A New Navigation Force Model for the Earth’s Albedo and Its Effects on the Orbital Motion of an Artificial Satellite

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Abstract

In this paper, we developed a new approach of an analytical model to calculate the radial and transversal components of the acceleration due to the effects of Earth’s albedo. Its effects on the orbital motion of an artificial satellite are introduced. It is assumed that the satellite’s horizon is illuminated and the sun lies on the equator. The magnitudes of those components are obtained and their effects on orbital evolution have been tested for different satellites elements. The perturbations in orbital elements due to Earth’s albedo have been obtained using Lagrange Planetary equation in Gaussian form, in particular the case of LAGEOS satellite, have been found using this new analytical formalism.

Keywords: Satellite Dynamics, Non-Gravitational Forces, Albedo Effect, Orbital Perturbations, Lagrange Planetary Equations

1. Introduction

Satellite orbital dynamics is primarily influenced by the earth gravitational field, but there are several other factors which affect orbital motion and must be taken into account in order to prevent escape from the desired orbit and collision with another satellite or space debris in the neighboring orbit. The precise knowledge of the position and velocities of an artificial satellite is essential to the current technologies involving geodetic, communications satellites and GPS system as in Jaggi [1].

Such precisions require accurate models of perturbing gravitational and non-gravitational accelerations which affect the motion of an Earth satellite.

Gravitational perturbations are dominating the force spectrum for most earth orbits. They are caused by non-uniform mass distribution inside the Earth, ocean, atmosphere, Earth tides, and by third body attraction (Sun, Moon, planets). These perturbations can be modeled with a high level of confidence as all of them are conservative causing mainly periodic changes in the orbit energy. A complementary class of orbit perturbation is denoted as non-gravitational. This class comprises aerodynamic forces, direct and indirect radiation pressure effects, thermal radiation, and charged particle drag. Models of these non gravitational forces are affected by uncertainties in the molecule-surface and photon-surface interaction processes, in molecule and photon flux models, and in the solar and geomagnetic activity levels and their effect on the thermosphere an ionosphere. Some of these perturbations cause a secular, time-proportional decrease of the orbital energy, and hence in the orbital altitude. For low-Earth orbits (LEO), these altitude decays must be compensated by periodic maintenance maneuver.

Earth’s albedo effect is one of the most interesting non-gravitational forces, which have significant effects on the orbital motion. Albedo is the fraction of solar energy reflected diffusely from the planet back into space ([2]). It is the measure of the reflectivity of the planet’s surface.

Therefore, the Earth albedo can be defined as the fraction of incident solar radiation returned to the space from the Earth’s surface as in Marconi [3]

\[
\text{Albedo} = \frac{\text{radiation reflected back to the space}}{\text{incident radiation}}
\]

A detailed review of Earth’s albedo as constant or variable with the changing of the latitude is performed by Green [4] and Sehnal [5]. Sehnal considered the Earth’s albedo as the potential function of the Earth.

The Earth’s albedo was considered as constant in the
analysis for the reflected radiation pressure in many literatures for example see [6-9]. Moreover [10-14] have taken into account a constant albedo.

Therefore, in this paper we are interested in an accurate analytical model of the acceleration due to the Earth’s albedo which will be introduce in section 2. In section 3 we will study the effects of the albedo forces on the orbital motion of Earth’s satellite.

2. The Perturbing Acceleration

As in [4], the albedo function can be written as:

\[
\zeta = \sum_{m=0}^{\infty} \sum_{n=0}^{m} P^m_n(\sin \varphi)(\zeta_0 + \zeta_1 \cos \lambda + \zeta_2 \sin \lambda)
\]  

(1)

where \( P^m_n(\sin \varphi) \) is the associated Legendre polynomial, \( \varphi \) is the latitude of an arbitrary element of area on the Earth’s surface, \( \lambda \) is the geocentric longitude of that element, \( \zeta_0, \zeta_1, \zeta_2 \) are constants to be determined. Using the measures data of the satellites yields to no reliable dependence on the Earth’s albedo on the longitude \( \lambda \), so that the Earth’s albedo be written as:

\[
\zeta = \sum_{m=0}^{\infty} \zeta_m P^m_0 (\sin \varphi)
\]  

(2)

where \( \zeta_m \) are constants, to be determined using satellites’ observation.

A polynomial fitting of second degree in \( \cos \varphi \) is used, \( \zeta = \zeta_0 - \zeta_2 \cos^2 \varphi \), where \( \zeta \) being the Earth’s albedo constants, \( \zeta_0 \) and \( \zeta_2 \) to be determined. The data together with the polynomial approximation was provided by [4]; these were done by taking the measurements of the Earth’s albedo by Tiros 7 satellite. The results are given for the four seasons of the year.

In the present work we shall use

\[
\zeta = 0.62997 - 0.40893 \cos^2 \varphi
\]  

(3)

To illustrate how albedo affects the satellite orbits, see Figure 1 at which the Earth’s center at \( O \), the \( OX \) axis is directed towards the sun. We denote the \( OX \) axis by the vector \( \mathbf{R}_o \). Moreover, the satellite will be at a point \( S \) at any moment, \( \mathbf{r} \) is the position vector of the satellite from \( O \), \( dE \) represents an arbitrary small element of area on the Earth’s surface, and its position vector is \( \mathbf{r} \). The angle \( \angle AOA_s \) is \( -\varphi \) and the angle \( \angle AOA_t \) is \( +\varphi \), \( \chi \) is the angle between the sun and \( \mathbf{r} \), and \( OZ \) is perpendicular to the \( OXY \) plane. In fact, we have three cases:

1) The satellite’s horizon lies completely in the illuminated hemisphere, the required condition for the albedo effects on the satellite is \( \theta - \varphi \leq 90^\circ \).

2) The satellite’s horizon lies partially in the illuminated hemisphere and partially in the darkened hemisphere, the required condition for the albedo effects on the satellite is \( \theta - \varphi \geq 90^\circ \).

3) The satellite’s horizon lies completely in the darkened hemisphere and in this case \( \theta - \varphi \geq 90^\circ \).

In the present work, the accuracy of computing the albedo acceleration in the case of constant albedo is increased by using powers of \( 1/r \) till \( (1/r)^5 \), while the previous works used powers of \( 1/r \) till \( (1/r)^4 \) only.

Therefore, the equations of the radial and transverse components of the reflected radiation pressure are given by

\[
a_r^* = \frac{N}{r} \int_{G} \int_{D} \zeta \cos^2 \varphi \cos \theta \left( \cos \varphi \cos \theta D - \frac{1}{r} \right) dG dD
\]

\[
a_t^* = \frac{N}{r} \int_{G} \int_{D} \zeta \left( \cos \varphi \cos \theta D - \frac{1}{r} \right) dG dD
\]

where \( N = kA/mr^2 \), \( k \) is the solar constant, and \( (A/m) \) is the area to mass ratio of the satellite, and \( G \) changes from \( -\varphi \) to \( +\varphi \) and \( D \) changes from \( -\omega \) to \( +\omega \), and \( \omega = \cos^{-1}(\cos \varphi \cos \theta) \) (see Figures 2 and 3). Also we have;

\[
\zeta = \zeta_0 - \zeta_2 \cos^2 \varphi,
\]

where \( \zeta \) is the variable albedo coefficient and \( \zeta_0 \) is the constant albedo coefficient, and the normal component of the Earth’s albedo is

\[
a_n^* = -\frac{N}{r} \int_{G} \int_{D} \zeta \cos^2 \varphi \cos \theta \left( 1 - \frac{1}{r} \right) dG dD
\]

\[
a_r^* = \frac{N}{r} \int_{G} \int_{D} \zeta \cos^2 \varphi \cos \theta \left( \cos \varphi \cos \theta D - \frac{1}{r} \right) dG dD
\]

\[
\frac{N}{r} \int_{G} \int_{D} \zeta \left( \cos \varphi \cos \theta D - \frac{1}{r} \right) dG dD
\]
Figure 2. Shows the angles $\theta$, $H$, $G$, and $D$.

Figure 3. A coordinate system to express $\phi$ in terms of $G$, $D$, and $\theta$ with the $\delta_S$ and $a_S$ for the satellite.

The above equations will be solved when the Earth’s albedo is variable and depend on the latitude $\phi$. Then, from the spherical triangle ZNE in Figure 3, it is convenient to use the formula:

\[
\sin^2 \phi = (1 - A_1^2) \sin^2 D + A_1 \sqrt{1 - A_1^2} \sin 2D \sin (\theta + G) + A_1^2 \cos^2 D \sin (\theta + G)
\]

where $A_1 = \sin \delta_S / \sin \theta$, put

$\overline{B}_1 = 1 - A_1^2, \overline{B}_2 = A_1 \sqrt{1 - A_1^2}, \overline{B}_3 = A_1^2$

and

$B_1 = \zeta_S \overline{B}_1, B_2 = \zeta_S \overline{B}_2, B_3 = \zeta_S \overline{B}_3$, also we have

$a'_v = \tilde{a}_v$ (variable albedo) + $a_v$ (constant albedo),

$a'_s = \tilde{a}_s$ (variable albedo) + $a_s$ (constant albedo),

$a'_n = \tilde{a}_n$ (variable albedo) + $a_n$ (constant albedo),

So

\[
\tilde{a}_r = N \int_{G_D} B_1 \sin^2 D + B_2 \sin 2D \sin (G + \theta) + B_3 \cos^2 (G + \theta) \cos (G + \theta) \times \left( \cos G \cos D - \frac{1}{r} \right) \\
\times \left( \frac{r}{\rho} \right)^4 \left( 1 - \frac{1}{r} \cos G \cos D \left( \frac{r}{\rho} \right)^4 \right) dGdD \\
+ NB_2 \int_{G_D} \sin 2D \cos^2 D \sin (G + \theta) \cos (G + \theta) \\
\times \left( \cos G \cos D - \frac{1}{r} \right) \left( 1 - \frac{1}{r} \cos G \cos D \left( \frac{r}{\rho} \right)^4 \right) dGdD \\
+ \frac{\pi}{2r} \sin^2 \theta + \frac{1}{r} \left( -\frac{22\pi}{105} + \frac{32\pi}{35} \sin^2 \theta \right) \\
+ \frac{1}{r^3} \left( \frac{-5\pi}{24} + \frac{32\pi}{45} (3 \sin^2 \theta - 1) \right) \\
+ \frac{1}{r^3} \left( -\frac{-338\pi}{1184\pi} + \frac{1184\pi}{315} \sin^2 \theta \right) \\
+ \frac{1}{r^3} \left( \frac{17\pi}{8} + \frac{176}{15} \sin^2 \theta + \left( \frac{-283\pi}{240} + \frac{484}{225} \right) \right) \\
+ NB_3 \int_{G_D} \cos^4 D \cos^2 D \sin^2 (G + \theta) \cos (G + \theta) \\
\times \left( \cos G \cos D - 1 \right) \\
\times \left( 1 - \frac{1}{r} \cos G \cos D \left( \frac{r}{\rho} \right)^4 \right) dGdD \\
\tilde{a}_r$ may be written as:

$a'_r = C_1 + C_2 + C_3$, where

\[
C_1 = NB_2 \int_{G_D} \sin 2D \cos^2 (G + \theta) \left( \cos G \cos D - \frac{1}{r} \right) \\
\times \left( 1 - \frac{1}{r} \cos G \cos D \left( \frac{r}{\rho} \right)^4 \right) dGdD,
\]

\[
C_2 = NB_2 \int_{G_D} \sin 2D \cos^2 D \sin (G + \theta) \cos (G + \theta) \\
\times \left( \cos G \cos D - \frac{1}{r} \right) \\
\times \left( 1 - \frac{1}{r} \cos G \cos D \left( \frac{r}{\rho} \right)^4 \right) dGdD,
\]

To evaluate $C_1$, we have

\[
(r/\rho)^4 = a_v + a_s \cos H + a_c \cos^2 H + a_c \cos^3 H \\
+ a_c \cos^4 H + a_c \cos^5 H + a_c \cos^6 H
\]

where $\cos H = \cos G \cos D$, and

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\[ a_0 = \frac{1}{r} + \frac{2}{r^3} - \frac{3}{r}, \quad a_1 = \frac{5}{r^3} + \frac{13}{r}, \]
\[ a_2 = \frac{3}{r^2} + \frac{57}{r^4}, \quad a_3 = \frac{8}{r^2} + \frac{56}{r^4}, \]
\[ a_4 = \frac{20}{r} - \frac{160}{r^3}, \quad a_5 = \frac{80}{r^3}; a_6 = \frac{112}{r^3}, \]

\[ C_i = N B_i \int_\varphi^\theta \cos G \sin \varphi dG \int_{D=\omega} \sin^2 D \cos^2 D \]
\[ \left\{ a_0 + a_1 \cos G \cos D + a_2 \cos^2 G \cos^2 D \right. \]
\[ + a_3 \cos^3 G \cos^3 D + a_4 \cos^4 G \cos^4 D \]
\[ + a_5 \cos^5 G \cos^5 D + a_6 \cos^6 G \cos^6 D \}
dD

where \( \omega = \cos^{-1} \frac{1}{r \cos G} \).

Two more integrals are required, which are

\[ \int \cos^a D dD = \frac{\sin D}{315} \left( 128 + 64 \cos^2 D + 48 \cos^4 D \right) \]
\[ + 40 \cos^6 D + 35 \cos^8 D, \]

and

\[ \int \cos^b D dD = \frac{63D}{256} + \frac{\sin D}{1280} \left( 315 \cos D + 210 \cos^3 D \right) \]
\[ + 168 \cos^5 D + 144 \cos^7 D + 128 \cos^8 D \]

Finally arranging the terms w. r. to. \((1/r)\), this yields:

\[ C_i = N B_i \cos \theta \left[ \frac{2 \pi}{15} + \frac{1}{r^3} \left( \frac{-22 \pi}{105} \right) + \frac{1}{r^3} \left( \frac{-\pi}{24} + \frac{7}{45} \right) \right] \]
\[ + \frac{1}{r^3} \left( \frac{338 \pi}{315} \right) + \frac{1}{r^3} \left( \frac{-43 \pi}{240} + \frac{301}{450} \right) \]

Evaluating \( C_2 \),

\[ C_2 = N B_2 \int_{\varphi=0}^{\theta} \sin (\theta + G) \cos(\theta + G) dG \int_{D=\omega} \sin 2D \]
\[ \cos^2 D \left( \cos G \cos D - \frac{1}{r} \right) \]
\[ \times \left( 1 - \frac{1}{r} \cos G \cos D \right) \frac{r^4}{p^4} dD \]

Finally, we can see that \( C_2 = 0 \)

Evaluating \( C_3 \),

\[ C_3 = N B_3 \int_{\varphi=0}^{\theta} \sin^2 (\theta + G) \cos(\theta + G) dG \int_{D=\omega} \cos^4 D \]
\[ \times \left( \cos G \cos D - \frac{1}{r} \right) \left( 1 - \frac{1}{r} \cos G \cos D \right) \frac{r^4}{p^4} dD \]

this yields:

\[ C_3 = N B_i \cos \theta \left[ \frac{2 \pi}{15} + \frac{\pi}{2r^2} \sin^2 \theta \right. \]
\[ + \frac{1}{r^3} \left( \frac{-22 \pi}{105} + \frac{32 \pi}{35} \sin^2 \theta \right) \]
\[ + \frac{1}{r^3} \left( \frac{-5 \pi}{24} + \frac{32}{45} \sin^2 \theta - 1 \right) \]
\[ + \frac{1}{r^3} \left( \frac{-338 \pi}{315} + \frac{1184 \pi \sin \theta}{315} \right. \]
\[ + \frac{1}{r^3} \left( \frac{17 \pi}{8} + \frac{176}{15} \sin^2 \theta + \left( \frac{-283 \pi}{240} + \frac{848}{225} \right) \right) \]

Then, the radial component \( \bar{a}_r \) can be written as:

\[ \bar{a}_r = C_i + 0 + C_1 \]
\[ = N B_i \cos \theta \left[ \frac{2 \pi}{15} + \frac{1}{r^3} \left( \frac{-22 \pi}{105} \right) + \frac{1}{r^3} \left( \frac{-\pi}{24} + \frac{7}{45} \right) \right] \]
\[ + \frac{1}{r^3} \left( \frac{338 \pi}{315} \right) + \frac{1}{r^3} \left( \frac{-43 \pi}{240} + \frac{301}{450} \right) \]
\[ + \left[ N B_2 \cos \theta \left( \frac{2 \pi}{15} + \frac{\pi}{2r^2} \sin^2 \theta \right) \right] \]
\[ + \frac{1}{r^3} \left( \frac{-22 \pi}{105} + \frac{32 \pi}{35} \sin^2 \theta \right) \]
\[ + \frac{1}{r^3} \left( \frac{-5 \pi}{24} + \frac{32}{45} \sin^2 \theta - 1 \right) \]
\[ + \frac{1}{r^3} \left( \frac{-338 \pi}{315} + \frac{1184 \pi \sin \theta}{315} \right. \]
\[ + \frac{1}{r^3} \left( \frac{17 \pi}{8} + \frac{176}{15} \sin^2 \theta + \left( \frac{-283 \pi}{240} + \frac{848}{225} \right) \right) \]

Finally \( \bar{a}_r \) can be taken the form:

\[ \bar{a}_r = N B_i \cos \theta \left[ \frac{2 \pi}{15} + \frac{1}{r^3} \left( \frac{-22 \pi}{105} \right) + \frac{1}{r^3} \left( \frac{-\pi}{24} + \frac{7}{45} \right) \right] \]
\[ + \frac{1}{r^3} \left( \frac{338 \pi}{315} \right) + \frac{1}{r^3} \left( \frac{-43 \pi}{240} + \frac{301}{450} \right) \]
\[ + N B_2 \cos \theta \left[ \frac{2 \pi}{15} + \frac{\pi}{2r^2} \sin^2 \theta + \frac{1}{r^3} \left( \frac{-22 \pi}{105} + \frac{32 \pi}{35} \sin^2 \theta \right) \right] \]
\[ + \frac{1}{r^3} \left( \frac{-5 \pi}{24} + \frac{32}{45} \sin^2 \theta - 1 \right) \]
\[ + \frac{1}{r^3} \left( \frac{-338 \pi}{315} + \frac{1184 \pi \sin \theta}{315} \right. \]
\[ + \frac{1}{r^3} \left( \frac{17 \pi}{8} + \frac{176}{15} \sin^2 \theta + \left( \frac{-283 \pi}{240} + \frac{848}{225} \right) \right) \]

and

\[ \zeta_1 = \zeta_2 - \zeta_2, \quad \zeta_2 = 0.40893, \quad \zeta_0 = 0.62997. \]
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So, the variable Earth’s albedo
\[ \zeta = 0.62997 - 0.40893 \cos \varphi. \]

Similarly, the final form of the parameter \( \tilde{a}_r \) is given by
\[
\tilde{a}_r = -NB \cos \theta \left[ \frac{\pi^2}{32r^2} + \frac{1}{r^3} \left( \frac{4013}{24} \pi + \frac{1}{r^3} \left( \frac{-5\pi^2}{256} \right) \right) \right] - NB \cos \theta \left[ \frac{5\pi^2}{128r^2} + \frac{1}{r^3} \left( \frac{416}{1575} + \frac{1}{r^3} \left( \frac{-2656 \sin^2 \theta}{1755} \right) \right) \right] + \frac{1}{r^3} \left( \frac{5\pi}{8} \right) \left( \frac{208}{147} \sin^2 \theta + \left( \frac{-5\pi^2}{24} + \frac{19856}{33075} \right) \right) + \frac{1}{r^3} \left( \frac{1095\pi^2}{2048} + \frac{175\pi^2}{1024} \sin^2 \theta \right) \right]
\]

3. Perturbation in Orbital Elements Due to Earth’s Albedo

Using Lagrange Planetary equations in Gaussian form:
\[
\dot{a} = 2 \sqrt{\frac{a^3}{\mu(1-e^2)}} \left[ \sin \bar{f}_a + \frac{a(1-e^2)}{r} \tilde{a}_r \right],
\]
\[
\dot{e} = \sqrt{\frac{a(1-e^2)}{\mu}} \left[ \sin \bar{f}_a + \left( e + \cos f \left( \frac{r}{a} + 1 \right) \right) \tilde{a}_r \right],
\]
\[
i = \frac{r \cos (\omega + f)}{\sqrt{\mu a(1-e^2)}} \tilde{a}_N,
\]
\[
\Omega = \frac{r \sin (\omega + f)}{\sin i \sqrt{\mu a(1-e^2)}} \tilde{a}_N,
\]
\[
\dot{\omega} = -\Omega \cos i - \frac{1}{e} \sqrt{\frac{a(1-e^2)}{\mu}} \left[ \cos \bar{f}_a - \left( 1 + \frac{r}{a(1-e^2)} \sin \bar{f}_T \right) \right],
\]
\[
\dot{M} = -\frac{2r}{\sqrt{\mu a}} \tilde{a}_r \left( 1 - e^5 (\dot{\omega} + \Omega \cos i) \right).
\]

And according to the components of the acceleration of the albedo force \( \dot{a}_{albedo} \), we find out the perturbation in the orbital elements due to the effects of Earth’s albedo as the following:

\[ \langle \dot{a} \rangle = \frac{1}{2\pi} \int_0^{2\pi} \dot{a} df \]
\[ \langle \dot{e} \rangle = \frac{1}{2\pi} \int_0^{2\pi} \dot{e} df \]
\[ \langle \dot{\omega} \rangle = \frac{1}{2\pi} \int_0^{2\pi} \dot{\omega} df \]

4. Numerical Realization

Depending on latitude \( \varphi \) and for constant albedo as in [14], we shall consider \( \alpha_s = 0 \) from the right ascension, of the satellite and \( a_N = 0 \) for constant albedo. Also we study the case of \( \delta_s = 0 \), after that \( a_s = 0 \), so we have the declination of the satellite and putting \( M = k (A/m) = 5.23 \times 10^{-5} \text{cm/sec} \), and the Earth’s radius \( R = 1 \).

Using these conditions and value of the parameters, we obtained the following results

1) The acceleration \( a_{albedo} \) is considered as two components only (radial and transverse), which \( a_{albedo} = \sqrt{\tilde{a}_r^2 + \tilde{a}_T^2} \).

2) Figure 4 illustrates the change in the acceleration \( a_{albedo} \) with different values of \( r \) (\( r \) change from 1.04 to 7 R) and \( \theta \) which is the angle between the Sun’s position and the radius vector of the satellite (\( \theta \) change from 0 to \( \pi \)), with \( M = k (A/m) = 5.23 \times 10^{-5} \text{cm/sec} \), where R is the equatorial radius of the Earth.

3) Figures 5-7 represent the variation of the acceleration \( a_{albedo} \) versus \( \theta \) for the following satellites: a) GFO with semi major axis = 7162 km, b) LAGEOS1 with semi major axis = 12160 km, and c) ETALON1 with semi major axis = 255000 km, the figures shows the magnitude of the acceleration is increased in LOE and decreased in MEO, but in the case of LAGEOS1 satellite,
4) Figures 8 and 13 represent the variation in the orbital elements (semi major axis, eccentricity and the argument of perigee) versus the angle $\theta$ for LAGEOS and STARLETTE satellites. Figures 8 and 9 show that the variation in the semi major axes due to albedo force for LAGEOS and STARLETTE satellites is in order ($10^{-9}$) which is a significant effects. Also, Figures 10 and 11 show the variation in the eccentricity due to albedo force for LAGEOS and STARLETTE satellites is in order ($10^{-14}$, $10^{-13}$) which means the albedo force can affect the eccentricity. Moreover, Figures 12 and 13 show the variation in the argument of perigee due to albedo force for LAGEOS and STARLETTE satellites is in order ($10^{-10}$, $10^{-11}$) which means the albedo force can have a significant effects on the argument of perigee.
5. Conclusions

The net acceleration, $a_{\text{albedo}}$, arising from the effect of the diffusion of reflected radiation on the satellites, decreases with the distance between the Earth and the satellites. This acceleration is in the order of $10^{-9}$ for the satellites in low earth orbit which means that this force decreases when $r$ increases. We could conclude that this force is in the same order of the air drag force, radiation pressure and the effect of Sun and Moon on the satellite. This is the reason for including the albedo force on the orbital elements of the satellite. However, in our cases we could conclude that the best representation of the Earth’s albedo function is to consider the Earth’s albedo as a function of latitude $\phi$, which interferes with the equation of motion of the satellite. We found out that the Albedo force have a significant effects on the orbital elements of the satellites.

6. References


