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Low-altitude, near-polar and near-circular orbits around Europa ☆

J.P.S. Carvalho [a,b,*], A. Elipe [c], R. Vilhena de Moraes [a,b], A.F.B.A. Prado [d]

[a] UNESP – Univ Estadual Paulista, CEP. 12.516-410 Guaratinguetá – SP, Brazil

[b] UNIFESP – Instituto de Ciência e Tecnologia, Universidade Federal de São Paulo, CEP. 12.331-280 São José dos Campos – SP, Brazil

[c] Centro Universitario de la Defensa de Zaragoza, and Grupo de Mecánica Espacial-IUMA, Universidad de Zaragoza, Spain

[d] Division of Space Mechanics and Control – INPE, CEP. 12227-010 São José dos Campos – SP, Brazil

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Abstract

The dynamics of orbits around planetary satellites, taking into account the gravitational attraction of a third-body and the non -uniform distribution of mass of the planetary satellite, is studied. The Hamiltonian considered is explicitly time-dependent. Conditions for frozen orbits are presented. Low-altitude, near-polar orbits, very desirable for scientific missions to study planetary satellites such as the Jupiter's moon Europa, are analyzed. Lifetimes for these orbits are computed through the single and double averaged method. Comparison between the results obtained by the single and double averaged method is presented. The single-averaged model is more realistic, since it does not eliminate the term due to the equatorial ellipticity of the planetary satellite as done by the double-averaged problem. Considering the single-averaged method, we found unstable frozen orbits where the satellite does not impact with the surface of Europa for at least 200 days. We present an approach using the unaveraged disturbing potential to analyze the effects of these terms in the amplitude of the eccentricity.

Keywords: Planetary satellites; Artificial satellite; Frozen orbits

1. Introduction

Low-altitude, near-polar orbits, are very desirable for scientific missions to study natural satellites, such as Europa, one of the moons of Jupiter. However, previous researches, like Scheeres et al. (2001), Lara and Russell (2006), Paskowitz and Scheeres (2006) showed that an artificial satellite in a low-altitude, near-polar orbit impact with Europa's surface in a short time period. Frozen orbits around the Moon, natural satellites, or asteroids is of current interest because several space missions have the goal of orbiting around such bodies (see for instance Park and Junkins (1995), Elipe and Lara (2003), Folta and Quinn (2006), Carvalho et al. (2010a) and references therein).

The dynamics of orbits around a planetary satellite, taking into account the gravitational attraction of a third-body and the non-uniform distribution of mass of the planetary satellite, has been studied by several authors. Kozai (1963) makes a study on the motion of an orbit around a planetary satellite (Moon) that found stable and unstable orbits without integration of the equations of motion. In Paskowitz and Scheeres (2005b) the average problem is applied twice to reduce the original problem, a system with three degrees of freedom, to an integrable system with one degree of freedom. Carvalho et al. (2009a,b) shows the dynamics of an artificial satellite around the Moon, taking into account the non-uniform distribution of mass of the Moon and the perturbation caused by a third-body in elliptical orbit. It is also presented an approach to study frozen and sun-synchronous orbits. Applying the double-averaged method Russell and Brinckerhoff (2009) shows evolution of

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* Corresponding author at: UNESP – Univ Estadual Paulista, CEP. 12.516-410 Guaratinguetá – SP, Brazil.

E-mail addresses: jeanfeg@gmail.com (J.P.S. Carvalho), rodolpho.vilhena@gmail.com (R. Vilhena de Moraes).

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the eccentricities and inclinations for long-period orbits and discuss them for the dimensioned systems at Ganymede, Europa, Titan, Enceladus, and several other planetary moons. In Abad et al. (2009) an analytic model is presented to find frozen orbits for lunar satellites, where only the potential due to J_2 and J_7 zonal harmonics are taken into account. In Lara et al. (2010) the averaged problem up to the sixth order is used to obtain information on the dynamics close to Enceladus. In San-Juan (2010), an analytical theory based on Lie-Deprit transformation is used to locate family of frozen orbits for asteroids and natural satellites. The average is performed through Lie transformations and two different transformations are applied.

In this work we consider the effects caused by the non-sphericity (J_2, J_3, C_{22}) of Europa and the perturbation of the third-body (Jupiter), assumed to be in elliptical orbit, on the orbital motion of an artificial satellite. We present an analytical theory using the averaged model and the applications were done by integrating numerically the analytical equations developed here. A special study is made for the case of frozen orbits (Scheeres et al., 2001; Elipe and Lara, 2003; Lara and Russell, 2006), that are orbits that keeps the eccentricity, inclination and argument of the periapsis of the orbit simultaneously almost constant, to make the satellite to pass by a given latitude with the same altitude. We fix a parameter to get frozen orbits when new terms are added to the disturbing potential. Previous researches (Scheeres et al., 2001; Lara and Russell, 2006; Paskowitz and Scheeres, 2006) show that low-altitude, near-polar orbits around Europa are unstable and have short lifetimes. In order to analyze the influence of the short period terms we make a study with respect to the terms of short-period, taking into account the problem without averaging the equations of motion. A comparison between the single and double averaged models is presented, as suggested in Paskowitz and Scheeres (2005a). Considering low altitude orbits, the perturbation of the third-body (R_2) should be taken into account, because this perturbation creates a strong effect in the determination of frozen orbits with polar inclination, as we can verify in next sections. However, we can find in the literature works which take into account different sets of perturbations, thus, (a) $R_2 + J_2$ Scheeres et al. (2001), Lara and San-Juan (2005), San-Juan (2010), (b) $R_2 + J_2 + C_{22}$ De Saedeleer (2006), Carvalho et al. (2010a), (c) $R_2 + J_2 + J_3$ Paskowitz and Scheeres (2005a), (d) $R_2 + J_2 + J_3 + C_{22}$ Paskowitz and Scheeres (2005b), Lara and Russell (2006), Carvalho et al. (2010b), Tzirti et al. (2010). In this paper, we analyze the influence of different perturbations $(R_2 + J_2 + J_3 + C_{22})$ to search for orbits with longer lifetime.

The paper has six sections. Section 2 is devoted to the disturbing function, showing the terms due the non-sphericity of Europa and the Hamiltonian system. Applications taking into account the long-period disturbing potential using the double-averaged method are presented in Section 3. In Section 4, applications taking into account the unaveraged disturbing potential are presented while, in Section 5, an approach taking into account the averaged models is presented. Section 6 shows the conclusions.

2. Equations of motion

The equations for the disturbing potential due to the third-body has been developed in Carvalho et al. (2010a), where the potential is developed up to the fourth order with expansion in Legendre polynomials. Here, the potential is considered up to the second order in Legendre polynomials to perform the applications. We use expansions in the eccentricity and in the mean anomaly to replace the disturbing potential in the Lagrange planetary equations.

Section 2.1 provides the disturbing potential due to the third-body in elliptical orbit. Section 2.2 shows the disturbing potential due to the non-spherical shape of the central body. In Section 2.3 the Hamiltonian system is developed.

2.1. Disturbing function

It is assumed that the main body with mass m_E is fixed at the center of the system. The perturbing body, with mass m_J, moves on a fixed elliptic orbit with semi-major axis a_J, eccentricity e_J and mean motion n_J (given by the expression $n_J^2 a_J^3 = G(m_E + m_J)$. The mass of the planetary satellite is sufficiently small, when compared to the mass of the planet $(m_E \ll m_J)$. The artificial satellite is considered as a point mass on a three-dimensional orbit with osculating orbital elements: a (semi-major axis), e (eccentricity), i (inclination), ω (argument of the periapsis), Ω (longitude of the ascending node), $l = M$ mean anomaly, (f) true anomaly and n (mean motion).

The disturbing potential (R) can be written in the form (Murray and Dermott, 1999):

$$R = \frac{\gamma \mathbf{G}(m_0 + m_J)}{\sqrt{r^2 + r_J^2 - 2rr_J\cos(S)}}, \tag{1}$$

where $\gamma = \frac{m_J}{(m_0+m_J)}$, $\mathbf{G}$ is the gravitational constant, r and r_J are the radius vectors of bodies m_0 and m_J, respectively. Here, S is the angle between r and r_J.

Using the relation between the angle S and the true anomaly (f) of the satellite we get (Broucke, 1992):

$$\cos(S) = \alpha\cos(f) + \beta\sin(f). \tag{2}$$

For the case of elliptic orbits, α and β can be written in the form (Domingos et al., 2008):

$$\alpha = \cos(\omega)\cos(\Omega - f_J - \omega_J) - \cos(i)\sin(\omega)\sin(\Omega - f_J - \omega_J), \tag{3}$$

$$\beta = -\sin(\omega)\cos(\Omega - f_J - \omega_J) - \cos(i)\cos(\omega)\sin(\Omega - f_J - \omega_J), \tag{4}$$

where f_J and ω_J are the true anomaly and argument of the periapsis of the disturbing body, respectively.

For the model considered in the present paper, it is necessary to calculate the term R_2 of the disturbing function due to the P_2 term. In Carvalho et al. (2010a) the potential