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Author: Mrs. Elisa Boccolari
Politecnico di Milano, Italy

Ms. Martina Rusconi
Politecnico di Milano, Italy
Prof. Camilla Colombo
Politecnico di Milano, Italy

SYNERGIES BETWEEN PARTICLE-IN-A-BOX METHODS AND HIGH-FIDELITY METHODS FOR LONG-TERM LEO DEBRIS EVOLUTION

Abstract

The growing accumulation of orbital debris is a significant concern for the sustainability of space activities. Inactive satellites and fragmentation debris from collisions and explosions pose risks to operational spacecraft. To address this, space environment models have been developed to predict debris evolution, assess collision risks, and evaluate mitigation strategies.

Semi-deterministic models like ESA's DELTA and NASA's LEGEND simulate individual fragment trajectories with high accuracy, but they require significant computational resources, especially for smaller debris. Though flexible across orbital regimes, deriving statistical information from these models is computationally expensive.

A more efficient approach involves statistical descriptions of debris populations. Particle-In-a-Box (PIB) models divide space into predefined volumes and track debris in each bin, simplifying simulations at the cost of reduced accuracy. Tools like FADE, STAT, MISSD, MOCAT, and Politecnico di Milano's models use this approach. COMETA, developed by Politecnico di Milano, combines individual satellite propagation with modeling debris clouds as continuous density distributions. This hybrid approach reduces computational time for smaller debris and scales across various object sizes.

This work extends the PIB method, traditionally applied in one-dimensional altitude grids, to multiple variables such as semi-major axis, eccentricity, inclination, and area-to-mass ratio. The approach is applied to Low Earth Orbit (LEO) under atmospheric drag, describing the evolution of debris density using the method of characteristics and interpolation techniques. It categorizes debris based on size and characteristics, calculates collisions in bins statistically, and scales performance by size. The model improves collision and fragmentation calculations using a refined CUBE method and a probabilistic breakup model. It also incorporates post-mission disposal strategies, active debris removal, and varying launch models. Furthermore, it will explicitly account for the presence of constellations, treating them separately from other payloads while considering their unique characteristics.

The new methodology will be compared to the validated COMETA tool to assess computational performance, error sensitivity, and scalability. The comparison will highlight how the two methods complement each other: COMETA offers detailed simulations, while the new model provides faster results for preliminary assessments. The goal is to develop a robust, scalable framework that supports regulatory actions, debris removal strategies, and the long-term sustainability of space operations.