE ORBITS

BY
K.C. WANG

ANALYTICAL AND COMPUTATIONAL ANALYSIS, INC.
1275 SPACE PARK DRIVE, SUITE 114
HOUSTON, TEXAS 77058
JANUARY 1979

This report was prepared for the NASA/Johnson Space Center under Contract #15445.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 INTRODUCTION</td>
<td>5</td>
</tr>
<tr>
<td>2.0 METHOD OF SOLUTION</td>
<td>7</td>
</tr>
<tr>
<td>2.1 Notation</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Solution Algorithm</td>
<td>8</td>
</tr>
<tr>
<td>3.0 EQUATIONS FOR ELIMINATION OF LONG PERIODIC TERMS AND ANALYTICAL INTEGRATION OF PRIMED VARIABLES</td>
<td>11</td>
</tr>
<tr>
<td>3.1 Generating Function $S^*$</td>
<td>11</td>
</tr>
<tr>
<td>3.2 Derivatives of $S^*_1$</td>
<td>13</td>
</tr>
<tr>
<td>3.3 Derivatives of $F''_2$ with Respect to $DS\phi$ Elements</td>
<td>16</td>
</tr>
<tr>
<td>4.0 CONCLUSIONS</td>
<td>19</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>21</td>
</tr>
<tr>
<td>APPENDIX - COMPUTATIONAL PROCEDURE</td>
<td>23</td>
</tr>
</tbody>
</table>
LONG PERIOD PERTURBATIONS
OF
EARTH SATELLITE ORBITS
by
K.C. Wang

1.0 INTRODUCTION

In reference 1, Scheifele and Graf introduced a complete first order solution for the orbital motion of a satellite perturbed by earth oblateness. This solution was expressed in the DSO elements. In reference 2, Bond and Scheifele expressed the first order short period and secular $J_2$ solution in the non-singular PSO elements. This theory was implemented in an operational computer program named ASOP described in reference 3. In references 4 and 5, the PSO analytical theory was updated to include the drag effects. In reference 6, the theory was developed to account for the time dependent gravitational harmonics. The drag and time dependent geopotential terms have also been included in ASOP.

Bond also extended the PSO theory to include the first order long period terms and second order secular perturbations due to $J_2$, $J_3$, $J_4$ and $J_5$. However, no documentation of the equations was ever published. In reference 7, Mueller developed a recursive theory to include the first order long period terms and second order secular perturbations due to zonal harmonics of any order. Mueller's theory plus the second order $J_2$ theory developed by Bond have now been implemented in ASOP.
The purpose of this report is to document all the equations involved in extending the \( \Phi \) solution to include the long periodic and second order secular effects of the zonal harmonics.
2.0 METHOD OF SOLUTION

2.1 Notation

The DSN elements are a set of eight variables which have the following description:

Angle Elements:
- \( \alpha_1 = \phi \) true anomaly
- \( \alpha_2 = g \) argument of pericenter
- \( \alpha_3 = h \) longitude of ascending node
- \( \alpha_4 = \ell \) time element

Action Elements:
- \( \beta_1 = \phi \) related to two body energy
- \( \beta_2 = G \) total angular momentum
- \( \beta_3 = H \) z-component of the angular momentum
- \( \beta_4 = L \) total energy

These may be canonically transformed to the PSN elements by the following relations:

\[
\begin{align*}
\sigma_1 &= \phi + g + h \\
\sigma_2 &= -\sqrt{2(\phi - G)} \sin (g + h) \\
\sigma_3 &= -\sqrt{2(G - H)} \sin (h) \\
\sigma_4 &= \nu \\
\rho_1 &= \phi \\
\rho_2 &= \sqrt{2(\phi - G)} \cos (g + h) \\
\rho_3 &= \sqrt{2(G - H)} \cos (h) \\
\rho_4 &= L
\end{align*}
\]
The DSO Hamiltonian for the zonal oblateness problem is given by:

\[ F = F_0 + \varepsilon F_1 + \varepsilon^2 F_2 \]  

where

\[ F_0 = \phi - \frac{\mu}{2\sqrt{2L}} \quad \text{(two body contributions)} \]

\[ F_1 = \frac{1}{qr} \left( \frac{x_3^2}{r} - \frac{1}{3} \right) \quad \text{(J}_2\text{ contribution)} \]

\[ F_2 = \frac{1}{q} \sum_{n=3}^{N} \frac{\mathbf{J}_n}{r^{n-1}} \mathbf{P}_n \left( \frac{x_3}{r} \right) \quad \text{(higher zonal harmonics)} \]

\[ \varepsilon = \frac{3}{2} \frac{J_2^{\text{obl}}}{R_e} \]

\( \mathbf{P}_n \) are the Legendre polynomials, \( R_e \) is the mean equatorial radius of earth, and \( J_2 \) and \( \mathbf{J}_n \) are oblateness coefficients.

2.2 Solution Algorithm

Von Zeipel's method of elimination of the short and long periodic terms is used. The solution first requires the transformation to eliminate the short periodic terms due to \( J_2 \). The generating function is assumed to be of the form

\[ S = S_0 + \varepsilon S_1 \]

\( S_0 \) give the identity transformation, \( S_1 \) is so chosen that the new Hamiltonian is no longer a function of short period variable \( \phi \). The Hamiltonian has the form

\[ F'(\beta', \gamma') = F_0' + \varepsilon F_1' + \varepsilon^2 F_2' \]

A more thorough discussion of the elimination of short periodic terms can be found in reference 2.

An additional transformation must be made to eliminate the long periodic terms from \( F' \). This transformation is defined by the generating function

\[ S^* = S_0^* + \varepsilon S_1^* \]
Again, $S^*_0$ gives the identity transformation, $S^*_1$ is chosen such that the long period variable $g'$ is eliminated from the Hamiltonian. The new Hamiltonian has the form

$$F''(\beta') = F'_0 + \varepsilon F'_1 + \varepsilon^2 F'_2$$

A more thorough discussion of the elimination of the $J_2$ and higher order zonal perturbation long periodic terms can be found in references 1 and 7.

The solution algorithm can be divided into three steps:

1. Initialize the primed variables

   $$\sigma'_{k,0} = \sigma_{k,0} + \varepsilon \left( \frac{\partial S'_1}{\partial \sigma'_{k,0}} + \frac{\partial S'_2}{\partial \sigma'_{k,0}} \right)$$

   $$\rho'_{k,0} = \rho_{k,0} - \varepsilon \left( \frac{\partial S'_1}{\partial \sigma'_{k,0}} + \frac{\partial S'_2}{\partial \sigma'_{k,0}} \right)$$

   (3)

2. Analytical integration of primed variables

   $$\sigma'_1 = \sigma'_{1,0} + A_1 \tau$$
   $$\sigma'_2 = \sigma'_{2,0} \cos(A_2 \tau) - \rho'_{2,0} \sin(A_2 \tau)$$
   $$\sigma'_3 = \sigma'_{3,0} \cos(A_3 \tau) - \rho'_{3,0} \sin(A_3 \tau)$$
   $$\sigma'_4 = \sigma'_{4,0} + A_4 \tau$$

   $$\rho'_1 = \rho'_{1,0}$$
   $$\rho'_2 = \rho'_{2,0} \cos(A_2 \tau) + \sigma'_{2,0} \sin(A_2 \tau)$$
   $$\rho'_3 = \rho'_{3,0} \cos(A_3 \tau) + \sigma'_{3,0} \sin(A_3 \tau)$$
   $$\rho'_4 = \rho'_{4,0}$$

(4)

The definitions of $A_1$, $A_2$, $A_3$, $A_4$ are given in section 3.0 of this report. The relation between time $t$ and the new independent variable $\tau$ is given by $\frac{dt}{d\tau} = r^2/q$, the definition of $q$ is also given in section 3.0.
(3) Back transformation

\begin{align*}
\sigma_k &= \sigma'_k - \epsilon \left( \frac{\partial S}{\partial \rho_k} + \frac{\partial S^*}{\partial \rho_k} \right) \\
\rho_k &= \rho'_k + \epsilon \left( \frac{\partial S}{\partial \sigma_k} + \frac{\partial S^*}{\partial \sigma_k} \right)
\end{align*}

k = 1, 2, 3, 4
3.0 EQUATIONS FOR ELIMINATION OF LONG PERIODIC TERMS AND ANALYTICAL INTEGRATION OF PRIMED VARIABLES

A detailed description of generating function $S_1^*$ and derivatives of $S_1^*$ with respect to the PS\$ elements can be found in Appendix F of Reference 3. In this section a detailed description of generating function $S_1^*$ and derivatives of $S_1^*$ with respect to the PS\$ elements will be given. The derivatives of $F''_2$ with respect to the DS\$ elements will also be given.

3.1 Generating Function $S_1^*$

From Reference 1 we have:

$$S_1^* = \frac{1}{2F_1} \left[ \hat{S} - \frac{1}{2} \frac{f^2}{48} (2 - 3b + 6B)e^{2b} \sin(2g) \right]$$

(6)

$\hat{S}$ are terms related to higher order zonal perturbations. A detailed description of $\hat{S}$ can be found in reference 7.

Now we introduce $\sin(g)$ and $\cos(g)$

$$\sin(g) = \frac{1}{CD} (\sigma_6 \sigma_3 - \sigma_7 \sigma_2)$$
$$\cos(g) = \frac{1}{CD} (\sigma_6 \sigma_7 + \sigma_2 \sigma_3)$$

(7)

where

$$C = \sqrt{2(\Phi - G)}$$
$$D = \sqrt{2(G - H)}$$

To write $S_1^*$ in terms of PS\$ elements we introduce the following abbreviations

$$Q = \frac{\sigma_8}{2} \left[ \frac{2\mu}{\sqrt{2\sigma_8}} - \frac{1}{2} (\sigma_2^2 + \sigma_6^2) \right]^{\frac{1}{2}}$$

(8)

$$p = \frac{1}{\mu} \left[ - \frac{1}{2} (\sigma_2^2 + \sigma_6^2) + \frac{\nu}{\sqrt{2\sigma_8}} \right]^2$$

(9)

$$e = (1 - \frac{2\sigma_8}{\mu} p) = QD$$

(10)
\[ b = 1 - \frac{G^2}{H^2} \]  
\[ x = e^{b\tau} \sin(g) = \frac{1}{2} \frac{Q}{G} \sqrt{2(G + H)} \left( \sigma_6 \sigma_3 - \sigma_7 \sigma_2 \right) \]  
\[ \psi = e^{b\tau} \cos(g) = \frac{1}{2} \frac{Q}{G} \sqrt{2(G + H)} \left( \sigma_6 \sigma_7 + \sigma_2 \sigma_3 \right) \]  
\[ \Theta = e^{2b\tau} \sin(2g) = 2x\psi \]  

Now we have
\[ S_1^* = \frac{1}{\beta F} \left[ \Theta - \frac{1}{2} \frac{f^2}{48} \left( 2 - 3b + 6qB \right) \right] \]  

where
\[ q = -\frac{1}{2} \left( \sigma_6^2 + \sigma_2^2 - \sigma_5 \right) + \frac{1}{\sqrt{2\sigma_8}} \]  
\[ f = \frac{1}{p\mu} \]  
\[ B = \frac{2H^2}{G^3} \]  
\[ \frac{\beta F}{\beta G} = \frac{1}{2} f \left( \frac{2}{\mu} qd + p \right) \left( \frac{2}{3} - b \right) + B \]  

and
\[ d = (p\mu)^{\frac{1}{2}} \]  

Let
\[ T_a = -\frac{1}{2} \frac{f^2}{48} \]  
\[ T_b = (2 - 3b + 6qB)T_a \]  
\[ T_c = \Theta T_b \]  
\[ T = S + T_c \]  

then
\[ S_1^* = \left( \frac{\beta F}{\beta G} \right) q \]
3.2 Derivatives of $S^*$

Let

$$S^*_{1k} = \frac{\partial S^*}{\partial \sigma_k}, \quad k = 1, 2, 3, \ldots, 8$$

From now on the subscript $k$ represents partial derivatives with respect to the 8 PS elements, unless otherwise specified.

- $S^*_{1k} = - \frac{1}{(\beta F^*_1 G^*_1)} q \left\{ T \left[ \frac{2F^*_1}{\partial G^*_1} k + \frac{q_k}{q} \right] - T_k \right\}$ (23)

- $$(\frac{\partial F^*_1}{\partial G^*_1})_k = \frac{f_k + \frac{1}{2} \left[ f \left( \frac{2q_x^2 + p}{\mu} \right) \left( \frac{2}{3} - b \right) + B \right] + \frac{f}{2} \left[ B_k - f \left( \frac{2q_x^2 + p}{\mu} \right) b_k \right] + f \left( \frac{2}{3} - b \right) p_k + f \left( \frac{2}{3} - b \right) \frac{2}{\mu} (dq_k + qd_l) \right\}$$ (24)

- $T_k = \left( \frac{\partial S^*_s}{\partial p} - \frac{2}{p} T_c \right) p_k + \left( \frac{\partial S^*_s}{\partial b} - 3T_a \right) b_k + \frac{\partial S^*_s}{\partial x} a^2_k + \left( \frac{\partial S^*_s}{\partial \psi} + 2T_b \right) \psi_k + \left( \frac{\partial S^*_s}{\partial \psi} + 2T_b \right) \psi_k - \left( \frac{2}{|q|} T_c - 6BT_a \right) q_k + 6T_a q0B_k$ (25)

- $p_k = 0$ for $k = 1, 3, 4, 5, 7$

$$p_2 = -2 \frac{\sqrt{\mu p}}{\mu} \sigma_2$$ (26)

$$p_6 = -2 \frac{\sqrt{\mu p}}{\mu} \sigma_6$$

$$p_8 = -2 \frac{\sqrt{\mu p}}{\left(2\sigma_j\right)^{3/2}}$$

- $q_k = 0$ for $k = 1, 3, 4, 6, 7$

$$q_2 = -\sigma$$

$$q_5 = \frac{1}{2} \sigma^2$$

$$q_8 = -\frac{\mu}{2} \frac{1}{\left(2\sigma_j\right)^{3/2}}$$ (27)
\[ G_k = 0 \quad \text{for } k = 1, 3, 4, 7, 8 \quad (28) \]
\[ G_2 = -\sigma_2 \]
\[ G_5 = 1 \]
\[ G_6 = -\sigma_6 \]

\[ H_k = G_k \quad \text{for } k = 1, 2, 4, 5, 6, 8 \quad (29) \]
\[ H_3 = -\sigma_3 \]
\[ H_7 = -\sigma_7 \]

\[ f = -f \left( \frac{p_k}{p} + \frac{q_k}{q} \right) \quad (30) \]

\[ b_k = -\frac{2H_k}{G^2} \left( H_k - \frac{H}{G} G_k \right) \quad (31) \]

\[ d_k = \frac{1}{2} \left( \frac{\mu}{\nu} \right)^{\frac{1}{2}} p_k \quad (32) \]

\[ B_k = \frac{H_k}{G^3} \left( 4H_k - \frac{H}{G} G_k \right) \quad (33) \]

\[ e_k = -2\sigma_8 \mu \nu_k \quad \text{for } k = 1, 2, 3, 4, 5, 6, 7 \quad (34) \]
\[ e_8 = -2\sigma_8 \mu + 2\mu \]

\[ \chi_k = (\sigma_6 \sigma_2 - \sigma_7 \sigma_2) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_k - \frac{Q}{G} G_k + \frac{Q}{2(G + H)} (G_k + H_k) \right] \]
\[ k = 4, 5, 8 \quad (35) \]

\[ \chi_2 = (\sigma_6 \sigma_2 - \sigma_7 \sigma_2) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_2 - \frac{Q}{G} G_2 + \frac{Q}{2(G + H)} (G_2 + H_2) \right] \]
\[ - \sigma_2 \frac{\sqrt{2(G + H)}}{2G} \]

\[ \chi_3 = (\sigma_6 \sigma_3 - \sigma_7 \sigma_2) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_3 - \frac{Q}{G} G_3 + \frac{Q}{2(G + H)} (G_3 + H_3) \right] \]
\[ + \sigma_6 \frac{Q}{2G} \frac{\sqrt{2(G + H)}}{2G} \]
\[
\chi_6 = (\sigma_6 \sigma_3 - \sigma_7 \sigma_2) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_6 - \frac{Q}{G} G_6 + \frac{Q}{2(G + H)} (G_6 + H_6) \right] \\
+ \frac{\sigma_3 Q \sqrt{2(G + H)}}{2G}
\]

\[
\chi_7 = (\sigma_6 \sigma_3 - \sigma_7 \sigma_2) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_7 - \frac{Q}{G} G_7 + \frac{Q}{2(G + H)} (G_7 + H_7) \right] \\
- \frac{\sigma_2 Q \sqrt{2(G + H)}}{2G}
\]

\[
\psi_k = (\sigma_6 \sigma_7 + \sigma_2 \sigma_3) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_k - \frac{Q}{G} G_k + \frac{Q}{2(G + H)} (G_k + H_k) \right] \\
k = 1, 4, 5, 8 (36)
\]

\[
\psi_2 = (\sigma_6 \sigma_7 + \sigma_2 \sigma_3) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_2 - \frac{Q}{G} G_2 + \frac{Q}{2(G + H)} (G_2 + H_2) \right] \\
+ \frac{\sigma_3 Q \sqrt{2(G + H)}}{2G}
\]

\[
\psi_3 = (\sigma_6 \sigma_7 + \sigma_2 \sigma_3) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_3 - \frac{Q}{G} G_3 + \frac{Q}{2(G + H)} (G_3 + H_3) \right] \\
+ \frac{\sigma_2 Q \sqrt{2(G + H)}}{2G}
\]

\[
\psi_6 = (\sigma_6 \sigma_7 + \sigma_2 \sigma_3) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_6 - \frac{Q}{G} G_6 + \frac{Q}{2(G + H)} (G_6 + H_6) \right] \\
+ \frac{\sigma_2 Q \sqrt{2(G + H)}}{2G}
\]

\[
\psi_7 = (\sigma_6 \sigma_7 + \sigma_2 \sigma_3) \frac{\sqrt{2(G + H)}}{2G} \left[ Q_7 - \frac{Q}{G} G_7 + \frac{Q}{2(G + H)} (G_7 + H_7) \right] \\
+ \frac{\sigma_6 Q \sqrt{2(G + H)}}{2G}
\]
The partial derivatives of $\hat{S}$ with respect to $p, b, e^2,$ $\psi$ and $\chi$ can be found in Reference 3.

3.3 Derivative of $F_2''$ with Respect to DSΦ Elements

From Reference 1, one can find that

$$F_2'' = \frac{f^2}{288} \delta + \frac{\hat{H}}{\epsilon}$$

(37)

$$\delta = \frac{e^2}{q} (-3b^2 + 24b - 8) + 18 \frac{b^2}{q} - \frac{1}{\mu} d \left( \frac{e^2}{p} + \frac{L}{\mu} \right)$$

(38)

$$(60b^2 - 96b + 32) - 3b(24u^2 + 36)$$

$\hat{H}$ is the Hamiltonian of higher harmonics, see Reference 7 for detailed description. Because the new Hamiltonian is a function of only action DSΦ elements, from now on the subscript $k$ represents partial derivative with respect to those DSΦ action elements.

$$\delta_k = \frac{1}{q^2} \left[ (e_k^2 q - e_k q_k)(-3b^2 + 24b - 8) + \frac{e^2}{q} (-6b + 24)b_k \right]$$

$$+ \frac{36b}{q^2} (b_k q - \frac{b q_k}{2}) - \frac{1}{\mu} \left\{ (d_k (e_k^2 p + \frac{L}{\mu}) + d_k^2 (\frac{e^2 p}{p^2} - \frac{e_k^2 p}{p^2})) \right\}$$

$$+ \frac{L_k}{\mu} \right\} (60b - 96b + 32) + d_k \left( \frac{e^2}{p} + \frac{L}{\mu} \right) (120b_k - 96b_k)$$

(39)

$$- (24c^2 + 36) (B_k b + \bar{u} b_k) - 24c^2 B_b$$

where

$$B_1 = 0$$

$$B_2 = -\frac{6H^2}{G^4}$$

$$B_3 = \frac{4H}{G^3}$$

$$B_4 = 0$$

(40)
\[ d_1 = -1. \]
\[ d_2 = 1. \]
\[ d_3 = 0. \]
\[ d_4 = -\mu(2L)^{-3/2} \]  
(41)
\[ p_1 = -2(p_\mu)^4 \]
\[ p_2 = -p_1 \]
\[ p_3 = 0. \]
\[ p_4 = -2(p_\mu)^4(2L)^{-3/2} \]  
(42)
\[ e_1^2 = -\frac{2L}{\mu} p_1 \]
\[ e_2^2 = -e_1^2 \]
\[ e_3^2 = 0. \]
\[ e_4^2 = -\frac{2}{\mu}(p + Lp_4) \]  
(43)
\[ q_1 = -0.5 \]
\[ q_2 = 1.0 \]
\[ q_3 = 0. \]
\[ q_4 = -0.5\mu(2L)^{-3/2} \]  
(44)
\[ b_1 = 0 \]
\[ b_2 = \frac{2}{G} \left( \frac{H}{G} \right)^2 \]
\[ b_3 = -\frac{2}{G} \left( \frac{H}{G} \right) \]  
(45)
\[ b_4 = 0. \]
\[ L_1 = 0 \]
\[ L_2 = 0 \]
\[ L_3 = 0 \]
\[ L_4 = 1 \]  
(46)
\[ F''_{2k} = \frac{e}{288} (2f_k \delta + f \delta_k) + \frac{1}{q} \left( \frac{\hat{H}_k}{q} - \frac{q_k}{q} \frac{\hat{H}}{q} \right) \]  
\[ \hat{H}_k = \frac{3H_k}{3p} p_k + \frac{3H_k}{3e} e_k^2 + \frac{3H_k}{3b} b_k \]  

where

\[ f_1 = \frac{e^2}{\mu} \left( \frac{1}{2} \mu p + 2q \sqrt{\mu p} \right) \]
\[ f_2 = -\frac{e^2}{\mu} \left( \mu p + 2q \sqrt{\mu p} \right) \]
\[ f_3 = 0 \]
\[ f_4 = -\frac{e^2}{(2q)^{3/2}} \left( \frac{1}{2} \mu p + 2q \sqrt{\mu p} \right) \]  

Now the abbreviations \( A_1, A_2, A_3, A_4 \) in the expressions of analytical integration will be given:

\[ A_4 = \frac{e}{2} f_4 \left( b - 2/3 \right) + \mu(2L)^{-3/2} + \frac{e^2}{288} f \left( 2f_4 \delta + f \delta_4 \right) \]
\[ + \frac{e^2}{q} \left( \frac{\hat{H}_4}{q} - \frac{q_4}{q} \frac{\hat{H}}{q} \right) \]  
\[ A_3 = \frac{e}{2} fb_3 + \frac{e^2}{288} f^2 \delta_3 + \frac{e^2}{q} \left( \frac{\hat{H}_3}{q} - \frac{q_3}{q} \frac{\hat{H}}{q} \right) \]  
\[ A_2 = \frac{e}{2} \left[ f_2 \left( b - 2/3 \right) + fb_2 \right] + \frac{e^2}{288} f \left( 2f_2 \delta + f \delta_2 \right) \]
\[ + \frac{e^2}{q} \left( \frac{\hat{H}_2}{q} - \frac{q_2}{q} \frac{\hat{H}}{q} \right) + A_3 \]  
\[ A_1 = 1 + \frac{e}{2} f_1 \left( b - 2/3 \right) + \frac{e^2}{288} f \left( 2f_1 \delta + f \delta_1 \right) \]
\[ + \frac{e^2}{q} \left( \frac{\hat{H}_1}{q} - \frac{q_1}{q} \frac{\hat{H}}{q} \right) + A_2 \]  

\( f_1, f_2, f_3, f_4 \) are defined in the text.
4.0 CONCLUSIONS

The equations described in this report have been implemented into the ASOP program. The program has been checked out and verified with results documented in reference 8. Comparisons with numerical integrations show the long period theory to be accurate to within several meters after 800 revolutions. The extension of ASOP to include the long period terms, allows the solution to maintain a high degree of accuracy even for extremely long prediction intervals.
REFERENCES


APPENDIX

COMPUTATIONAL PROCEDURE

The computational procedure for elimination of long periodic terms and analytical integration of primed variables are described below. First subroutine \textsc{LONGPP}(NN) (long period perturbations) is called with parameter 0, it will return initialized primed variable. During the procedure subroutine \textsc{DETERM} is called to compute terms related to the higher order harmonics. Then subroutine will be called again with parameter 1, this time it will return the partial derivatives of primed Hamiltonian with respect to the DS\$ elements. During the procedure subroutine \textsc{FPRIME} is called to compute derivatives of higher order harmonics. The sequence of computation will be given below. The left column gives the quantity to be computed, and the right column references the equation number in the text.

\begin{tabular}{l|l}
\textbf{LONGPP(0)} & \\
\hline
Computing Sequence & From Equation \\
\textbf{d} & \textbf{(20)} \\
\textbf{B} & \textbf{(18)} \\
\textbf{e} & \textbf{(10)} \\
\textbf{\frac{\partial F_1}{\partial G}} & \textbf{(19)} \\
\textbf{\chi} & \textbf{(12)} \\
\textbf{\psi} & \textbf{(13)} \\
\textbf{\hat{S}_k} & \textbf{(14)} \\
\textbf{f_k} & \textbf{(30)} \\
\textbf{b_k} & \textbf{(31)} \\
\textbf{d_k} & \textbf{(32)} \\
\hline
\end{tabular}
Computing Sequence (continued)  

\[ B_k \]
\[ e_k^2 \]
\[ \left( \frac{\partial F_1}{\partial G} \right)_k \]
\[ \chi_k \]
\[ \psi_k \]
\[ T_k \]
\[ S_{1k} \]
\[ \sigma'(0), \rho'(0) \]

LONGPP(1)

\[ d \]
\[ B \]
\[ e \]
\[ B_k \]
\[ d_k \]
\[ p_k \]
\[ e_k^2 \]
\[ q_k \]
\[ \hat{H}_k \]
\[ \delta_k \]
\[ F_{2k}'' \]
\[ A_1, A_2, A_3, A_4 \]

From Equation (continued)

(33)
(34)
(24)
(35)
(36)
(25)
(23)
(3)

subroutine FPRIME

(39)
(47)
(50) - (53)