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The impact of the atmospheric model and of the space weather data on the dynamics of clouds of space debris

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Abstract

New tools are necessary to deal with more than hundred thousands of space debris, thus our aim is to develop software able to propagate numerous trajectories and manage collisions or fragmentations. Specifically in low orbits Earth, gravity and atmospheric drag are the two main forces that affect the dynamics of the artificial satellites or space debris. NIMASTEP, the local orbit propagator, initially designed for high altitudes, has been adapted to low altitude orbits.

To study the future debris environment, we propose a suitable model of space weather and we compare three different atmospheric density models (Jacchia–Bowman 2008, DTM-2013, and TD-88) able to propagate with accuracy and efficiency a large population of space debris on long time scales.

We compare the results in different altitudes and during the reentry regime; we show, with a ballistic coefficient constant, a trend to underestimate or overestimate the decrease of the semi-major axis, specifically during the periods of high solar activity. We parallelize our software and use the calculation power of a computing cluster, we propagate a huge cloud of debris and we show that its global evolution is in agreement with the observations on several years.

Keywords: Space debris; Atmospheric drag; Space weather; Orbit propagation

1. Introduction

The protection of the space environment is a major issue for the future of the space activities. Since the launch of the first artificial satellite, named Sputnik, in October 1957, space activities have constantly increased. In more than fifty years, we count more than 4500 space missions, 194 explosions or collisions (Johnson et al., 2008), with the creation, by fragmentation or corrosion, of 13,087 space debris with a size larger than 10 cm (Orbital Debris Program Office, 2015) and approximatively 500,000 objects larger than 1 cm (at the date of November 2015)[1]. These space debris represent a permanent danger for all space installations because of their relatively high-velocities which can produce important damages in case of collisions. Today, although space agencies make an effort to reduce the production of space debris by managing satellite measures, the rapid growth of satellite launches arising from the democratization of low cost space access, lets us foresee new problems. In 2007 and 2009, a voluntary destruction and an accidental collision between two satellites have increased of 40% the total number of space debris with sizes above 10 cm.

The main risk is the creation of cascade collisions between space debris, commonly referred as the “Kessler syndrome” (Kessler and Cour-Palais, 1978). Some works suggest that, without mitigation measures, the number of space debris will continue growing up (Rossi, 2005), and

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[1] http://orbitaldebris.jsc.nasa.gov/.

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that a rupture point has already been reached for the altitude between 900 km and 1,000 km, even if we stop launching new objects in space (Liou and Johnson, 2008). The projections of the report of IADC (Inter-Agency Space Debris Coordination Committee) with different models of six national space agencies (ASI, ESA, ISRO, JAXA, NASA, UKSA) are rather pessimistic in predicting catastrophic collisions every 5–9 years and a growth of approximately 30% of the LEO debris population in the next 200 years (Liou et al., 2012).

It is then urgent to study the evolution of the space debris population over short and long timescales. A good knowledge of the orbital environment allows us to make decision for better preventive actions and to develop efficient strategies of debris mitigation. We have to detect the regions characterized by high densities of space junk and to detect the objects which are the most susceptible to destabilize the whole population. Thus, we can determine how many objects and which objects have to be removed in priority (Liou, 2011).

We need not only to calculate their trajectories but also to detect the highly probable collisions. The main difficulty is the complexity of the problem because of the important number of objects at play. The calculation of the trajectories and the detection of collisions are very time-consuming but this problem can be reduced through a suitable choice of the integration method, the optimization of the algorithms, and the use of parallel computing techniques.

These last years, an important effort has been performed to develop new tools coming from classical celestial mechanics and adapted to the space debris studies. At the University of Namur, different techniques have been developed, to treat the orbital motion (Delsate and Compère, 2012; Hubaux et al., 2013; Hubaux and Lema itre, 2013) and to detect a collision risk (Casanova et al., 2014). Thus, we aim to upgrade these tools to study the huge space debris populations.

In this paper, we present an important improvement of the numerical orbit propagator named NIMASTEP. Exposed in Delsate and Compère (2012), this software is able to propagate an orbit in osculating cartesian coordinates around the Earth taking into account the geopotential, the Sun and the Moon, and non gravitational forces as the solar radiation pressure, with the Earth shadowing effects. Working with the Newtonian equations, no assumption on the motion is made. We add here the atmospheric drag, the only natural mitigation mechanism of space debris in low Earth orbits. Indeed, the atmospheric drag is necessary to predict orbital lifetimes, the date of reentry, the tracking of space debris, and any orbital strategy over long time scales. Another challenge is the propagation of a huge population in reasonable time. Thus, we implement a parallelization method suitable for intensive calculation clusters.

Let us summarize our approach. Firstly, we emphasize the difficulties to model the atmospheric drag and we present three different atmospheric density models, Jacchia–Bowman 2008, DTM-2013 and TD-88 in Sections 2 and 3. Secondly, we model some aspects of the space weather that affect the calculation of the atmospheric density (Section 4). We present the method and the produced data. Thirdly, we compare the calculation of orbits with NIMASTEP to the *two-lines element* data (Section 5); we show the ability of NIMASTEP to calculate orbits in different altitudes (MEO and LEO) and we investigate its accuracy. We focus on the decrease rate of the semi-major axis and the reentry dates. We show the limits for the propagation on long time scales. Finally, we present an application to the space debris population, propagating a cloud produced by the fragmentation of the satellite Fengyun 1C, using the parallel version of our software (Section 6). We discuss the quality of this propagation by comparing the results with the observations coming from the TLE series collected over the last 5 years.

2. The expression of the drag acceleration

Among the forces acting on the trajectory, the atmospheric drag is the most difficult to estimate with accuracy. Indeed, it depends on the shape and on the orientation of the satellite, on the density of the gas and on the interaction of the object with the surrounding medium, i.e. the interaction of its surface with the neutral and charged gas. The density of the atmosphere is the first source of uncertainties, while the other points can often be considered as constants. The gas density in the upper layers of the atmosphere, specifically the thermosphere and the exosphere, depends on the position (altitude, longitude, latitude), but also suffers important variations in time. The extreme ultraviolet (EUV) radiation flux heats the upper atmosphere leading to an increase of the density.

Since the beginning of space activities in the sixties, an important effort has been made to model the atmospheric behavior, to design the trajectories and to predict the orbital lifetimes but it is only this last decade that many new data have allowed to develop really efficient models.

With the acceleration due to J_2, the atmospheric drag is the second most important contribution in low Earth orbits (with a magnitude between 10^{-5} and 10^{-13} km s^{-2}). The drag acceleration is opposite to the relative velocity, and is expressed as Montenbruck and Eberhard (2000):

$$\mathbf{a}_{drag} = -\frac{1}{2} C_D \frac{A}{m} \rho ||\mathbf{v}_r||.\mathbf{v}_r, \quad (1)$$

where C_D is the drag coefficient, $\frac{A}{M}$ is the cross-sectional area-over-mass coefficient, $\mathbf{v}_r$ is the satellite relative velocity vector with respect to the atmosphere, and ρ the atmospheric density at the position of the satellite. Classically, we express the relative velocity as:

$$\mathbf{v}_r = \mathbf{v} - \boldsymbol{\omega} \times \mathbf{r}, \quad (2)$$

with $\mathbf{v}$ the inertial velocity of the object and $\boldsymbol{\omega}$ the instantaneous rotation vector of the Earth ($\omega = 0.7292 \cdot 10^{-4}$ rad s^{-1}). Indeed, we consider the atmosphere rotating with the Earth and neglect the