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New insights on the orbital debris collision hazard at GEO ☆

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ABSTRACT

An analysis is performed of the orbital debris collision hazard to operational spacecraft at geosynchronous orbit (GEO). As part of the examination, the contribution of individual components of the population are considered and presented to provide a clearer linkage between object characteristic and resulting risk. Our examination of GEO collision risk reveals several critical new insights: (1) the current probability of collision in GEO is relatively low, yet the future is difficult to predict due to our limited ability to observe objects in GEO and the uncertainty in past and future debris-generating events in GEO; (2) the probability of collision in GEO is not uniform by longitude — it is seven times greater in regions centered about the geopotential wells; (3) the probability of a mission-terminating collision is greatly dependent upon the approximately 2200 objects in the 10 cm–1 m range observed in GEO but not yet cataloged; (4) hardware relocated to GEO "graveyard" disposal orbits pose a potential additional, but not fully understood, collision hazard to operational GEO satellites; and (5) the collision hazard throughout the course of a day or year is highly episodic (i.e. non-uniform).

1. Introduction

The region of outer space where satellites orbit the Earth is a unique, limited resource that must be preserved for the global community to operate broadcast, remote sensing, meteorological, and communications systems. Space faring countries have perfected aerospace engineering solutions to produce ever more effective and reliable satellites to survive through and in harsh launch and orbital environments. However, one of the most daunting challenges to the space community is a hazard created of our own doing: orbital debris.

Since 1957, man has launched satellites into a variety of orbits to pursue national and international imperatives. When a typical space mission is executed it will deposit one or more payloads into orbit while releasing a variety of pieces of hardware along the way from the launch process such as depleted rocket stages, adapter rings, etc. Once the satellite is placed into its final orbit, hardware may also be released as the satellite is "started up", such as lens covers, yo-yo spin-up weights, solar panel clamps, etc. Through a variety of intentional and unintentional mechanisms the operational payload or derelict rocket body may be destroyed by: onboard self-destruct devices, overpressurization of propellant tanks, inadvertent mixing of hypergolic fuels, antisatellite testing, accidental collision with other orbital objects, overheating of batteries, etc. Once the payload has finished its mission and is no longer functional, it becomes orbital debris itself.

The US Space Surveillance Network (SSN) maintains a catalog of earth-orbiting objects. The catalog nominally includes objects in Low Earth orbit (LEO) greater than 10 cm in diameter and larger than 1 m in geosynchronous orbit (GEO — 24 h orbit) [1]. Orbital debris significantly skews the catalog population accounting for over 93% of the current 20,000 cataloged objects.

2. LEO vs GEO

There are no clear boundaries for orbital regions, however, the general classes of low Earth orbit (LEO) and

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geosynchronous orbit (GEO) comprise much of the overall on-orbit population of operational payloads and orbital debris. LEO is considered to be all orbits with average altitudes below about 2000 km. Within LEO, the manned spaceflight corridor (generally250–450 km) and the sun-synchronous orbit region (generally 600–1100 km and inclinations of 98–100°) constitute two major focus areas. While the first missions to LEO started in 1957, the first mission to GEO did not occur until 1963 though the rate at which current launches take place to these two locations are very nearly the same by number at this point: 35 launches to LEO and 25 launches to GEO in 2010 [1].

GEO, however, is of special significance due to the growing interest in deploying large, complex systems to this unique orbit; the lack of any natural cleansing mechanism (such as atmospheric drag); and the greater international participation in GEO with communications, broadcast, surveillance, and meteorological satellites.

Before examining the detailed debris behavior and collision risk in GEO, the LEO and GEO regions will be contrasted for context. Table 1 portrays the number and mass distribution in LEO and GEO.

As mentioned earlier, the number of objects in the SSN satellite catalog is skewed by different detection thresholds: about 10 cm for LEO objects and 1 m for objects in GEO. However, it is estimated that the GEO "catalog" would surpass ~3200 if objects in GEO down to 10 cm were cataloged [2–4]. Similarly, if only objects greater than 1 m were considered in LEO the catalog would drop to 1600: this is only 60% larger than the GEO cataloged population of the same sized objects (i.e. approximately 1 m).

A critical observation about collision hazard assessments is the fact that any collision hazard term described solely by altitude is insufficient to characterize the true threat from orbital debris. In LEO, the distribution of objects across many inclinations for most altitude regions creates a latitude-dependent functionality. This is most pronounced at typical sun-synchronous altitudes where the spatial density is five times larger at moderately high latitudes, ~80–85°, relative to the equator [5]. As all of the objects continue to orbit, in the same altitude region, the volume in which they reside decreases for higher latitudes. This occurs since the circumference at higher latitudes is less than at the equator so the same number of objects reside in a smaller volume, creating a higher spatial density. It should be noted that objects with complementary inclinations (i.e. the two inclinations sum to 180°) will traverse the same latitude expanse but going in opposite directions. The peak around 82° is contributed to by both 82° and 98° inclination orbits. A ramification of this latitude-dependency is that it is more likely that an accidental collision in these altitudes will occur at higher latitudes. Indeed, the 2009 Iridium/Cosmos 2251 event occurred at around 72°N while Iridium had an inclination of 86° and Cosmos 2251 had an inclination of 74°.

Alternatively, the spatial density in GEO will vary as a function of longitude rather than latitude. To characterize this distribution and highlight its relevance we will now examine the behavior of objects in GEO in more detail.

3. Detailed behavior of GEO objects

Fig. 1 illustrates the GEO (i.e. mean motion between 0.9–1.1rev/day) cataloged population in three ways: (1) by dynamics, (2) object type, and (3) age. The impact of the dynamics of the objects are discussed further later in the paper with an emphasis on the ~160 objects "trapped" in the two geopotential wells. The object type description highlights the large percentage of massive payloads, both operational and non-operational, in GEO. The age of GEO objects accentuates the increased level of activity at GEO with about 360 objects being on-orbit for

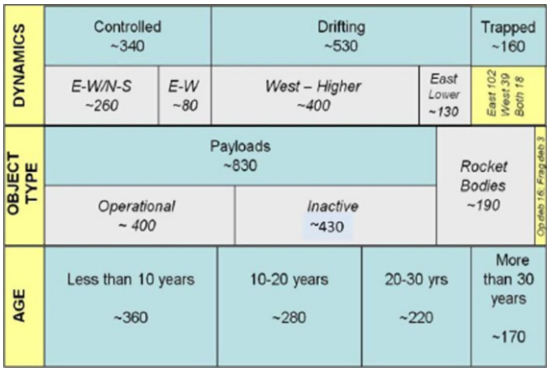

Fig. 1. Cataloged objects in GEO are generally massive payloads that have been deployed in the last twenty years [1,4].

Table 1
LEO and GEO have distinctly different distributions within the SSN Satellite Catalog by number and mass (Data as of January 1, 2010).

Object type	LEO (> 10 cm)		GEO (> 1 m)	
	Number	Mass (kg)	Number	Mass (kg)
Operational payloads	~550	~400,000	~400	~600,000
Non-operational payloads	~1,600	~800,000	~430	~600,000
Rocket bodies	~900	~1,100,000	~190	~400,000
Fragmentation debris	~8,100	~100,000	3	~10
Mission-related debris	~1,000	~500	16	~50
Total	**~12,000** **~1,600 if consider only > 1 m**	**~2,400,000**	**~1,000** **~3,200 if consider all objects > 10 cm**	**~1,600,000**