Paper ID: 100514
student

23rd IAA SYMPOSIUM ON SPACE DEBRIS (A6)
Interactive Presentations - 23rd IAA SYMPOSIUM ON SPACE DEBRIS (IP)

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QUANTIFYING THE THREAT OF LOCALIZED FRAGMENTATION EVENTS IN LOW EARTH ORBIT: SIMULATION-BASED ASSESSMENT OF DEBRIS EVOLUTION AND OPERATIONAL DISRUPTIONS

Abstract

In 2025 over 40.000 cataloged objects and more than 130 million of untracked space debris orbit Earth in LEO. Number of objects present in LEO is steadily increasing, with over 3000 objects launched in 2024. As the number of objects increases, so does the probability of a collision. In 2024 SpaceX's starlink satellite constellation conducted near 100.000 propulsive maneuvers for collision avoidance, averaging 20 per satellite annually. It is established that in order to sustain operations in LEO without major disruptions, post mission disposal rates must approach 90% in the short to mid-term, escalating to 95-99% over a 200-year horizon. Present PMD rates are critically deficient, with a stable 20-30% PMD rate. These figures however, do not account for a rapid increase in the number of debris, due to localised fragmentation events, which have occurred 650 times as of 2025, with an average of 11 annual incidents. Projections indicate a substantial increase in their occurrence in the foreseeable future. The paper delineates results of research on a comprehensive dataset of conducted simulations examining short-term effects of satellite collisions or self-inflicted fragmentations within LEO. In the course of the simulations, performed on proprietary developed and publicly available models, a range of fragmentation scenarios and randomised velocity distributions were utilised, allowing for a statistically robust exploration of the outcomes. The analysis quantified the hazard of post-fragmentation debris-satellite impacts based on proximity thresholds and considered the relative decay rates of debris, including the possibility for achieving escape velocities from LEO. The study rigorously assesses the threat posed by localized fragmentation events in LEO, with particular emphasis on the escalation of collision probabilities and the potential initiation of self-sustaining reaction – the Kessler Syndrome. Results of the study will outline the outcomes of localized fragmentation events in selected scenarios and render possible levels of disruption of operations in LEO. The study aims to establish required accuracy of collision avoidance systems necessary to preclude localized fragmentations with regards to collision inflicted events and a range of scenarios necessitating provision of active debris removal systems. Examined will be short to long-term consequences for the space operations by the debris created in localized fragmentation events, specifically in regards to continuous operations in LEO, including, but not limited to, a possibility of undisrupted operations on established orbits and possibility of continuous launches with respect to the launchsite geolocation.