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Conjunction challenges of low-thrust geosynchronous debris removal maneuvers

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ABSTRACT

The conjunction challenges of low-thrust engines for continuous thrust re-orbiting of geosynchronous (GEO) objects to super-synchronous disposal orbits are investigated, with applications to end-of-life mitigation and active debris removal (ADR) technologies. In particular, the low maneuverability of low-thrust systems renders collision avoidance a challenging task. This study investigates the number of conjunction events a low-thrust system could encounter with the current GEO debris population during a typical re-orbit to 300 km above the GEO ring. Sensitivities to thrust level and initial longitude and inclination are evaluated, and the impact of delaying the start time for a re-orbiting maneuver is assessed. Results demonstrate that the mean number of conjunctions increases hyperbolically as thrust level decreases, but timing the start of the maneuver appropriately can reduce the average conjunction rate when lower thrust levels are applied.

1. Introduction

The geostationary (GEO) regime is a unique commodity of the terrestrial satellite industry that is becoming increasingly contaminated with orbital debris [11,13], but is heavily populated with high-value assets [5]. 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, as the resident space object population at GEO continues to increase, the fuel cost required to remain at a particular longitude slot while performing collision avoidance with uncontrolled objects will begin to increase in tandem. Ultimately, global adherence to end-of-life mitigation guidelines must be combined with environmental remediation—active debris removal (ADR)—to curtail debris growth in this regime [1]. The necessity for cost-effective ADR implementation in the GEO ring is becoming more prominent, especially for larger debris (payloads, upper stages) that pose the greatest threat to operational assets.

Proposed ADR techniques for the GEO arena typically involve re-orbiting of large-scale derelicts to "graveyard" disposal orbits at perigee altitudes above the GEO ring, factoring the GEO protection zone [6] and area-to-mass ratio of the object into the minimum altitude calculation [11,12,19]. A chief space-tug concept is often envisioned for performing the re-orbiting maneuver once contact with the target debris object has been established. However, as rendezvous, proximity operations, and docking with an uncontrolled—and potentially tumbling—object are challenging, several proposed methods have focused on contactless technologies such as an electrostatic tractor [24] or ion beam shepherd [4] for ADR at GEO. Each of these contactless ADR technologies rely on low-thrust engines for performing the required re-orbit maneuver. With lower maneuverability, however, collision avoidance for such low-thrust re-orbit systems is challenging. Potential conjunctions must be detected multiple revolutions in advance, to give the tug guidance system enough lead time to place the tug on a sufficient evasive trajectory, especially if this craft is designed to operate autonomously with minimal ground support. Of interest is investigating how many conjunction events with the current debris population at GEO could be experienced during a typical continuous thrust re-orbiting maneuver to an IADC-compliant graveyard orbit 300 km above the GEO ring [11]. Specifically, quantifying the "conjunction challenge" for a particular thrust level —that is, the global average of the number of conjunctions that could be expected for a re-orbit trajectory at this thrust level, regardless of initial longitude or inclination—is a useful tool for architecture and system design for potential ADR demonstration missions at GEO.

Evaluating the global conjunction challenge for low-thrust GEO disposal maneuvers is beneficial not only for remediation concepts, but also for operational end-of-life mitigation activities as

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well. Since lightweight, all-electric busses are becoming more prominent in the satellite industry,[1] lower-thrust electric propulsion is now being harnessed both for orbit raising and station-keeping of GEO assets. Previously, GEO satellites with chemical thrusters have used a two- to three-impulse Hohmann-like transfer to re-orbit to a disposal orbit at end-of-life [15,21] but GEO satellites equipped with low-thrust electric engines must use continuous thrust orbit raising strategies to achieve the desired increase in semi-major axis. Since continuous thrust re-orbiting performed under mN levels of thrust takes from weeks to months to achieve a 300 km increase in semi-major axis [24], it is important to investigate the number of conjunctions that such satellites might experience during this phase of decommissioning. It is undesirable to be responsible for a debris-generating event while engaged in an act of mitigation or remediation—thus, characterizing the conjunction challenges of low-thrust re-orbit maneuvers is critical knowledge for both all-electric satellite operators and designers of low-thrust ADR systems.[2]

2. Current Resident Space Object (RSO) population at GEO

The RSO population in the GEO regime is classified with a taxonomy used by the European Space Agency's DISCOS database (Database and Information System Characterising Objects in Space) [6]. 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 uncontrolled objects are assumed to contribute to local 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 [6]: eccentricity less than 0.2 ($e < 0.2$), inclination less than 70° ($i < 70°$), and mean motion between 0.9 and 1.1 revs per sidereal day ($0.9 < n < 1.1$), corresponding to the semi-major axis range $-2596\text{ km} < a < 3068\text{ km}$ with respect to GEO.

Orbital data is obtained from the publicly-available two-line element (TLE) sets provided by U.S. Strategic Command (USSTRATCOM).[3] For this study, a reference TLE set obtained on 02/28/2014 is employed; the class distribution for the 1145 objects extracted from this set is shown in Fig. 1. TLE data are provided in the form of doubly-averaged Keplerian elements with mean motion instead of semi-major axis [15], transformed into Cartesian states in the true equator, mean equinox (TEME) frame [25] with SGP-4 theory [10].[4] Note that because of the limited accuracy of TLE data sets, these data are not intended for studies that require highly-precise orbit prediction capabilities. Furthermore, as only objects larger than approximately 0.8–1.0 m in effective diameter are actively tracked at the GEO altitude [6], only objects at least of this size are considered here. Since this analysis only includes the trackable, cataloged, and unclassified GEO population with recent TLE sets, the findings of this study serve to illustrate a lower bound of the actual potential for conjunctions during GEO re-orbit.

[1] de Selding, P. B., "News from Satellite 2014: Boeing Electric Satellite Backlog Posed to Grow, includes Previously Undisclosed U.S. Gov't Order", *Space News*, 13 March 2014, Web.

[2] In this paper, GEO satellites using continuous thrust during end-of-life operations, and ADR space-tug concepts that use continuous thrust to re-orbit derelict objects to disposal orbits, are collectively termed *re-orbit systems* for generality.

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

[4] C implementation of SGP-4/SDP-4 is available at http://www.sat.dundee.ac.uk/~psc/sgp4.html [26].

Table 1
Orbit classifications for geosynchronous objects used in GEO conjunction study.

Class	Type	Description
C1	Controlled	Longitude/inclination control (E–W/N–S control)
C2	Controlled	Longitude control only (E–W control only)
D	Drifting	Circulating above/below/through GEO altitude
L1	Librating	Libration about Eastern stable point at 75°E
L2	Librating	Libration about Western stable point at 105°W
L3	Librating	Libration about Eastern and Western stable points
IN	Indeterminate	Unknown status (e.g., recent TLE not available)

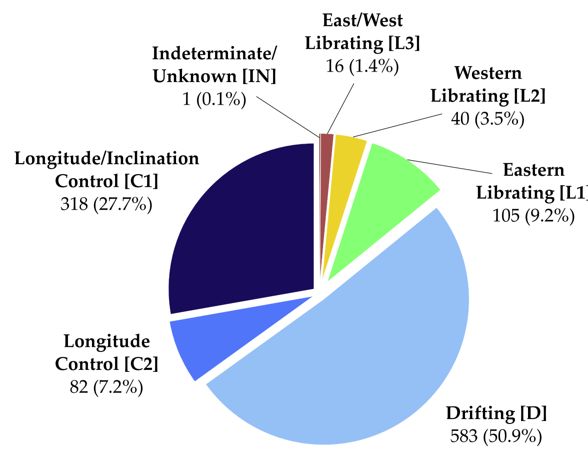

Fig. 1. GEO orbit classifications for 02/28/2014 reference TLE set.

3. Analytic results for continuous thrust trajectories

In the framework of two-body mechanics, analytic expressions that describe the semi-major axis and longitude profiles for a continuous thrust re-orbit trajectory—as a function of thrust acceleration and elapsed time since the start of the re-orbit maneuver—are now derived. Following Prussing and Conway [20], the temporal derivative of the specific two-body orbit energy is

$$\epsilon = -\frac{\mu_\oplus}{2a} \Longrightarrow \dot{\epsilon} = \frac{\mu_\oplus}{2a^2}\dot{a} \tag{1}$$

where $\dot{a}$ denotes the time rate of change of the semi-major axis. From elementary physics, the rate of change of specific energy due to a thrust vector $\mathbf{\Gamma}$ is $\dot{\epsilon} = \mathbf{\Gamma}\cdot\boldsymbol{v}$, where $\boldsymbol{v}$ is the inertial velocity vector. Assuming that the thrust acceleration is directed along the instantaneous velocity direction, we have $\dot{\epsilon} = \Gamma v$, such that

$$\frac{\mu_\oplus}{2a^2}\dot{a} = \Gamma v \Longrightarrow \dot{a} = \frac{2a^2\Gamma}{\mu_\oplus}v \approx \frac{2a^{3/2}\Gamma}{\sqrt{\mu_\oplus}} \tag{2}$$

where it is assumed that the osculating orbit remains approximately circular during the continuous-thrust re-orbit, such that $v = \sqrt{\mu_\oplus/a}$ is applicable. Separating variables and assuming constant Γ, we have

$$\int a^{-3/2}\,\mathrm{d}a = \frac{2\Gamma}{\sqrt{\mu_\oplus}}\int \mathrm{d}t \tag{3}$$

Performing the integration and enforcing the initial condition $a(0) = a_0$:

$$-\frac{1}{\sqrt{a}} = \frac{\Gamma}{\sqrt{\mu_\oplus}}t - \frac{1}{\sqrt{a_0}} \Longrightarrow a(t) = \frac{a_0\mu_\oplus}{(\sqrt{\mu_\oplus} - \Gamma\sqrt{a_0}\,t)^2} \tag{4}$$