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Review

Review of uncertainty sources affecting the long-term predictions of space debris evolutionary models

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A B S T R A C T

Since the launch of Sputnik-I in 1957, the amount of space debris in Earth's orbit has increased continuously. Historically, besides abandoned intact objects (spacecraft and orbital stages), the primary sources of space debris in Earth's orbit were (i) accidental and intentional break-ups which produced long-lasting debris and (ii) debris released intentionally during the operation of launch vehicle orbital stages and spacecraft. In the future, fragments generated by collisions are expected to become a significant source as well.

In this context, and from a purely mathematical point of view, the orbital debris population in Low Earth Orbit (LEO) should be intrinsically unstable, due to the physics of mutual collisions and the relative ineffectiveness of natural sink mechanisms above ~700 km. Therefore, the real question should not be “if”, but “when” the exponential growth of the space debris population is supposed to start. From a practical point of view, and in order to answer the previous question, since the end of the 1980's several sophisticated long-term debris evolutionary models have been developed.

Unfortunately, the predictions performed with such models, in particular beyond a few decades, are affected by considerable uncertainty. Such uncertainty comes from a relative important number of variables that being either under the partial control or completely out of the control of modellers, introduce a variability on the long-term simulation of the space debris population which cannot be captured with standard Monte Carlo statistics.

The objective of this paper is to present and discuss many of the uncertainty sources affecting the long-term predictions done with evolutionary models, in order to serve as a roadmap for the uncertainty and the statistical robustness analysis of the long-term evolution of the space debris population.

Contents

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1. Introduction

Since the launch of Sputnik-I in 1957, human activities in space have led to the production and release of hundreds of millions of objects of various sizes, from particles smaller than 1 mm to non-operational spacecraft measuring many square metres. In addition to abandoned intact objects, i.e. spacecraft and orbital stages, the primary sources of space debris have been accidental and intentional break-ups, as well as the intentional release of mission related objects. The growing amount of space debris makes the risk of collision among space objects increasingly likely. In this context, and from a purely mathematical point of view, the orbital debris population in LEO should be intrinsically unstable, due to the physics of mutual collisions and the relative ineffectiveness of natural sink mechanisms above ~700 km (cf. Fig. 1).

Therefore, the real question should not be “if”, but “when” the exponential growth of the space debris population were supposed to start. To address such important question, since the end of the 1980's several sophisticated long-term debris evolutionary models have been developed [2–6]. These tools have grown in complexity and capabilities, incorporating accurate orbit propagators, detailed launch traffic models, all the relevant sources and sinks mechanisms, updated on-orbit explosion/fragmentation statistics, improved break-up models for explosions and collisions (in terms of debris number, area, mass and velocity distributions), various methods for collision probability estimation, Monte Carlo statistical methods based on discrete-time Markov chains, etc. Currently these models are frequently used to probe reasonable future scenarios, being very well suited to evaluate the relative effectiveness of mitigation and remediation measures. The predictions done with these models are compared and fine-tuned, for instance in the framework of studies promoted by the Inter-Agency Space Debris Coordination Committee (IADC) [5].

Unfortunately these predictions, in particular beyond a few decades in the future, rely on our ability to predict and model a series of exogenous (e.g. future solar activity, the nature and magnitude of space traffic activities, etc.) and endogenous (e.g. the number of fragments generated after each collision, the number of future collisions among orbiting objects, etc.) variables, many of which are completely out of the control of modellers. Therefore, the actual predictions done with these models are affected by considerable uncertainty. This uncertainty is higher than that resulting from the analysis of Monte Carlo statistics, as the latter only measures the intrinsic variability in the occurrence of stochastic events modelled in the simulations [7–14].

2. Uncertainty sources

Mid-term and long-term projections of the Earth's satellite population performed with actual evolutionary models are affected by several important sources of uncertainty. Some of these uncertainty sources can be considered under the partial control of modellers, while some of them are completely outside their control [15].

Among the variables being under the partial control of modellers we can list:

- Initial debris environment;
- Atmospheric density models;
- Long term trajectory propagation;
- Collision probability estimation;
- Collision energetic threshold for catastrophic break-up;
- Collision geometry leading to catastrophic break-up;
- Collision class leading to catastrophic break-up (debris vs. debris, debris vs. intact, intact vs. intact);
- Break-up models (fragment number, area, mass and velocity distributions);
- Target ranking for active debris removal.

Among the variables being completely outside the control of modellers we can list:

- Future launch traffic and space technology evolution;
- Quality of mitigation measures adopted and overall levels of compliance;
- Viable technological options for remediation measures with active removal;
- Irresponsible deliberate actions endangering the environment (e.g. ill-conceived anti-satellite weapons tests);
- Evolution of solar and geomagnetic activity;
- Evolution of the upper atmosphere of the Earth at satellite altitudes.