Acta Astronautica 128 (2016) 262–276

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Dynamical modeling and lifetime analysis of geostationary transfer orbits

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ARTICLE INFO

Article history:
Received 20 September 2015
Received in revised form
13 May 2016
Accepted 30 June 2016
Available online 1 July 2016

Keywords:
Geostationary transfer orbits
Semi-analytical orbital model
Orbital lifetime
Earth oblateness
Luni-solar perturbations
Atmospheric drag

ABSTRACT

The dynamics and lifetime reduction of geostationary transfer orbits (GTOs) are of great importance to space debris mitigation. The orbital dynamics, subjected to a complex interplay of multiple perturbations, are complicated and sensitive to the initial conditions and model parameters. In this paper, a simple but effective non-singular orbital dynamics model in terms of Milankovitch elements is derived. The orbital dynamics, which include the Earth oblateness, luni-solar perturbations, and atmospheric drag, are averaged over the orbital motion of the GTO object, or, as needed, also over the orbital motions of the Moon and Sun, to eliminate the short-period terms. After the averaging process, the effect of the atmospheric drag assumes a simple analytical form. The averaged orbital model is verified through a numerical simulation compared with commercial orbit propagators. GTO lifetime reduction by using the luni-solar perturbations is studied. It is shown that the long-period luni-solar perturbation is induced by the precession of the GTO orbital plane and apsidal line, whereas the short-period perturbation is induced by the periodic luni-solar orbital motions. The long- and short-period perturbations are isolated and studied separately, and their global distribution with respect to the orbital geometry is given. The desired initial orbital geometry with a short orbital lifetime is found and verified by a numerical simulation.

1. Introduction

Geostationary transfer orbits (GTOs) have been broadly used to transfer satellites from circular low Earth orbits (LEOs) to geostationary orbits (GEOs). GTOs are highly eccentric orbits, characterized by a low perigee, normally at an altitude of 180–650 km, and a high apogee, near the geostationary altitude. After the payload is boosted into a GTO from a LEO, the spent upper stage is usually left uncontrolled in the GTO to become space debris. The upper stages, which are large objects and have large relative velocities, are a potential source for collisions and future debris. The space debris in GTOs have become a threat to satellites both in GEOs and LEOs, which are the two most important and populated orbital regions [1]. In this aspect, knowledge of the GTO dynamics under natural perturbations is needed for predicting the distribution, decay, and lifetime of the space debris. More importantly, a global picture of the dynamics will enable us to determine the optimal launch window with the minimum lifetime for spent upper stages, and to design the deorbit maneuvers.

Many have investigated the dynamical evolution, decay, and lifetime of GTOs, including King-Hele [2], Janin [3], Siebold and Reynolds [4], Takano et al. [5], Sharma et al. [6], Da Costa et al. [7], Morand et al. [8], Lamy et al. [9], Bonaventure et al. [10], and David and Braun [11]. King-Hele [2] developed an approximate analytical method for the lifetime prediction of highly eccentric transfer orbits. Janin [3] showed that the atmospheric drag at perigee may considerably change the orbital evolution of GTOs, and may render the lifetime prediction totally uncertain. Siebold and Reynolds [4] presented a model for reducing the orbital lifetime of GTOs with the help of the luni-solar perturbations. Takano et al. [5] also discussed the GTO orbital lifetime reduction by the luni-solar perturbations. Sharma et al. [6] investigated the basic physics of the luni-solar perturbations on GTOs and their interaction with the atmospheric drag, with special attention paid to the influence of the launch time on the orbital lifetime. Based on a semi-analytical solution of the Gauss equations, Da Costa et al. [7] have developed a long-term orbit propagator to integrate the natural decay of upper stages into the design process of European launchers. Morand et al. [8] and Lamy et al. [9] have studied the dynamical properties of GTOs over long time scales, especially the orbital lifetime estimation, by using numerical methods. Sharma et al. [6], Da Costa et al. [7], Morand et al. [8], and Lamy et al. [9] have all shown that the launch date and the local time of the initial perigee

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http://dx.doi.org/10.1016/j.actaastro.2016.06.050

have a strong impact on the orbital lifetime and even small changes in the launch time can result in large changes in the orbital lifetime. This strong impact and sensitivity are attributed to the solar third-body perturbation and the resonance between the solar orbital motion and the rotation of the apsidal line caused by Earth oblateness. Bonaventure et al. [10] have studied the de-orbiting maneuvers of the SPIRALE GTO satellites. David and Braun [11] investigated the influence of different methods for the solar activity forecasts on the residual lifetime of upper stages in GTOs.

Besides GTOs, there are other kinds of highly eccentric orbits, which are used for penetrating into the interplanetary space at a relative low energy, such as NASA's S-3 ($e=0.867$), Eccentric Geophysical Observatories (EGO) ($e=0.893$), Interplanetary Monitoring Platforms (IMP) ($e=0.95$), and the European scientific satellite HEOS-1 ($e=0.94$); or for communications in high latitudes, such as the Russian Molniya orbits ($e=0.74$). These highly eccentric orbits, more eccentric than a GTO, are perturbed by the Moon and Sun more strongly, and are more unstable. The luni-solar perturbations induce an oscillation and bring the satellite back to Earth sooner or later. Many works have studied the dynamics and lifetime of these highly eccentric orbits to determine the launch window, see Upton et al. [12], Shute [13], Paddack and Shute [14], Shute and Chiville [15,16], Cook and Scott [17], and Janin and Roth [18]. As opposed to the case of space debris in GTOs, these works are aimed at guaranteeing a long enough orbital lifetime to meet mission requirements.

The studies on GTOs and highly eccentric orbits have revealed important characteristics of the dynamics. With a high eccentricity ($e > 0.7$), the orbit has a low perigee and a high apogee, and then the orbital dynamics are subjected to a complex interplay of multiple perturbations, including Earth oblateness, luni-solar perturbations, and atmospheric drag.

The atmospheric drag takes effect near the perigee, reduces the semi-major axis, eccentricity, and apogee height, and finally ends the orbit when the perigee height is low enough. However, the orbital decay caused by the atmospheric drag alone takes a long time. The effect of atmospheric drag, which is predominant at altitudes lower than 300 km, strongly depends on the atmospheric density. Then, the fluctuation of the atmospheric density with the solar activity and the local time has a strong impact on the lifetime of GTOs [8,11]. The uncertainty of the atmospheric drag, induced by uncertainties of the atmospheric density and the cross-sectional area, renders the lifetime prediction of GTOs highly uncertain.

With the luni-solar perturbations affecting the orbit near apogee, the semi-major axis is kept nearly constant and the eccentricity has an oscillation with the perigee height decreasing or increasing, as shown by Janin [3], Siebold and Reynolds [4], Da Costa et al. [7], and Morand et al. [8]. The eccentricity oscillation is a superposition of a long-period oscillation with a period of several years and two relatively short-period oscillations, which are associated with the orbital motions of the Moon and Sun, with periods of about 14 days and 180 days, respectively, i.e., half the orbital periods of the perturbing bodies, as shown by Shute [13], Paddack and Shute [14], Shute and Chiville [15,16], Cook and Scott [17], and Fischer [19]. The initial phase of the long-period oscillation is determined by the initial relative geometry of the luni-solar orbital planes with respect to the orbit's apsidal line, as shown by Kozai [20] and Shute [13], while the initial phases of the 14-day and 180-day oscillations are determined by initial relative positions (azimuths) of the Moon and Sun with respect to the orbit's apsidal line, respectively, as shown by Shute [13], and Shute and Chiville [15].

The orbital lifetime is determined by both the perigee height change by the luni-solar perturbations and the decaying effect of the atmospheric drag. Through the eccentricity oscillation, the luni-solar perturbations can lower or raise the initial perigee height remarkably, i.e., can reduce or enhance the orbital lifetime. The amplitudes of the 14-day and 180-day perigee height oscillations are 15 km and 100 km for the S-3 satellite, and 25–35 km and 100–200 km for the EGO satellite, as shown by Shute [13]. The resultant curve of the perigee height is a superposition of the long-period oscillation and two short-period oscillations, and the trend of its variation is determined by the initial phases and amplitudes of these oscillations. Siebold and Reynolds [4], Takano et al. [5], and Sharma et al. [6] have shown that by choosing a proper launch window, which determines the initial orbital geometry and then determines the initial phases of oscillations, the luni-solar perturbations can be used to lower the initial perigee height and cause the space debris to decay quickly. Conversely, Upton et al. [12], Shute [13], Paddack and Shute [14], Shute and Chiville [15,16], Cook and Scott [17] have tried to find the launch window for the desired initial phases of oscillations, so that the initial perigee is raised by the luni-solar perturbations after launch and a long lifetime can be achieved.

With the perturbation of Earth oblateness only, the orbital plane and apsidal line will precess with the orbital shape nearly unchanged. Therefore, Earth oblateness alone is not directly responsible for the natural orbit decay. However, Earth oblateness has a significant indirect effect on the orbital evolution and lifetime. The precession of the orbital plane and apsidal line will change the relative geometry of the Moon and Sun with respect to the orbit apsides, which will in turn change the luni-solar effect on the eccentricity, as shown by Shute [13], Cook and Scott [17], Janin [3], Siebold and Reynolds [4], Sharma et al. [6], Da Costa et al. [7], and Morand et al. [8].

In particular, a 1:1 resonance between the solar orbital motion and the apsidal line precession caused by Earth oblateness can exist when the semi-major axis and eccentricity are reduced by the atmospheric drag to the resonance condition. This solar apsidal resonance keeps a nearly constant Sun azimuth with respect to the orbit apsides, and the 180-day eccentricity oscillation becomes a monotonically increasing or decreasing for a relatively long duration. Then, the solar perturbation will lower or raise the perigee height continuously, as shown by Sharma et al. [6], Da Costa et al. [7], Morand et al. [8], Lamy et al. [9], Bonaventure et al. [10], and Le Fèvre et al. [21]. The continuous lowering or raising of the perigee height during the solar apsidal resonance can totally change the orbital evolution and lifetime. Moreover, the solar apsidal resonance is highly sensitive to the initial conditions, computational accuracy and the model parameters of the perturbations, and then it can be neither predicted nor managed, as shown by Da Costa et al. [7], Morand et al. [8], Lamy et al. [9], and Bonaventure et al. [10]. This is exactly the mechanism behind the phenomenon wherein small launch time changes can result in large orbital lifetime changes, as reported by Sharma et al. [8], Da Costa et al. [7], Morand et al. [8] and Le Fèvre et al. [21].

As stated above, the orbital evolution and lifetime of the highly eccentric orbits are determined by the complex interplay between the Earth oblateness, luni-solar perturbations and atmospheric drag. The dynamical evolution is complicated and sensitive to initial conditions and model parameters. Although previous works, most of which used numerical methods, have revealed many important characteristics, more rigorous insights and a global analysis of the dynamics are still required.

In the present paper, we will investigate the orbital dynamics and lifetime reduction of GTOs based on a simple, but effective, averaged orbital dynamics model formulated in terms of Milankovitch elements. The Milankovitch elements use two vectorial integrals, the angular momentum vector $\boldsymbol{H}$ and the Laplace vector $\boldsymbol{b}$, to describe the orientation, shape, and size of the osculating Keplerian orbit [22]. The elements, which are free of singularities