Limitations of the cube method for assessing large constellations

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ABSTRACT

Due to the significant computational demands involved in the long-term projection of large debris populations, evolutionary models make use of fast and efficient algorithms for orbit propagation and collision risk assessment. By necessity, these algorithms represent simplifications of the real-world and only provide estimates of true motion and collision probabilities. A commonly used algorithm for collision risk assessment is the Cube method, introduced by Liou et al. in 2003. The objective of this method is to estimate long-term collision probabilities between orbiting objects using a fast and efficient "sampling in time" approach: at every propagation time-step, the mean anomaly of every object is randomized and the ensuing set of states are evaluated to identify all instances where two objects are co-located within the same cubic volume element. Subsequently, the collision probability for co-located object pairs is determined through an application of the kinetic theory of gases, which assumes that the objects are equally likely to be found anywhere within the cube. Recent work by Diserens et al., focused on the case of the Jovian moons, has shown that errors in the collision probability estimates for object pairs arise due to an insufficient number of iterations of the method and due to a failure to identify an appropriate size for the cubic volume element. As indicated by Diserens et al., these errors are especially important when assessing the collision risk associated with large constellations because of the structure and the relatively high number of spacecraft involved. Consequently, the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) evolutionary model was used to determine the appropriate choice of model parameters for a robust assessment of the collision risk arising from the deployment of the OneWeb constellation. In particular, the cube size, propagation time-step and number of Monte Carlo runs were investigated and the results were compared against those produced by a novel Deterministic Collision Assessment (DCA) method, which was established to provide reliable collision probability estimates.

The results showed that cube sizes between 4 km and 8 km were required to deliver reliable collision rate estimates for discrete object pairs and that time-steps of less than 0.1 days were also necessary. For long-term projections involving many objects in the Low Earth Orbit (LEO) environment, such small time-steps are impractical, as simulation run-times for a single Monte Carlo run would increase from hours to days, or even weeks. Alternatively an increase in the number of Monte Carlo runs by a factor of at least 50 would enable a more robust outcome, but again this would lead to significant computational expense. However, as noted by Diserens et al., the problems associated with longer time-steps (or fewer Monte Carlo runs) tends to reduce when the error is accumulated across a large population of objects (i.e. via regression to the mean). Nevertheless, it is likely that errors in the collision probability estimates produced by the cube method will persist when it is used for long-term projections of the orbital debris population. The corresponding errors for projections involving the OneWeb constellation were quantified for a variety of different scenarios using the DCA method and were used to provide a calibration of the cube method for future studies.

Finally, it was found that the cube algorithm incorrectly identified collisions between spacecraft in neighboring orbital planes of the OneWeb constellation that were separated in altitude. The separation of the orbital planes is a reasonable orbital debris mitigation measure for large constellations, as per the recommendations made by the Inter-Agency Space Debris Coordination Committee (IADC), but the cube approach is not an appropriate method to evaluate the benefits. Consequently, other collision assessment methods are needed and care should be taken when using the cube method to appraise the long-term implications of deploying large constellations.