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Wholesale debris removal from LEO ☆

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ABSTRACT

Recent advances in electrodynamic propulsion make it possible to seriously consider wholesale removal of large debris from LEO for the first time since the beginning of the space era. Cumulative ranking of large groups of the LEO debris population and general limitations of passive drag devices and rocket-based removal systems are analyzed. A candidate electrodynamic debris removal system is discussed that can affordably remove all debris objects over 2 kg from LEO in 7 years. That means removing more than 99% of the collision-generated debris potential in LEO. Removal is performed by a dozen 100-kg propellantless vehicles that react against the Earth's magnetic field. The debris objects are dragged down and released into short-lived orbits below ISS. As an alternative to deorbit, some of them can be collected for storage and possible in-orbit recycling. The estimated cost per kilogram of debris removed is a small fraction of typical launch costs per kilogram. These rates are low enough to open commercial opportunities and create a governing framework for wholesale removal of large debris objects from LEO.

1. Introduction

Space debris from discarded upper stages, dead satellites, and assorted pieces from staging, tank explosions, and impacts has been growing since the beginning of the space age. There are currently about 9000 tracked debris objects in LEO per 450 operational satellites (20 to 1 ratio), while the number of untracked lethal impactors in the centimeter range is simply staggering, on the order of 500,000. The risk to active satellites and the need for avoidance maneuvering have increased dramatically in the past few years [1].

Up until 2009, the dangers of space debris were generally ignored under the "big sky" theory, but the Cosmos–Iridium collision changed that. On February 10, 2009, a fully maneuverable and "well-behaved" operational satellite ran into a 16-year-old derelict satellite at 11.6 km/s. In less than a millisecond, the two satellites disintegrated, producing nearly 2000 tracked debris objects and on the order of 100,000 untracked fragments in the centimeter range. This came as a sobering preview of things to come.

After years of debris accumulation, the LEO debris cloud has crossed critical density thresholds over a wide range of altitudes [2], as predicted by Kessler, and entered into a phase of accelerated debris creation in collisions that become more and more frequent. The collision rate scales with the second power of the density of large debris, which has grown nearly linearly over the last 50 years. In this deteriorating environment, a collision like Cosmos–Iridium was bound to happen, and the theory predicts that we may witness another catastrophic collision in this decade [2]. The Cosmos–Iridium collision involved a total mass of 1.5 tons, which was substantially less than the average mass statistically expected to be involved in a collision between intact objects. The next catastrophic collision is more likely to be on a scale comparable to the Chinese ASAT test and the Cosmos–Iridium collision combined.

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The NASA Orbital Debris Program Office has been arguing for quite some time that in addition to debris mitigation we need to start removing at least five large objects per year to prevent the "debris runaway" or "Kessler Syndrome" [2]. This is the minimum rate required just to stabilize the current environment, which means still having catastrophic collisions every decade or so, but at least not more frequently. A recent study conducted for the International Academy of Astronautics suggested removing 10–15 large intact objects from LEO per year [3,4]. In 2011, the ESA Space Debris Office concluded that half-measures are not enough, and the goal should be to remove LEO debris en masse as soon as possible [1].

In this paper, we will discuss some general relations and one practical implementation of the wholesale removal of large debris from LEO.

2. LEO debris ranking

The LEO debris environment is well characterized by models like ORDEM, MASTER, LEGEND, and others, even though there are some noticeable differences in their estimates of the number of small debris particles in certain regions [5]. There are three major groups of lethal debris objects in LEO. Using a highway analogy for illustrative purposes [6], we can say that satellites and stages are like cars, small components shed along the way are like hubcaps, but those hundreds of thousands of small fragments generated in "car" collisions are more like shrapnel, whizzing all around active satellites at orbital speeds (Table 1).

Due to the large numbers, the "shrapnel" is the primary threat to operational satellites, and most new pieces will come from collisions involving "cars", because the "cars" account for nearly all collision area and mass of the debris. This means that we must remove the old "cars" to prevent LEO pollution with more "shrapnel." The collision-generated debris potential associated with large objects can be estimated by the statistically expected cumulative yield of fragments generated in catastrophic collisions,

$$R_k = M_k P_k, \tag{1}$$

where M_k is the mass of the debris object, and P_k is the probability of a catastrophic collision involving this object over a certain period of time. A risk measure of this kind has been also suggested by NASA [2,7]. The probabilities P_k can be evaluated from the debris environment models or computed from the catalog with averaging over a representative period of time,

$$R_k = M_k \sum_n P_{kn}, \tag{2}$$

where P_{kn} are the probabilities of a collision between objects k and n, assuming that they are small enough to disregard event dependency. Collisions between "cars" are usually catastrophic, and even a very small "car" like a 4-kg 3U CubeSat can smash a really large "car" into small pieces, especially in a head-on collision. The whole LEO debris cloud is dynamic, and the probabilities P_{kn} vary with time, as the orbits and population change. For example, after the Cosmos–Iridium collision, the corresponding terms P_{kn} dropped out of the probability matrix.

An important feature of the probabilities P_{kn} is their sensitivity to "inclination pairing" observed when $i_k + i_n$ is approaching 180°. Fig. 1 illustrates this notion by plotting typical multipliers β_{kn} resulting from "inclination pairing," as described in [6]. For objects at $i_k = 98^\circ$, the multiplier peaks at $i_n = 82^\circ$ (a), while for objects at $i_k = 82^\circ$, it peaks at $i_n = 98^\circ$ (b). This happens because the orbits at 82° and 98° precess in the opposite directions, and when they become nearly coplanar, the objects move head-on, greatly increasing the probability of collision. The implications are significant, as we will see below. One of the examples is that the satellites of the NASA Earth Observing System operating in Sun-sync orbits encounter a high percentage of head-on conjunctions [8].

We can now evaluate collision-generated debris potential of selected groups of debris objects,

$$R_g = \sum_{k,n} M_k P_{kn}, \tag{3}$$

and analyze its cumulative distributions by location and ownership. Fig. 2(a) shows the cumulative distribution of the collision-generated debris potential by 5° inclination bins compared to the distribution of the number of operational satellites in LEO (b) according to [9].

Three clusters stand out, 71–74°, 81–83°, and Sun-sync, of which the last two are "inclination paired," as explained above, and represent elevated collision threats to each other. Removing just old upper stages from these

Table 1
Lethal debris objects in LEO.

Type	Characteristics	Hazard
"Shrapnel"	Untracked, over ~1 cm, 98% of lethal objects	Primary threat to satellites; too small to track and avoid, too heavy to shield against
"Hubcaps"	Tracked, > 10 cm, < 2 kg, 2% of lethal objects	Most conjunctions and avoidance maneuvers for operational satellites
"Cars"	Tracked, over 2 kg, < 1% of lethal objects	Primary source of new shrapnel; 99% of the collision area and mass

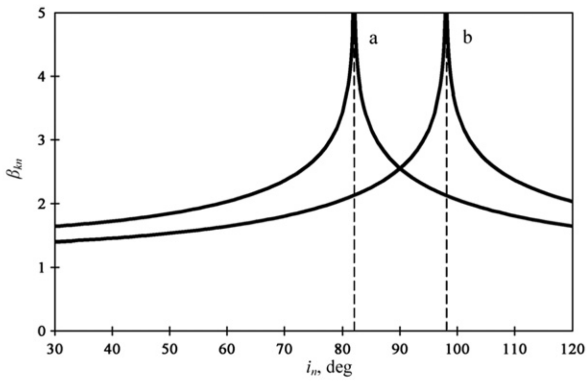

Fig. 1. Inclination pairing coefficient for $i_k = 98^\circ$ (a) and $i_k = 82^\circ$ (b).