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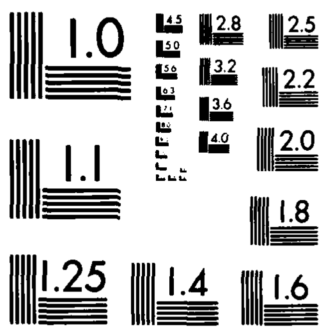

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FOREWORD

Series expansion formulae have been applied to the Gaussian form of the Lagrange planetary equations in order to develop a compact formalism that represents satellite drag perturbations produced by an exponentially varying atmospheric density distribution. The compact result lends itself to facile manipulation, either manually by the user or automatically by the electronic computer. This document has been reviewed and approved by R. W. Hill.

Released by:

T. A. CLARE, Head
Strategic Systems Department

CONTENTS

TABLE

INTRODUCTION

In recent years, much attention has been devoted to the analytic representation of artificial satellite aerodynamic disturbances produced by the earth's atmosphere[1-6]. Such representations tend to generally address satellite orbits in the small eccentricity regime (e.g. $e \lesssim .2$), so that truncated expansions about the eccentricity can be used to simplify the complicated perturbation equations. Quite satisfactory results are produced in this way for a variety of assumed atmospheric density structures.

This report has been prepared to demonstrate that when one is concerned with an exponentially varying atmospheric density distribution, the aerodynamic perturbation equations can be written in a compact form without resorting to series truncation. This formalism lends itself to computational expediency, especially for applications using the electronic computer, and allows the user to readily inflate the expressions to any desired order in the orbital eccentricity.

The following sections of this report discuss in detail the derivation of this compact formalism. The Gaussian form of the planetary equations and their preliminary manipulation into a more utilizable configuration are presented in the next section. The operations used in the expansion process of the derivation are then discussed and, in the following section, are applied to the reconfigured planetary equations to yield the desired results.

THE VARIATION OF THE ELEMENTS

The Gaussian form of the equations describing the variation of the Keplerian element set a, e, i, ω, and Ω are well known and given by[7]

$$\dot{a} = 2a^2\left(\frac{v}{\mu}\right)F_I \tag{1}$$

$$\dot{e} = \left(\frac{\sqrt{1 - e^2}\sin E}{v}\right) F_R + \frac{2}{v}\left(\frac{\cos E}{1 - e\cos E}\right) F_I \tag{2}$$

$$(i)^{\cdot} = \left(\frac{r \cos u}{h}\right) F_C \tag{3}$$

$$\dot{\Omega} = \frac{r \sin u}{h}\left(\frac{1}{\sin i}\right) F_C \tag{4}$$

and

$$\dot{\omega} = -\left(\frac{\cos E + e}{ev}\right) F_R + 2\,\frac{\sqrt{1 - e^2}}{ev}\left(\frac{\sin E}{1 - e \cos E}\right) F_I - \dot{\Omega}\cos i \tag{5}$$

where u is the true argument of latitude defined as

$$u = \theta + \omega \tag{6}$$

θ is the true anomaly, and E is the eccentric anomaly. The quantities r, v, and h are the satellite radial distance, speed, and angular momentum, respectively, and are given by the following expressions:

$$r = a(1 - e \cos E) \tag{7}$$

$$v = \left(\frac{\mu}{a}\right)^{\frac{1}{2}} \left(\frac{1 + e\cos E}{1 - e \cos E}\right)^{\frac{1}{2}} \tag{8}$$

and

$$h = [\mu a(1 - e^2)]^{\frac{1}{2}} \tag{9}$$

where μ is the earth's gravitational constant.

The acceleration components $F_i (i = R, I, C)$ appearing in the Gaussian equations are defined by the vector equation

$$\vec{F} = F_R \hat{R} + F_I \hat{I} + F_C \hat{C} \tag{10}$$

where

$$\hat{C} = \frac{\vec{r} \times \dot{\vec{r}}}{|\vec{r} \times \dot{\vec{r}}|} \tag{11}$$

$$\hat{I} = \frac{\dot{\vec{r}}}{|\dot{\vec{r}}|} \tag{12}$$

and

$$\hat{R} = \hat{I} \times \hat{C} \tag{13}$$

Here $\vec{r}$ and $\dot{\vec{r}}$ are the satellite position and velocity vectors.

The drag force $\vec{F}_D$ per unit satellite mass can be well represented by the equation

$$\vec{F}_D = -\frac{C_D A}{2m} \rho V_A \vec{V}_A \tag{14}$$

where C_D is the drag coefficient, A is the effective cross sectional area of the satellite normal to the direction of motion, m is the satellite mass, ρ is the local atmospheric density, and $\vec{V}_A$ is the relative velocity given by

$$\vec{V}_A = \vec{V} - \vec{V}_a \tag{15}$$

this expression, $\vec{V}$ is the satellite velocity and $\vec{V}_a$ is the atmospheric rotational locity. To a very good approximation the atmospheric drag acceleration components n be expressed as[7]

$$F_R = -\frac{C_D A}{2m}\alpha\left(\frac{a^5}{\mu}\right)^{\frac{1}{2}} e\rho V\omega_e \cos i \sin E \frac{(1 - e\cos E)^{\frac{3}{2}}}{(1 + e\cos E)^{\frac{1}{2}}}\dot{E} \qquad (16)$$

$$F_I = -\frac{C_D A}{2m}\alpha a\rho V(1 + e\cos E)^{\frac{1}{2}}(1 - e\cos E)^{\frac{1}{2}}\dot{E} \qquad (17)$$

$$F_C = -\frac{C_D A}{2m}\alpha\left(\frac{a^5}{\mu}\right)^{\frac{1}{2}}\rho V\omega_e \sin i(1 - e\cos E)^2 \cos u\, E \qquad (18)$$

ıere ω_e is the earth's angular rotation rate and

$$\alpha = 1 - \left[\frac{a^3(1 - e^2)}{\mu}\right]^{\frac{1}{2}}\omega_e \cos i \qquad (19)$$

Assume now that the atmospheric density varies exponentially with r and has ıe form

$$\rho = \rho_p \exp[\beta(r_p - r)]$$

.

$$\rho = \rho_p \exp[-\beta ae + \beta ae\cos E] \qquad (20)$$

ıere ρ_p is the local atmospheric density at perigee and β is the inverse density :ale height that is assumed to be constant. Using Equations (7), (8), (9), (16), .7), (18), and (20) along with the identities

$$\cos^2 u \equiv \sin^2\omega + \cos 2\omega\left(\frac{\cos E - e}{1 - e\cos E}\right)^2 - (1 - e^2)^{\frac{1}{2}}\sin 2\omega\frac{\sin E(\cos E - e)}{(1 - e\cos E)^2} \qquad (21)$$

$$\sin u \cos u \equiv -\sin \omega \cos \omega + \sin 2\omega \left(\frac{\cos E - e}{1 - e \cos E}\right)^2$$

$$+ (1 - e^2)^{\frac{1}{2}} \cos 2\omega \frac{\sin E (\cos E - e)}{(1 - e \cos E)^2} \qquad (22)$$

in Equations (1) through (5), one finds that after much algebraic manipulation the Gaussian equations for the variation of the elements can be cast into the following forms:

$$\frac{da}{dE} = -\lambda a^2 \exp[\beta ae \cos E](1 - e^2 \cos^2 E)^{-\frac{1}{2}} (1 + 2e \cos E + e^2 \cos^2 E) \qquad (23)$$

$$\frac{de}{dE} = -\frac{\lambda}{2} \exp[\beta ae \cos E](1 - e^2 \cos^2 E)^{-\frac{1}{2}} \Bigg\{ e(1 - e^2)^{\frac{1}{2}} \omega_e \cos i \left(\frac{a^5}{\mu}\right)^{\frac{1}{2}} \bullet$$

$$\left[1 - 2e \cos E - (1 - e^2) \cos^2 E + 2e \cos^3 E - e^2 \cos^4 E\right]$$

$$+ 2a\left[\cos E + e \cos^2 E\right]\Bigg\} \qquad (24)$$

$$\frac{di}{dE} = -\frac{\lambda}{2} \omega_e \sin i \left[\frac{a^5}{\mu(1 - e^2)}\right]^{\frac{1}{2}} \exp[\beta ae \cos E](1 - e^2 \cos^2 E)^{-\frac{1}{2}} \bullet$$

$$\Big\{(\sin^2 \omega + e^2 \cos 2\omega) - 2e(\sin^2 \omega + \cos 2\omega) \cos E$$

$$+ (1 - e^4) \cos 2\omega \cos^2 E + 2e^3(\cos 2\omega + \sin^2 \omega) \cos^3 E$$

$$- e^2(\cos 2\omega + e^2 \sin^2 \omega) \cos^4 E + (1 - e^2)^{\frac{1}{2}} \sin 2\omega \sin E \bullet$$

$$(e - \cos E - e^3 \cos^2 E + e^2 \cos^3 E)\Big\} \qquad (25)$$

$$\frac{d\Omega}{dE} = -\frac{\lambda}{2}\,\omega_e \left[\frac{a^5}{\mu(1-e^2)}\right]^{\frac{1}{2}} \exp[\beta ae\cos E](1-e^2\cos^2 E)^{-\frac{1}{2}} \bullet$$

$$\Big\{\sin\omega\cos\omega\big[(2e^2-1) - 2e\cos E + 2(1-e^4)\cos^2 E$$

$$+ 2e^3\cos^3 E + e^2(e^2-2)\cos^4 E\big] - (1-e^2)^{\frac{1}{2}}\cos 2\omega\sin E \bullet$$

$$\big[e - \cos E - e^3\cos^2 E + e^2\cos^3 E\big]\Big\} \tag{26}$$

$$\frac{d\omega}{dE} + \frac{d\Omega}{dE}\cos i = \frac{\lambda a}{2}\exp[\beta ae\cos E](1-e^2\cos^2 E)^{-\frac{1}{2}}\sin E \bullet$$

$$\left\{\left(\frac{a^3}{\mu}\right)^{\frac{1}{2}}\omega_e\cos i\big[e + (1-2e^2)\cos E - e(2-e^2)\cos^2 E\right.$$

$$\left. + e^2\cos^3 E\big] - \frac{2(1-e^2)^{\frac{1}{2}}}{e}(1+e\cos E)\right\} \tag{27}$$

re

$$\lambda = \frac{C_D A}{m}\,\alpha\rho_o \exp[-\beta ae] \tag{28}$$

Finally, in order to obtain the changes produced in the orbital elements atmospheric drag during one orbital revolution, Equations (23) through (27) be integrated with respect to E over 2π radians; i.e.,

$$\begin{pmatrix}\Delta a\\ \Delta e\\ \Delta i\\ \Delta\Omega\\ \Delta\omega\end{pmatrix}_{DRAG} = \int_0^{2\pi}\frac{d}{dE}\begin{pmatrix}a\\ e\\ i\\ \Omega\\ \omega\end{pmatrix}dE \tag{29}$$

INTEGRAND EXPANSION AND THE $J_{n,k}$ FUNCTION

In this section, a novel method will be used to provide expansion formulae for Equation (29). As can be seen, the right-hand side of this equation is composed of sums of integrals of the form

$$R_n(\beta ae) = \int_0^{2\pi} \exp[\beta ae \cos E](1 - e^2 \cos^2 E)^{-\frac{1}{2}} \cos^n E \, dE \tag{30}$$

The radical appearing in the integrand of R_n can readily be expanded using the Legendre polynomial generating function[8]

$$(1 - 2tx + t^2)^{-\frac{1}{2}} = \sum_{k=0}^{\infty} t^k P_k(x) \tag{31}$$

if one lets

$$x = 0 \tag{32}$$

and

$$t = ie \cos E \quad (i = \sqrt{-1}) \tag{33}$$

The $P_k(x)$ in Equation (31) is the Legendre polynomial.

When Equations (32) and (33) are used, then

$$\cos^n E(1 - e^2 \cos^2 E)^{-\frac{1}{2}} = \sum_{k=0}^{\infty} \binom{2k}{k} \left(\frac{e}{2}\right)^{2k} \cos^{2k+n} E \tag{34}$$

$$\binom{2k}{k} = \frac{(2k)!}{(k!)^2} \tag{35}$$

has been made of the equalities

$$P_\ell(0) = \begin{cases} \dfrac{(-1)^p}{2^\ell} \dbinom{2p}{p} & \text{for } \ell = 2p \\ 0 & \text{for } \ell = 2p + 1 \end{cases} \tag{36}$$

the relations[9]

$$\cos^{2k+n} E = \begin{cases} \left(\dfrac{1}{2^{2k+n}}\right) (2k+n)! \displaystyle\sum_{j=0}^{k+\frac{n}{2}} \dfrac{\varepsilon_j \cos(2jE)}{(k+j+\frac{n}{2})!(k-j+\frac{n}{2})!} & \text{for } n \text{ even} \\ \left(\dfrac{2}{2^{2k+n}}\right) (2k+n)! \displaystyle\sum_{j=0}^{k+\frac{n-1}{2}} \dfrac{\cos\left[(2j+1)E\right]}{(k+j+\frac{n+1}{2})!(k-j+\frac{n-1}{2})!} & \text{for } n \text{ odd} \end{cases} \tag{37}$$

is Neumann's number defined as

$$\varepsilon_j = \begin{cases} 1 & \text{for } j = 0 \\ 2 & \text{for } j \geq 1 \end{cases} \tag{38}$$

in Equation (34), one finds that Equation (30) may be written as

$$R_n(\beta ae) = \sum_{k=0}^{\infty} e^{2k} J_{n,k}(\beta ae) \tag{39}$$

In this expression,

$$J_{n,k}(\beta ae) = \frac{\pi(2k+n)!}{2^{4k+n-1}} \binom{2k}{k} \left\{ \Delta_{n,e} \sum_{j=0}^{k+\frac{n}{2}} \left[\frac{\varepsilon_j}{(k+j+\frac{n}{2})!(k-j+\frac{n}{2})!} \right] \cdot \right.$$

$$I_{2j}(\beta ae) + 2\Delta_{n,0} \sum_{j=0}^{k+\frac{n-1}{2}} \left[\frac{1}{(k+j+\frac{n+1}{2})!(k-j+\frac{n-1}{2})!} \right] \cdot$$

$$\left. I_{2j+1}(\beta ae) \right\} \tag{40}$$

where

$$\Delta_{n,e} = \begin{cases} 1 & \text{for even } n \\ 0 & \text{for odd } n \end{cases} \tag{41}$$

$$\Delta_{n,0} = \begin{cases} 1 & \text{for odd } n \\ 0 & \text{for even } n \end{cases} \tag{42}$$

and $I_m(\beta ae)$ is a Bessel function of the first kind and imaginary argument defined by

$$I_m(\beta ae) = \frac{1}{2\pi} \int_0^{2\pi} \exp\left[\beta ae \cos E\right] \cos(mE)\,dE \tag{43}$$

THE CONSUMMATIVE DRAG PERTURBATION EQUATIONS

It should be noted that those portions of the right-hand sides of Equations (25), (26), and (27) that contain sin E multipliers, will vanish from the right-hand side of Equation (29), since

$$\int_0^{2\pi} \exp[\beta ae \cos E] \cos^m E(1 - e^2 \cos^2 E)^{-\frac{1}{2}} \sin E \, dE = 0 \tag{44}$$

Thus, Equations (30) and (39) may be used to express Equations (23) through (29) in the following compact matrix form

$$\underset{\sim}{\Delta\varepsilon} = -\frac{\lambda}{2}\sum_{k=0}^{\infty}\sum_{n=0}^{4} e^{2k+n}\, \underset{\sim}{\mathfrak{C}}_n \underset{\sim}{\mathbb{J}}_{n,k} \tag{45}$$

where

$$\underset{\sim}{\Delta\varepsilon} \equiv \begin{pmatrix} \Delta a \\ \Delta e \\ \Delta i \\ \Delta\Omega \\ \Delta\omega \end{pmatrix}_{DRAG} \tag{46}$$

$$\underset{\sim}{\mathfrak{C}}_n \equiv \begin{pmatrix} \alpha_n^a & \beta_n^a & \gamma_n^a & \xi_n^a & \sigma_n^a \\ \alpha_n^e & \beta_n^e & \gamma_n^e & \xi_n^e & \sigma_n^e \\ \alpha_n^i & \beta_n^i & \gamma_n^i & \xi_n^i & \sigma_n^i \\ \alpha_n^\Omega & \beta_n^\Omega & \gamma_n^\Omega & \xi_n^\Omega & \sigma_n^\Omega \\ \alpha_n^\omega & \beta_n^\omega & \gamma_n^\omega & \xi_n^\omega & \sigma_n^\omega \end{pmatrix} \tag{47}$$

and

$$\underset{\sim}{\mathbb{J}}_{n,k} \equiv \begin{pmatrix} J_{n-2,k}(\beta ae) \\ J_{n-1,k}(\beta ae) \\ J_{n,k}(\beta ae) \\ J_{n+1,k}(\beta ae) \\ J_{n+2,k}(\beta ae) \end{pmatrix} \tag{48}$$

The elements of the matrix $\underset{\sim}{\mathfrak{C}}_n$ *are generally functions of* a, e, ω, and i and are presented in an easy to use format in Table 1.

TABLE 1. EXPRESSIONS FOR FORMING THE $\mathfrak{C}_n$ MATRICES†

Coefficient \ Element (ε)	a	e	i	Ω	ω
α_n^ε	0	0	$\cos 2\omega(\delta_{n2} - \delta_{n4})Y$ **	$2(\delta_{n2} - \delta_{n4})Z$ ***	$-2(\delta_{n2} - \delta_{n4})Z \cdot \cos i$
β_n^ε	0	$X(\delta_{n1} - 2\delta_{n2} + \delta_{n3})$ *	0	0	0
γ_n^ε	$2a^2(\delta_{n0} + 2\delta_{n1} + \delta_{n2})$	0	$\sin^2 \omega(\delta_{n0} - 2\delta_{n1} + 2\delta_{n3} - \delta_{n4})Y - 2 \cos 2\omega(\delta_{n1} - \delta_{n3})Y$	$-\left[\delta_{n0} + 2(\delta_{n1} - \delta_{n3}) - \delta_{n4}\right]Z$	$\left[\delta_{n0} + 2(\delta_{n1} - \delta_{n3}) - \delta_{n4}\right] \cdot Z \cos i$
ξ_n^ε	0	$2a(\delta_{n0} + \delta_{n1}) + X(2\delta_{n2} - \delta_{n1} - \delta_{n3})$	0	0	0
σ_n^ε	0	0	$\cos 2\omega(\delta_{n0} - \delta_{n2})Y$	$2(\delta_{n0} - \delta_{n2})Z$	$-2(\delta_{n0} - \delta_{n2})Z \cdot \cos i$

†The δ_{ij} are Kronecker deltas

*$X = (1 - e^2)^{1/2} \omega_e \cos i (a^5/\mu)^{1/2}$

**$Y = \omega_e \sin i \left[a^5/\mu(1 - e^2)\right]^{1/2}$

***$Z = \omega_e \left[a^5/\mu(1 - e^2)\right]^{1/2} \sin \omega \cos \omega$

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