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ENHANCING REENTRY RISK ANALYSIS FOR SPACE OBJECTS: METHODOLOGIES AND IMPROVEMENTS

Abstract

The increasing frequency of space launches and the resultant rise in space debris in low Earth orbit (LEO) have made the risk of uncontrolled reentries more pressing. Accurate forecasting of reentry locations is challenged by uncertainties in objects' ballistic coefficients, breakup behaviors, and atmospheric conditions. This paper reviews methodologies for reentry risk analysis of space objects and proposes improvements. We systematically examine the key steps of the reentry risk analysis process: break-up scenarios, debris dispersion, and population exposure. By contrasting existing methods with higher fidelity solutions, we quantify the differences through test cases and emphasize the impact on risk estimations and hazard area derivations, with a focus on aircraft risk.

To enhance reentry risk predictions, this paper advocates for the use of higher-fidelity consequence models, which consider risks beyond unsheltered persons, and the integration of state-of-the-art nowcasting models to predict thermospheric states during critical short-term reentry periods. We propose improvements in accuracy, efficiency and information availability to enable rapid model updates, a crucial requirement for global airspace closures. Given the aviation sector's vulnerability and need for responsiveness, we discuss relevant aspects to reduce interference with air traffic.

The necessity for timely published and trustworthy hazard mitigation strategies is underscored by an incident in November 2022, when multiple zero-rate (closures) NOTAMs were issued by EUROCONTROL due to the uncontrolled reentry of a 20-tonne Long March 5B rocket body. The air traffic delays added up to 309 hours, with extremely short lead-times (¡ 30 minutes) of the closures and higher concentration of air traffic at the outer bounds of the NOTAMs, still below the reentry trajectory of the rocket body. The latest dramatic uncontrolled reentry on 19 February 2025 illuminated large parts of the sky across Europe. A SpaceX Falcon 9 second stage reentered the atmosphere, resulting in debris impacts in Poland. To the knowledge of the authors, no airspace closures have been issued.

The paper is organized into sections covering the randomization strategy of reentry trajectories, utilization of high-fidelity space weather forecasts, impact probability density derivation, population exposure assessments, and enhancements in casualty expectation estimation. We demonstrate these improvements through long-term and short-term predictions of the well-documented Tiangong-1 and Delta II reentries.

We aim to improve the accuracy of uncontrolled space vehicle reentry predictions. These advancements are essential for understanding and mitigating risks to the public and avoiding high consequence outcomes.