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SPACE CARRYING CAPACITY ASSESSMENT BASED ON A MULTIDISCIPLINARY SPACE DEBRIS ENVIRONMENT EVOLUTION MODEL

Abstract

In recent years, the rapid growth of human space activities, especially the deployment of mega constellations, has worsened the space debris environment. It is crucial to predict overall space debris evolution for analyzing space's carrying capacity.

The space debris environment evolution model can be categorized into two types: micro and macro. The microscopic models track the individual objects and use the Monte Carlo method to form debris events, requiring significant computational resources and time. The macroscopic models utilize debris count or density variables and employ differential equations to describe debris evolution. Macroscopic models offer significant efficiency in the context of constellations and have become a widely adopted and continuously evolving approach.

However, the precision of macroscopic models is limited by overly simplistic spatial segmentation (often based solely on altitude or, in some cases, not grouping objects at all). As a result, these models fail to accurately represent the true orbital characteristics of objects. The perturbation models they use are also simplified, such as neglecting Earth's nonspherical perturbations, as well as solar and geomagnetic activities. Moreover, previous models often treat different types of space objects independently, overlooking the interactions among objects.

Focusing on the above issues, this paper innovatively applies multidisciplinary approaches to the macroscopic space debris evolution model and analyzes space's carrying capacity, yielding two key contributions:

1) A three-dimensional (a, i, Ω) space debris environment evolution model is established, incorporating multidisciplinary approaches. It uses a topological network to structure the relationships among space objects, integrates fluid mechanics and spacecraft dynamics to describe the source and sink mechanisms under atmospheric drag, J2 perturbation, and solar and geomagnetic activities, and employs AI-based methods replacing traditional Monte Carlo simulations for breakup modeling. This model inherits the computational efficiency of macroscopic models and intelligent algorithms, while also providing a detailed representation of the characteristics of space objects and the topological relationships among them.

2) A constellation activity model is constructed based on actual mega constellation plans and on-orbit data, including the constellation's scale and configuration, satellite parameters, and satellite explosion rates. Meanwhile, various popular post-mission disposal (PMD) strategies have been modeled, such as

space tug towing, laser propulsion, and drag augmentation, among others. Using the aforementioned models, the boundaries of space's carrying capacity, along with the corresponding coupled parameters of constellations and PMD strategies, are analyzed.