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THE LONG-TERM COST OF DEBRIS REMOVAL FROM LEO

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It is commonly accepted now that large debris objects, such as derelict satellites and rocket bodies, should be removed from LEO to prevent or at least reduce the frequency of new catastrophic collisions. Such collisions can produce hundreds of thousands of debris fragments in the centimeter range ("shrapnel") that are hard to track, but could be long-lived and lethal to operational spacecraft. Different technologies are being proposed and developed for debris removal. While it is important to begin the process of debris removal in the near future, it is not less important to assess the sustainability and long-term implications of the proposed debris removal campaigns. In this paper, we describe a high-level statistical model of shrapnel production and use it to evaluate the average cost of a catastrophic collision as the statistically expected loss due to the damage to operational satellites and loss of their functions as a result of future collisions in LEO. The model is phenomenological and based on the two most relevant empirical data points, the Fengyun-1C and Cosmos-Iridium events. Using this model, we have found that the primary loss occurs not in the catastrophic collision itself, but within a decade after the collision, when a piece of untracked shrapnel produced in that collision hits a high value asset. It could be a "hidden" loss, because it may be hard to determine the true reason for the asset failure. Knowing the average anticipated loss resulting from future catastrophic collisions, we estimate the annual insurance premium that could be reasonably associated with coverage of the losses from such events. This could be treated as a gauge for rationality of the financial burdens of different debris removal campaigns. We then review long-term financial implications of debris removal campaigns and touch upon the question of the exit strategies and a transition to a low-cost self-regulating regime in the future after the bulk of the large legacy debris is removed from LEO.

I. INTRODUCTION

The Kessler syndrome[1], a slow runaway growth of the number of large debris fragments in LEO, is only one of the symptoms of the deterioration of the LEO environment. Even more troubling is the fact that future collisions between large debris objects can produce hundreds of thousands of debris fragments in the centimeter range ("shrapnel") that are hard to track, but could be lethal for operational spacecraft. A single catastrophic collision between intact objects in LEO can negate many years of debris mitigation efforts. It has now a ~6% chance/year of occurring. We know that the Fengyun-1C and Cosmos-Iridium events produced on the order of several hundred thousand fragments in the centimeter range, an amount comparable to the accumulation of explosion fragments over 50 years of spaceflight. These fragments are currently untracked and impossible to avoid, but they can disable or seriously damage operational satellites.

In order to prevent further LEO pollution with more fragments produced in catastrophic collisions, large debris objects, the primary source of future shrapnel, should be removed from densely populated regions in LEO. NASA recommends removal of at least five of the most dangerous large objects per year[2], assuming that 90% post-mission disposal compliance is achieved. Other studies indicate that there may be a need to remove tens of objects per year[3]. These campaigns would be long-term in nature, and it would take a very long time to get rid of the 2,200 large debris objects currently in low Earth orbits. During this time, catastrophic collisions and production of shrapnel will continue.

Debris removal with rockets can be costly[4]. Before decisions can be made on debris removal campaigns, we need to better understand the potential financial impact of future catastrophic collisions on operational spacecraft, formulate long-term approaches, and find suitable exit strategies. One of the pioneering studies in this area was conducted by the Aerospace Corporation[5]. The study evaluated added costs of operating three types of constellations in a gradually deteriorating LEO environment. This paper offers further insights into the financial aspects of the LEO debris problem.

II. THE COST OF FUTURE COLLISIONS IN LEO

Levin and Carroll[6] have recently developed a new phenomenological model for evaluation of the average statistically expected loss of assets after a catastrophic collision. The model is suitable for direct parametric analysis by decision makers, the space insurance industry, and the scientific community.

We used the two most relevant empirical data points, the Fengyun-1C and Cosmos-Iridium events, to formulate a high-level phenomenological model[6] of production and accumulation of small but lethal fragments in future collisions. While it is more common these days to use size distributions, we used mass distributions, because damage is determined not so much by the size, but by the mass of a fragment hitting the asset. The parameters of the model can be easily adjusted when more data becomes available.

We considered a set of objects B_k large enough to cause catastrophic collisions with spacecraft and upper stages in LEO. This set includes operational spacecraft as a subset A_n. To evaluate the impact of future catastrophic collisions and estimate the results of removing large debris objects, we excluded all small debris fragments currently in orbit from calculations. They represent the background risk that already exists and does not depend on the future removal of large debris. The risk of damage to the assets A_n has two components that strongly depend on the persistence of large debris: a) the assets can collide with one of the tracked objects B_k, and b) they can be hit by mostly untracked fragments S_k generated in future catastrophic collisions between the objects B_k. Figure 1 illustrates these two possibilities. The damage of the first kind is done immediately by the collision, while the damage of the second kind is delayed and may not even be identified as debris-related when it occurs.

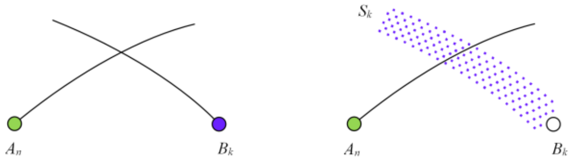


Figure 1. Collisions with objects (a) and their fragments (b)

We calculated collision probabilities and evaluated the average statistically expected yield of fragments in a future collision. In the current LEO debris field, the average yield is about 2.7 tons, which is more than the yield of the Fengyun-1C and Cosmos-Iridium events combined.

Figure 2 shows the distribution of the expected fragment yields by 1-ton ranges. The last bar covers the range from 10 to 17 tons. We see that the Cosmos-Iridium collision was on the small side. Over 60% of the catastrophic collisions will yield more than 2 tons of fragments.

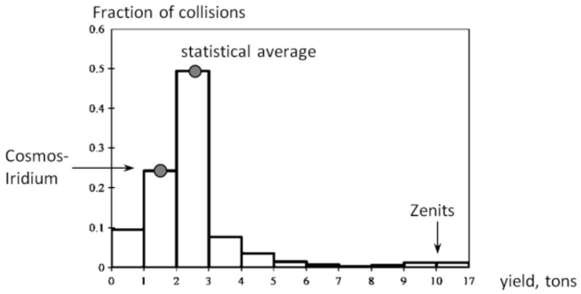


Figure 2. Distribution of the yield of total fragment mass from a catastrophic collision

Judging by the number of small fragments produced in the Fengyun-1C and Cosmos-Iridium events, up to half a million shrapnel pieces in the centimeter range could be released in an average catastrophic collision. Collision fragments form streams initially centered around the orbits of the originating objects, but with time, their nodes spread due to the differential nodal regression, forming shells around the Earth and creating substantial additional risk to the operational satellites. This risk can be expressed in terms of the average statistically expected damage to the assets in LEO. We used a concept of a virtual stream of collision fragments for this purpose.

The virtual stream is synthesized from the probability-weighted and time-averaged streams of all possible catastrophic collisions between intact objects in LEO. It represents a superposition of the individual sub-streams S_k of the future collision fragments of the objects B_k, as illustrated in Figure 3. This approach reflects the current trends in terms of the average statistically expected rates of growth of the population of small collision fragments for any given population of intact debris objects in LEO.

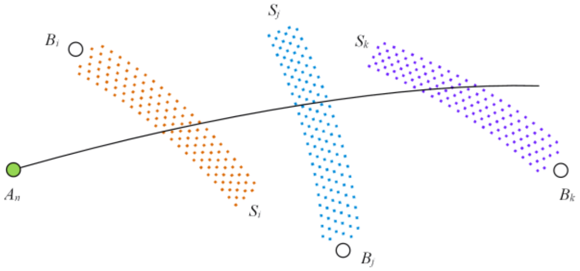


Figure 3. Superimposed probability-weighted virtual streams of future collision fragments

We focused on a narrow range of fragment masses around 1 g (see Figure 4) that are believed to be at the “threshold of lethality” in terms of the impacts on the operational satellites. We used power law distributions for the masses and calibrated them based on the data from the Fengyun-1C and Cosmos-Iridium events. We also derived altitude distributions around the collision altitude from the Fengyun-1C, Cosmos-2251, and Iridium-33 data.

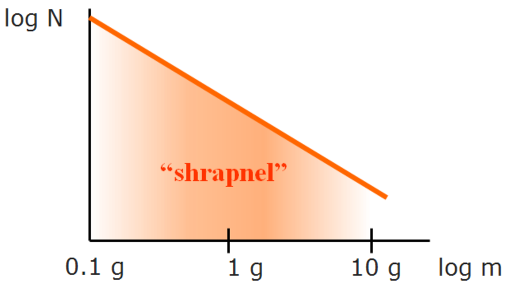


Figure 4. Distribution of the masses of the shrapnel pieces

The cost of a catastrophic collision includes an immediate loss, if an asset was destroyed in the collision, and a delayed loss, if other assets were damaged later by the fragments produced in the collision. Based on our model, the average statistically expected immediate loss caused by a catastrophic collision will be on the order of $30M. This amount is comparable with the actual loss in the Cosmos-Iridium collision.

However, it pales in comparison with the amount of the post-collision (delayed) damage. To evaluate the statistically expected delayed damage to the assets A_n from the fragments produced in a catastrophic collision, we specified their loss functions. A hit by a relatively large fragment within the body area will typically result in a total loss, while a hit by a relatively small fragment may cause only minor damage. Fragments of intermediate sizes may disable some components, but not cause a total loss. We also accounted for the depreciation of the asset values with time by introducing depreciation coefficients.

The total statistically expected delayed damage to all assets in LEO resulting from a catastrophic collision was estimated to be on the order of $200M, assuming a "lethality threshold" in shrapnel masses around 1 g. This value is a free parameter in our model and can be changed to reflect the latest data. A recent study of satellite survivability[7] conducted by Hiscox Ltd., a large insurance company, indicates that the threshold of 1 g chosen in our calculation is very conservative, and that spacecraft could be disabled by impacts of much smaller particles. This means that our estimate of the cost of a future collision may be on the low side, and that the statistically expected damage could be several times higher.

A substantial fraction of this damage will come from impacts on high-value assets, not only because they are expensive, but are also large targets.

III. INSURANCE ASPECTS

Before 2013, there were six cases[7] when debris fragments hit satellites. In two cases, the satellites were operational. In one case, a debris fragment hit a rocket body.

2013 started with a destruction of the operational BLITS satellite by a small particle[8], possibly an untracked debris fragment. The event was detected by the orbit and attitude change of BLITS.

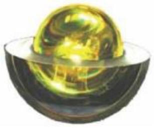


Figure 5. The BLITS satellite was hit by an untracked particle on January 22, 2013

On May 22, 2013, the NOAA GOES 13 satellite was possibly hit by a small particle, causing a drift in its attitude[9]. Then, on May 23, 2013, the NEE‑01 Pegaso satellite changed its attitude, presumably also after being hit by a small particle[9].

These events did not result in any insurance claims, but such claims may be filed in the future for insured assets, if the LEO environment continues to deteriorate.

If we take our conservative estimate of $200M for the average damage resulting from debris fragments produced in a catastrophic collision in LEO and spread it over an estimated average time of 16 years between the catastrophic collisions, we will find that it would take on the order of $13M per year to insure all assets in LEO from impacts of the untracked debris from future catastrophic collisions. It seems like a comparatively small amount, but keep in mind that our estimate is conservative, and that a lower "lethality threshold" revealed in the recent tests by Hiscox Ltd.[7] will drive the estimated premium up, possibly to $40-50M per year.

Despite the uncertainty of its current value, the annual premium estimate can serve as a very useful measure in evaluation of the LEO debris environment and the effectiveness of debris removal campaigns. Today, there is no separate coverage for damages from debris fragment impacts—it is included in the overall coverage. However, this can change, and the change will be reflected in the premiums.

Of course, there is no buyer for an aggregate coverage for all LEO assets, but let us take this quantity and study how it can be reduced by debris removal. The results are shown in Figure 6. We find that removal of a small number of intact debris objects cannot really change the premium and the effective annual damage to assets from the future collision fragments. Only wholesale removal of hundreds of tons, and preferably over a thousand tons of large debris from LEO, will make a noticeable difference.

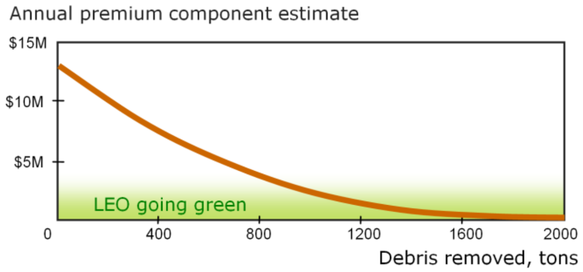


Figure 6. Annual premium component due to future collision fragments

IV. WHOLESALE DEBRIS REMOVAL CAMPAIGNS

The authors of this paper recently argued in favor of a short-term wholesale debris removal campaign[10], in which electrodynamic "garbage trucks" of the latest design could remove several hundred objects per year at a very reasonable cost[11], and LEO could be mostly free of large debris objects in a decade or so. In this scenario, catastrophic collisions will become very unlikely, and practically no more shrapnel will be produced.

Our "garbage truck" is called ElectroDynamic Debris Eliminator (EDDE)[11]. It is solar-powered and uses electric current in a long conductor to thrust against the Earth's magnetic field. Operating without propellant, EDDE can repeatedly change its altitude by hundreds of kilometers per day and its orbital plane by several degrees per day. EDDE weighs about 100 kg, but it can move multi-ton payloads.

We considered three possible debris removal campaigns in low Earth orbit using EDDE[11]. The first campaign aims at removal of all large debris from LEO. A dozen EDDE vehicles can do it in 7 years, and they can all be launched on one ESPA ring (two per slot), but phased deployment has advantages. Two EDDE vehicles can be launched each year and retired 5 years later. In 9 years of operation, 2,000 tons of large legacy debris and 97% of the collision-generated debris potential in LEO can be removed, at an average cost of less than $400/kg and an average annual cost of less than $90M.

The second campaign targets only upper stages in LEO. This eliminates any need to capture satellites with large appendages. In 7 years of operation, 1,000 tons of upper stages and 79% of the collision-generated debris potential can be removed, at an average cost of less than $500/kg and an average annual cost of about $70M.

In these campaigns, debris objects are dragged to altitudes below ISS and released into short-lived orbits. But 3/4 of the LEO debris mass is in objects over 1 ton, and they may not burn up completely.

In the third campaign, old upper stages between 650 km and 1200 km in the 71-74°, 81-83°, and the Sun-sync clusters are captured and delivered to slightly maneuverable "orbiting scrapyards" near 650 km. Objects are collected as they pass through nodal coincidence with the scrapyard. Within 7 years 400 tons can be collected. This will reduce collision-generated debris potential by 40%. Each scrapyard can be propelled electrodynamically without fuel expenditure for collision avoidance and orbit maintenance. This will allow time to develop in-orbit recycling technologies[11].

Note that the cost of these wholesale debris removal campaigns is comparable to the average statistically anticipated damage from one or two catastrophic collisions (depending on the "lethality threshold" discussed in Section II). The result of these campaigns will be that the time between catastrophic collisions will become much longer than today, and the near-Earth environment will have time to heal, while we will have time to develop new and more effective debris removal technologies. This can justify the expense of these campaigns.

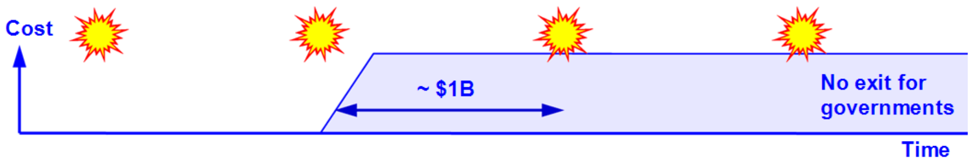
V. LONG-TERM PERSPECTIVES

When considering long-term plans for removal of large debris, we should keep in mind the following:

1. Primary losses from the fragments produced in future collisions will result from their impacts on high-value assets;
2. High-value assets are typically owned by governments;
3. Governments are mostly self-insured;
4. Anticipated annual loss (long-term average) is relatively low;
5. To appeal to the governments economically, debris removal campaigns should substantially reduce the anticipated annual loss at a comparable cost.

Scenario 1: Doing nothing

Scenario 2: Selective removal of large debris



Scenario 3: Wholesale removal of large debris

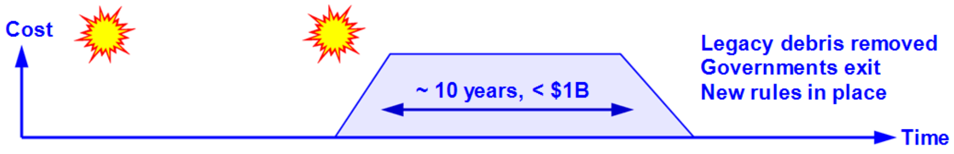


Figure 7. Debris removal scenarios in LEO

With the current statistical projections for the catastrophic collisions in LEO, there are generally three options for dealing with the situation.

The first option involves doing nothing about debris removal. In this case the space environment will continue to deteriorate, endangering LEO assets. It can be a valid posture while debris removal technologies mature.

The second option involves selective removal of intact debris objects aimed at stabilization of the population of large debris. It can be achieved with rocket propulsion, which is well developed, but could be costly. Judging by the capabilities and costs of such missions discussed in the literature, it could require governments to spend on the order of $1 billion every decade or so only to keep the population of large debris at the current level. It is important to understand, however, that this course of action will not prevent future catastrophic collisions—they will continue at the current rate, adding new fragments of all sizes to the LEO debris population. There would be no exit for governments, as the expenditure will have to recur indefinitely.

The third option involves wholesale removal of debris with emerging propellantless technologies. One of the examples is given by electrodynamic propulsion implemented in the EDDE vehicles. They are capable or wholesale removal of large debris at surprisingly low cost. As described above, pursuing this option would require governments to make a one-time expenditure under $1 billion over a 10 year period in order to remove all the existing intact legacy debris.

The wholesale removal option will not only allow the LEO environment to heal, but will open a door to a new regime in LEO. The states paying for wholesale debris removal will be "buying" something very valuable—an opportunity to establish new rules for prompt disposal of new debris objects. As standard debris removal practices evolve, this process will in turn give a new meaning to the term "fault" in the Liability Convention when applied to events involving debris left in orbit by their owners.

The same technology that will make wholesale debris removal possible can then be used to create an on-call debris removal service available to all LEO operators, which will no longer require government involvement and spending. That can be the exit strategy for governments after the legacy debris is removed.

VI. CONCLUSIONS

Catastrophic collisions between the large objects in LEO will produce hundreds of thousands of debris fragments in the centimeter range ("shrapnel"). The fragments of these sizes are currently untracked and impossible to avoid, but they can disable or seriously damage operational satellites. Statistically, the fragment yield of an average future catastrophic collision will be comparable to the yield of the Fengyun-1C and Cosmos-Iridium events combined, and such events currently have a ~6%/year chance.

We used the two most relevant empirical data points, the Fengyun-1C and Cosmos-Iridium events, to develop a high-level phenomenological model of production and accumulation of shrapnel in future collisions and estimate the cost of future collisions.

While the average immediate damage in a collision is estimated to be on the order of $30M, most of the cumulative damage will be indirect, delayed, and often not traceable to the original impact: it will result from later impacts of untracked shrapnel on valuable assets over the years after the original collision. We conservatively estimate that the average delayed damage from shrapnel produced in a catastrophic collision in LEO will be on the order of $200M, assuming a "lethality threshold" in shrapnel masses around 1 g. However, recent impact tests indicate that this threshold can be substantially lower. This can substantially raise estimates of indirect post-collision damage.

Looking at the potential insurance coverage of satellite failures due to collision-generated shrapnel impacts, we can treat it as a criterion for the relative effectiveness of debris removal campaigns. We find that only wholesale removal of hundreds of large debris objects from LEO can radically reduce the annual premiums. The wholesale removal can be achieved with specially designed electrodynamic vehicles at a cost comparable to the cost of one or two catastrophic collisions.

The wholesale removal option will not only allow the LEO environment to heal, but will open a door to establishing new rules for prompt disposal of new debris objects and redefining fault for events involving debris left in orbit by their owners. The same technology that will make wholesale debris removal possible can be used to create a commercial debris removal service available in LEO. It will no longer require government involvement and spending and can allow governments to exit after the legacy debris is removed.

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