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Methodology for characterizing high-risk orbital debris in the geosynchronous orbit regime

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Abstract

Forecasting of localized debris congestion in the geostationary (GEO) ring is performed to formulate and investigate methodology for identifying the debris objects that pose the highest risk to operational satellites in this ring. Proximity and speed relative to GEO during near-miss events detected under a torus intersection metric are translated into a combined risk factor that is accumulated during propagation. This accumulated risk is then used to identify the objects that have the highest risk contributions, either globally or in the vicinity of one of the two gravitational wells at 75°E and 105°W. Results show that nearly 60% of the total risk surrounding the Western well is attributed to 10 derelicts alone, which has critical implications for active debris removal (ADR) target selection for attenuating risk levels in this ring.

Keywords: Orbital debris; Geosynchronous orbit; ADR target selection

1. Introduction

The geostationary (GEO) regime is a unique commodity of the terrestrial satellite industry that is becoming increasingly contaminated with orbital debris (Johnson, 1999; Jehn et al., 2005), but is heavily populated with high-value assets (Chrystal et al., 2011). As the lack of atmospheric drag effects at the GEO altitude renders lifetimes of these debris essentially infinitely long, conjunction assessment must be performed to safeguard operational GEO satellites from potential collisions with the uncontrolled derelict field. GEO satellites must maintain a specified longitude slot, and cannot simply shift in phase to evade debris. Therefore, studies of the macroscopic behavior of the GEO debris population are required to describe debris fluxes through particular GEO longitude slots, and forecast how frequently operational assets in these regions must potentially perform maneuvers to mitigate conjunctions. Rather than presenting the high-precision analysis demanded by risk assessment and mitigation measures, this study builds upon the methods of Anderson and Schaub (2013), which illustrates a one-year, macroscopic congestion forecast for debris at GEO, to determine which localized regions of the GEO ring are, in general, most susceptible to rising levels of debris congestion. As overcrowding of this ring is growing into a serious concern for owners and operators internationally, knowledge of debris flux patterns—termed debris weather—is critical for space situational awareness activities at GEO. Of a significant interest is determining which classes of uncontrolled derelicts contribute the most to congestion and risk levels, both globally and locally, over a specified time frame. Assessing if subsets of the debris

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population contribute homogeneously to congestion and risk levels across GEO is imperative information for active debris removal (ADR) initiatives seeking to attenuate localized risk in particular longitude slots to sustain slot utilization.

Existing debris analysis tools (Lewis et al., 2001; Klinkrad, 2006) rely upon inertially-fixed cells to detect debris cell passage events (CPE), such that densities are often averaged over cell right ascension, and provided as a function of altitude and declination (Klinkrad, 2006). Following Anderson and Schaub (2013), this study harnesses a toroidal cell configuration in the GEO ring to investigate the impact of various classes of large-scale, uncontrolled objects on congestion and risk levels from a longitude-dependent perspective. Small-scale debris sources such as explosion and collision events, although considered recently in Hansen and Sorge (2013) and Oltrogge and Finkleman (2008), are not considered in this study, nor are other growth mechanisms such as ejection of solid rocket motor (SRM) slag or shedding of multi-layered insulation (MLI) (Wegener et al., 2004).

Using publicly-available U.S. Strategic Command tracking data and an orbit classification system established by the European Space Agency (Flegel et al., 2009; Flohrer, 2014), this paper will illustrate a five-year debris forecast in the GEO ring for large-scale, trackable, and unclassified resident space objects (RSOs) with up-to-date two-line element (TLE) sets. The results of this five-year debris simulation—which performs parallel propagation using 4×4 EGM-96 gravitation, luni-solar perturbations, and a nominal solar radiation pressure effect—are used to characterize which classes of uncontrolled debris objects contribute the most to longitude-dependent risk levels, globally and over a defined subset of longitude slots. In particular, methodology for identifying the objects that contribute the largest percentage to the total risk level accumulated either globally or locally during the forecasting period is presented. For ADR initiatives geared towards slot clean-up at particular longitudes, information such as that determined from debris simulations harnessing the torus intersection metric to evaluate longitude-dependent risk is especially useful in helping to determine which individual objects should be removed to maximize reduction in risk, either globally or across a defined subset of longitude slots, namely, in the vicinity of the high-impact and debris-critical gravitational wells positioned at 75°E and 105°W (Anderson and Schaub, 2013).

The results of this work may thus be harnessed in tandem with long-term debris prediction studies, such as that performed in Anderson and Schaub (2014), to provide recommendations for architecture and design of potential ADR demonstration missions in the GEO regime. Studies led by the NASA Orbital Debris Program Office use the product of a debris object's mass and its probability of collision at a desired epoch as the ADR target selection criterion for identifying the top ADR targets in the LEO regime (Liou, 2011). ADR target selection studies for the GEO regime have received less attention than equivalent LEO ADR target studies (Liou, 2011; Peterson, 2012; Quinlan et al., 2011). This study seeks to begin filling this void in the literature by formulating methodology for identifying the top ADR targets at GEO, based on the torus intersection metric and independent of the statistical probability of collision measure often used in conjunction assessment, a computation that requires position covariance information. Note that this torus intersection metric—which is useful for gauging localized congestion at GEO—does not claim that the identified ADR targets might actually collide with specific operational satellites at GEO. The source of orbital data for this study is the publicly-available TLE sets, which are not accurate enough to forecast conjunction events over the long-term, and do not include covariance information. Rather, instead of evaluating satellite-specific probabilities of collision against the large-scale debris population, this study seeks to identify the specific GEO debris objects in this population that contribute the highest levels of macroscopic risk to the GEO regime in general, both globally and in the vicinity of the gravitational wells. In this sense, potential conjunction events with high-macroscopic-risk objects are more threatening in that these derelicts are routinely passing through particular longitude slots at GEO with non-trivial, potentially catastrophic velocities relative to GEO.

2. Current RSO population at GEO

The RSO population in the GEO regime is categorized using the orbit taxonomy applied in the European Space Agency's DISCOS database (Database and Information System Characterising Objects in Space) (Flohrer et al., 2013). For GEO objects, seven categories are selected to classify the types of orbits exhibited – two controlled classes and five uncontrolled classes (see Table 1). Note that only the uncontrolled objects are assumed to contribute to localized debris congestion in this study. GEO RSOs are selected according to the orbit element bounds used in the European Space Agency's *Classification of Geosynchronous Objects* reports (Flohrer, 2014): eccentricity less than 0.2 ($e < 0.2$), inclination less than 70° ($i < 70°$), and mean motion between 0.9 and 1.1 revolutions per sidereal day ($0.9 < n < 1.1$), corresponding to the semi-major axis range $-2596\text{ km} < a - a_{\text{GEO}} < 3068\text{ km}$ relative to GEO. Per these element bounds, launch vehicle upper stages are only included in the congestion forecast if they exhibit GEO-like orbits. As a result, rocket bodies in highly-eccentric geostationary transfer orbits (GTOs) are not considered, even though these trajectories are closely approaching—or crossing through—the GEO altitude at or near apogee.

Orbital data is obtained from the publicly-available two-line element (TLE) sets provided by U.S. Strategic Command (USSTRATCOM).[2] For this study, a reference

[2] Publicly-available TLE data sets are available for bulk download from https://www.space-track.org/.