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Averaged solar radiation pressure modeling for high area-to-mass ratio objects in geosynchronous orbits

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Abstract

Space Situational Awareness, among other efforts, is aimed at providing a comprehensive and accurate knowledge of all Earth-orbiting objects. This is done by maintaining a catalog of space objects' states (position and velocity). In the absence of observations, the orbits of these objects need to be numerically simulated. In this work, we study the high area-to-mass ratio class of objects which are sensitive to very small changes in perturbations, particularly the attitude dependent solar radiation pressure. This attitude dependency renders the orbit-attitude motion to be coupled. Traditionally, a cannonball model would be used to model these perturbations. While this is acceptable for an attitude stabilized active satellite, for non-functional space debris, the cannonball model does not seem to approximate the true dynamics accurately. Hence, a more precise, albeit computationally expensive propagation model needs to be developed, which warrants a better modeling of the perturbations in the near-Earth space. This work introduces a new model that averages the solar radiation pressure force experienced by multi-layer insulation foil in geosynchronous orbits. While speeding up the computational time by 66%, this model produces errors that are small enough to stay within the field of view of surveying telescopes over the propagation period of four days. The approach is compared with other existing models.

Keywords: Space debris; High area-to-mass ratio objects; Geosynchronous orbit; Solar radiation pressure; Astrodynamics; Space situational awareness

1. Introduction

Space Situational Awareness (SSA) involves understanding and maintaining awareness of the Earth's orbital population, the space environment, and possible threats. This incorporates three major areas: tracking, space weather effects and near-Earth objects (Schoenmaker, 2007; Catena, 2008) as espoused by European SSA Preparatory Program. The US Strategic Command maintains the only publicly available catalog of artificial space objects up to sizes of 10 cm or higher in low Earth orbit (LEO) and 30 cm and higher at geostationary Earth orbit (GEO). Only about 6% of the cataloged objects are active satellites. The rest is composed of non-operative spacecrafts, mission-related debris and about 40% of the objects are products of fragmentation (Rossi, 2011). The accidental collision between the Iridium 33 and Cosmos 2251 on February 10, 2009, at 11:56 EST demanded an extension to the existing scope of SSA. The requirement to protect and warn of a potential interference with a manned vehicle was expanded to include a warning of all collision threats to any operational satellite irrespective of the owner (Weeden, 2009). This implies that a precise orbit has to be determined for not just operational satellites but also for other non-functional objects.

The propagation of the orbit in general Cartesian coordinates is a non-linear one. Compact, satellite-like objects have an area-to-mass ratio of 1 m^2/kg or less and are

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categorized as low area-to-mass ratio objects. A special class of objects especially sensitive to perturbations and having a large, and/or very light foil-like structure have a high area-to-mass ratio (HAMR) (Frueh and Schildknecht, 2012; Herzog and Schildknecht, 2012).

The first results by Schildknecht et al. (2003) showed a population of HAMR objects in the geostationary ring. These class of objects had a large area exposed to the Sun which made it extremely sensitive to orbital perturbations caused due to non-conservative forces. In the geostationary ring, the most dominant perturbations are those due to solar radiation pressure (SRP). For such non-stable and non-spherical objects, the orbit dynamics are coupled with the attitude at that epoch. Hence, for HAMR objects, even the slightest change in the orientation may have huge effects on the evolution of its dynamics (Frueh et al., 2012, 2013).

Using light curves and comparisons of spectral measurements with those of space materials (Flegel et al., 2011), a good candidate for such space debris was found to be Multi-layer Insulation (MLI). These MLI shed of aging satellites (Schildknecht et al., 2008, 2010; Cowardin et al., 2009; Jorgensen et al., 2003; Abercrombie et al., 2009; Townsend et al., 1999). These materials have densities of 1.4–2.2 g/cm^2, which translates to a mean area-to-mass ratio of up to 115 m^2/kg for the inner layers. Townsend et al. (1999) studied the samples of MLI returned after the Second Servicing Mission aboard the Hubble. Results showed curling of MLI material which explains the non-flat nature of these objects. Twenty or more MLI layers are used with the outer layers having thicknesses as low as 0.5 mm and the inner layers, 0.25 mm.

The long-term orbital evolution of space debris in GEO has been studied (Liou and Weaver, 2005; Rosengren and Scheeres, 2013). This involved studying the cannonball model at first. This simple model ensured an attitude independent propagation. As shown in (Frueh et al., 2013; Frueh and Jah, 2014), the orbit and attitude motion are highly coupled for HAMR objects. It has also been shown (Frueh and Schildknecht, 2012; McMahon and Scheeres, 2015) that the cannonball model is not a good approximation of the true solar radiation pressure force. Actual measurements showed that a constant AMR could not be fitted to the observational data which suggests tumbling (Frueh and Schildknecht, 2012). Results confirm that the initially suggested notion of attitude motion averaging out and resulting in an effective cannonball model was wrong.

Propagating a full six degree of freedom model is computationally expensive. Hence, averaging techniques have been used to reduce this computational load. A method to average the secular and short-term SRP is given in (McMahon, 2011). The SRP accelerations were modeled as a Fourier series as a function of the Sun's location and the objects' properties (McMahon and Scheeres, 2010). It is shown therein that the Fourier coefficients estimated also allows the modeling of secondary photon impact and accounts for the differences between the physical properties used to obtain the a priori Fourier coefficients and the actual object.

In the work presented here, a new method has been developed to average the short term solar radiation pressure to compute the net force over one complete orbit. Using the information of the object and the orbit it is in, the force maps that are obtained over a single orbit are used in the prediction of the orbit over a longer time period based on the periodicity of the Sun exposure. In a second step, the force maps are predicted a priori relying on the information on the object's physical properties. This is then used in a fast orbit propagation. The results are compared to a fully coupled high fidelity model.

Sections 2 and 3 focus on developing the governing equations of the dynamical system and setting up the initial conditions for the simulation. Sections 4 and 5 discuss in detail the averaging techniques and the tools required to develop the averaged model. Section 6 outlines the major results obtained while testing the fidelity of the averaged models.

2. Orbit and attitude perturbations in near earth space

To simulate the true dynamics of the MLI foil, a ground truth high fidelity model is used (Frueh et al., 2013). This six degree of freedom model incorporates coupling between orbit and attitude dynamics. The coupling takes place via the perturbation forces only. All averaged models are compared to this model. We first introduce the orbital and attitude equations of motion.

2.1. Dynamics

The geocentric equations of motion for an object are defined as follows:

$$\ddot{\bar{x}} = -GM_{\oplus}\nabla V(\bar{x}) - G\sum_{k=1,2} M_k \left[\frac{\bar{x}-\bar{x}_k}{|\bar{x}-\bar{x}_k|^3} + \frac{\bar{x}_k}{|\bar{x}_k|^3} \right] + \sum_i \bar{a}_i \tag{1}$$

here, $\bar{x}$ is the geocentric position of the object, G is the gravitational constant, $M_{\oplus}$ is the Earth's mass and $V(\bar{x})$ is the normalized Earth's gravitational potential. For its representation, the formulation by Pines (1973) is chosen. The third body gravitational effects of the Sun and Moon $(k = 1, 2)$ with states $\bar{x}_k$ have also been taken into account. $\sum_i \bar{a}_i$ corresponds to the sum of all non-conservative perturbations acting on the object. In this work, the last term relates to the direct solar radiation pressure and the influence of Earth's shadow and self-shadowing on it.

For non-uniform, non-spherical objects, the attitude motion is modeled using the dynamic equations expressed in Euler's equations (Wertz, 1978), where the body is approximated over the sum of n facets and volume elements that specify the object's shape and mass.

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