Pay Me Now or Pay Me More Later: Start the Development of Active Orbital Debris Removal Now

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ABSTRACT

The objective of this paper is to examine when the aerospace community should proceed to develop and deploy active debris removal solutions. A two-prong approach is taken to examine both (1) operational hazard thresholds and (2) economic triggers. Research in the paper reinforces work by previous investigators that show accurately determining a hazard metric, and an appropriate threshold for that metric that triggers an imperative to implement active debris removal options, is difficult to formulate. A new operational hazard threshold defined by the doubling of the "lethal" debris environment coupled with the threshold that would affect insurance premiums is disclosed for the first time. The doubling of the lethal hazard at 850km and the annual probability of collision in the 650-1000km region may both occur as early as 2035.

A simple static (i.e. no temporal dimension) economic threshold is derived that provides the clearest indicator that active debris removal solutions development and deployment should start immediately. This straightforward observation is based on the fact that it will always be at least an order of magnitude less expensive, quicker to execute, and operationally beneficial to remove mass from orbit as one large (several thousand kilograms) object rather than as the result of tens of thousands of fragments that would be produced from a catastrophic collision. Additionally, the ratio of lethal fragments to trackable objects is only ~1,000x yet there is a need for the collection efficiency to be ~10,000x so "sweeping" of lethal fragments is not viable.

The practicality of the large object removal is tempered by the observation that one may have to remove ~10-50x derelict objects to prevent a single collision. This fact forces the imperative that removal needs to start now due to the delays that will be necessary not only to perfect/deploy approaches to debris removal and establish supporting policies/regulations but also because of the time it takes for the actions to reap benefits.

Additionally, if the growth of the lethal hazard grows faster than anticipated it may be necessary to replace some satellites, execute large object removal, and perform medium debris (i.e. lethal fragments) sweeping operations. The sooner the community starts to remove large derelict objects, the more likely satellite damage will be minimized and the less likely that medium debris sweeping will have to be implemented. While the research is focused on starting debris removal, the ensemble of observations reinforces the need to continue to push for as close to 100% compliance to debris mitigation guidelines as possible.

This analysis is unique in its pragmatic application of advanced probability concepts, merging of space hazard assessments with space insurance thresholds, and the use of general risk management concepts on the orbital debris hazard control process. It is hoped that this paper provides an impetus for spacefaring organizations to start to actively pursue development and deployment of debris removal solutions and policies.

1. INTRODUCTION

There is much debate as to whether the space community needs to start actively removing space debris from orbit now or whether it should delay such action. While there is still a question as to the technical efficacy of many of the debris removal options, especially for removing centimeter-size fragments, an examination of the urgency to implement specific solutions is necessary now since many technologies will have to be refined and tested before they can be used reliably.

Recent analyses have clearly shown that the orbital debris population will continue to grow even without future satellite launches. [1, 2] However, even if the cataloged and "lethal" populations both continue to grow at only a linear rate, consistent with history, the hazard will be a concern within the next 2-4 decades.

The very largest objects (derelict payloads and rocket bodies) may collide with and terminate missions of operational systems when involved in a collision and the collision in turn will create tens of thousands of lethal fragments. It is these lethal fragments that will eventually be the hazard driving the need for active debris removal even though they may not be the most critical, or advantageous, to remove first.

This situation presents two questions: 1) when will an operational hazard threshold be reached that requires active object removal for all spacefaring nations; and 2) is it prudent and cost-effective to wait until this threshold is reached to implement debris removal?

2. SCOPE

This paper will focus on operational and economic issues for active debris removal. While other factors are important to be considered, they will not be handled in this analysis. These unaddressed factors include, but are not limited to, the following:

- which are the appropriate agencies to lead these efforts;
- how will removal guidelines and laws evolve;
- how will the debate be affected by US and international policy issues;
- consideration of reentry debris impact risks;
- influence of legal statutes and codes of conduct;
- impact of regulatory frameworks; and
- how will technology trade and export requirements constrain potential removal options.

It is clear that the process by which debris mitigation guidelines have evolved and been implemented to date should be heavily leveraged due to its success. This would include not only rules codification and technical workshops but also, potentially, debris removal demonstrations to prove the efficacy of removal options. On the other hand, active debris removal policy evolution may require the involvement of more entities and issues than debris mitigation has needed due to the extra dimensions of object ownership and active movement of space objects.

3. THRESHOLDS

The current environment can be scrutinized by examining three general debris risk regimes as portrayed in Fig. 1. The vertical blue bars represent the uncertainty in the thresholds between the regimes due to ambiguity in on-orbit fragment characteristics, uncertainty in impact/breakup physics, and variability in spacecraft design.

The sub-millimeter-size fragments (i.e. small) can usually be handled fairly well through the typical satellite structure, the design of which is driven largely by the vibration and acceleration loads during the launching of a satellite. If there is a need for increased shielding or redundancy to counter the small debris threat, these will typically add mass and size to the system which in turn may add to the orbital debris hazard due to larger collision cross-sections and more mass being involved in collisions.

Despite the minimal risk from this family of debris, there have been a small number of satellites that have failed due to impacts by sub-millimeter size fragments. [21] In addition, there have been many tens of windows that have been replaced on the U.S. Space Shuttle over several decades of operations due to impacts with debris in this size range.

In the figure below three impact risk regimes are overlaid on the flux for a sun-synchronous orbit to highlight the relative numbers of objects in each size category. The probability of collision from lethal (i.e. medium) fragments is almost two orders of magnitude greater than that posed by the trackable population (i.e. large).

The larger size, trackable objects (>10cm) can easily be observed and cataloged and, thus, avoided if a satellite has (1) maneuver capability and an operator has (2) access to accurate conjunction data with (3) enough warning to permit a maneuver to be executed. The satisfaction of these three “ifs” is not trivial – which will be addressed later in this paper.

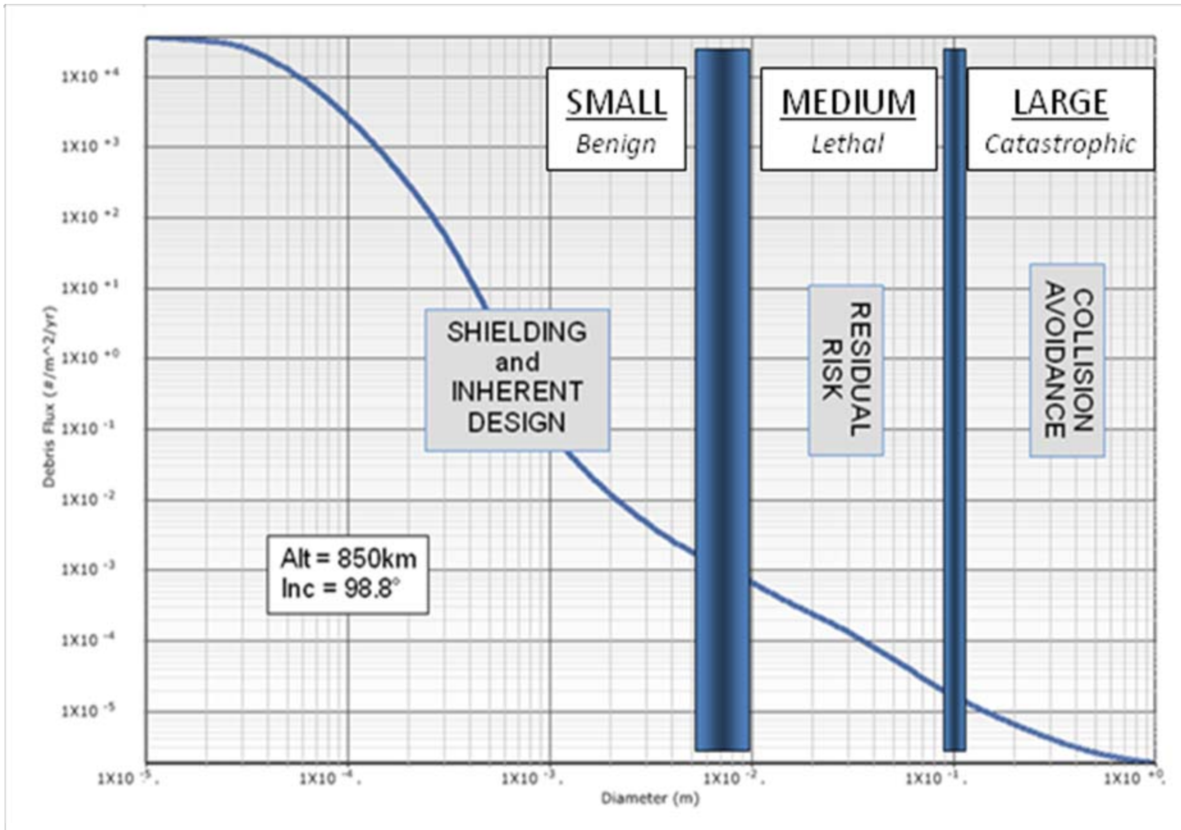


Fig.1. There are three general risk regions from orbital debris. Overlaid on this figure is the flux for the debris sizes for a typical sun-synchronous mission (850km and 98.8°) according to NASA's ORDEM model. [Source: Joel Slotten prepared for DARPA]

Around one hundred collision avoidance maneuvers have been performed to date, most occurring since 2008 [3]. These events are driven by special risks (such as manned spaceflight), an increased level of awareness, and an increased perception of risk. Since the collision of Iridium-33 and Cosmos 2251 in February of 2009, the US Joint Operations Center (JSpOC) has provided close approach data for many more satellites than before – around 100 payloads before the collision to over 1000 payloads now.

Collision avoidance maneuvers are being performed in both LEO and GEO by international space actors in response to calculated impact collision risks. These maneuvers currently impose little cost or operational impact on the mission and are often executed in conjunction with other operational actions. For this reason, it is unlikely that a threshold for action to initiate active debris removal will result from a threshold number of collision avoidance maneuvers until there is an impact on operational capability, performance, and workload from these maneuvers. In addition, until the means to predict, distribute, and execute a collision avoidance maneuver is standardized and shared with all spacefaring countries, there is little quantitative insight gained by any number of collision avoidance maneuvers taking place.

Detailed examinations of satellite anomalies for a wide variety of satellites over several decades and a broad range of altitudes in low Earth orbit (LEO) have not identified any definitive mission-terminating debris impact events from centimeter-size (i.e. nontrackable) debris. [4, 5] However, this analysis did highlight tens of events that might have been debris impact-induced yet due to inconsistent logging and characterization of the specific situations the causes could not be assigned with high confidence as a debris impact.

The primary concern regarding orbital debris is “residual risk” posed by 5mm – 10cm-size (i.e. cm-size) fragments. These objects are large enough to terminate a mission upon impact, cannot be seen reliably from the ground, and yet are 10-100 times more populous than the cataloged population.

Projected Satellite Failure Rates from Orbital Debris Hazard

In the 650-1000 km altitude region of LEO, where the population of orbital debris and relative collision velocities are the highest, two operational satellites are known to have been involved in collisions with a trackable object – Cerise at 670 km in 1996 returned to service with a modified control arrangement and Iridium-33 was destroyed in 2009 at 790km.

In addition to these two collisions, there have been many operational missions deployed and other types of breakup events in this general region. The resulting collision probability with the >1cm debris population, as provided by NASA’s ORDEM model, at 850km is 8E-3 per year for a satellite with a collision cross-section of $10m^2$. The backdrop to Fig. 1 provides a good representation of the orbital environment in this region of LEO.

Space insurance is one domain where there is a quantifiable threshold that will produce economic impacts. Nominally, the bulk of the 10-15% average premium for a space mission covers the launch vehicle flight and the initial (first year) satellite operations while only a small portion of the total premium (i.e. about 1.5% of the satellite value per year) is for on-orbit operations after startup. [15] When the collision risk reaches a value of 1.5% per year, insurance premiums will likely increase. However, once a collision with an insured satellite occurs, the urgency for starting active debris removal options will also likely accelerate.

While the probability of a single spacecraft being destroyed, or even just rendered non-operational, by a collision with a large trackable piece of debris is small, the probability that any large object will collide with another is quite a bit higher. The probability of collision for a specific satellite is proportional to the number of objects posing a collision hazard with it while the collision rate between objects is a function of the square of the number of objects present, assuming that the ratio of the large fragments to intact spacecraft is constant with time. [7]

In this way, while a hypothetical 20% increase in the population would only produce a 20% increase in collision probability for a single large object, the probability that <u>any</u> two large objects colliding goes up by over 40%. This collision rate is only an approximation since as collisions occur between large objects the ratio of large fragments to intact spacecraft will change. However, early in this process (i.e. for several decades) this approximation introduces very little error.

Eventually, this increased collision rate will result in a series of collisions between large objects and the total debris population will start to increase rapidly. In fact, before the 2007 Chinese ASAT event, the average annual increase to the cataloged population was around 250 objects per year. The Chinese test contributed over 2,700 trackable objects (while more than 3,000 have actually been identified) so, this single event contributed over ten years’ worth of population number growth.

While this event was a purposeful collision, rather than accidental, the debris creation issue is still relevant. The accidental collision in February 2009 of the operational Iridium and defunct Russian communications satellites created more than 1,600 trackable objects (while over 2,000 objects have been identified), which is still over six years of “typical” growth.

With a single event producing many years of “typical” debris accumulation, it is easy to see how quickly previous predictions of collision rates will have to be updated with new population levels. Work done in the 1970s by Don Kessler and Burton Cour-Palais hinted at the situation that is now becoming a reality: collisions between trackable objects are occurring with sufficient frequency such that these events are the main driver for future debris growth across all size ranges. [7] This is simple to understand since two colliding large trackable objects will create hundreds of trackable objects plus tens of thousands of lethal projectiles and so act as an accelerant to the growth of lethal (>1cm) debris fragments.

Recent analyses and empirical evidence in LEO shows that trackable objects are likely to collide with each other every three to six years. [1, 2, 8] The empirical evidence shows that trackable-on-trackable collisions have occurred in 1992, 1996, 2005, and 2009 – an average of every five years since 1990 though it can be argued that only one of these events was catastrophic. All of these occurred in the 670-885 km altitude range, with the most recent collision being the most severe. However, the first three events all occurred with about the same cataloged population of about 10,000 objects while the 2009 event took place when the cataloged population had grown to 13,000 (a 30% increase).

Yet, it is clear that there really is an insufficient legacy of events and knowledge to reliably predict the numbers and types of collision events accurately; therefore, these factors will be dealt with parametrically. **As will be discussed later in the paper, events often do not occur evenly at the average rate but rather occur quite erratically over time with the average rate often serving only as a mathematical anomaly that is high half of the time and low half of the time.**

NASA has developed the LEGEND model that incorporates an atmospheric decay model, empirical satellite fragmentation models, and historical/future launch traffic models within a Monte Carlo simulation framework to predict future debris growth including predicted collision rate. LEGEND predicts that trackable-on-trackable collisions will occur about every five years with the current on-orbit catalog population. [22, 26]

The figure below depicts the cataloged on-orbit population minus the 6,500 objects that are not reliably tracked or assigned to a parent launch. These 6,500 objects, called analyst satellites, are often omitted from population studies since it is difficult to characterize their source. However, most of them still pose a risk to operational spacecraft and so cannot be ignored when considering total growth and collision risk analyses.

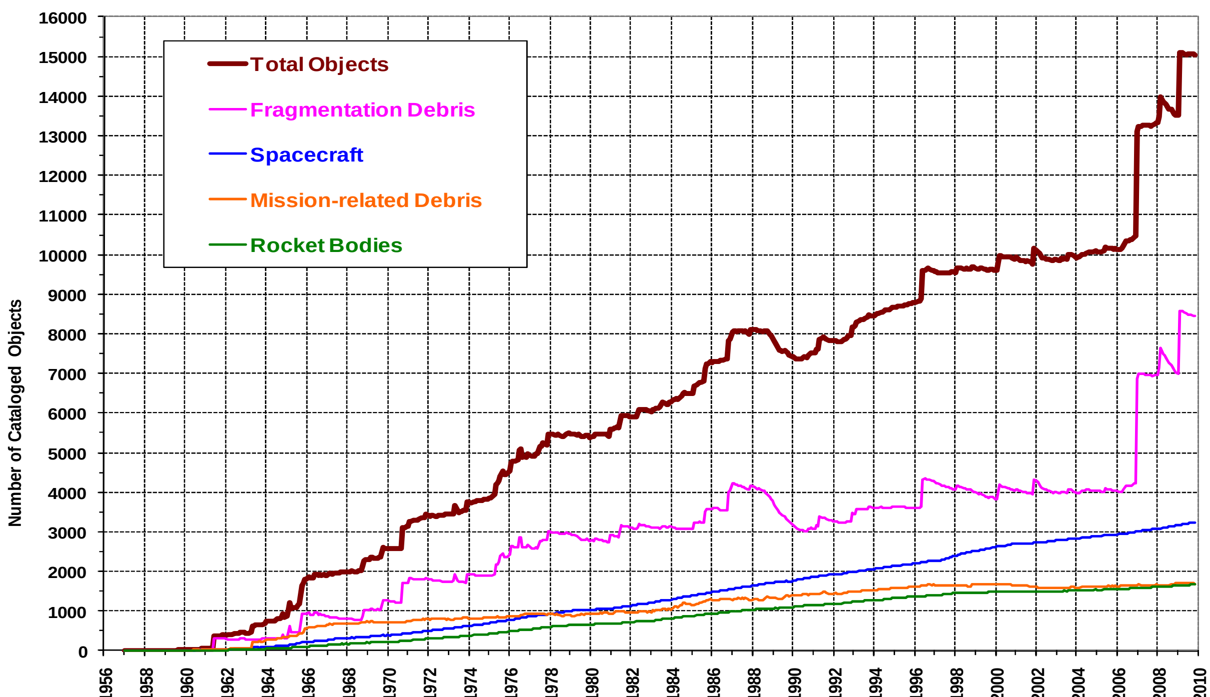


Fig. 2. The cataloged population growth, minus analyst satellites, has had three major phases: A. 1960-1996 during which the growth was fairly linear at a rate of 260/year; B. 1996-2006 during which time the cataloged population remained fairly constant largely due to implementation of debris mitigation guidelines and a hiatus in significant breakup events; and C: 2006-2010 during which two major events created a ~1250/year growth rate. You could also lump the entire space age together (1960-2010) resulting in about a 280/object per year catalog growth rate. [Figure Source: NASA/JSC, Orbital Debris Quarterly News, January 2010]

In summary, there is no “clear and present danger” from orbital debris but the cascading effect of hypervelocity collisions between large trackable objects in LEO will eventually push the population toward a state where there is an adverse operational impact on functioning satellites by creating many more objects in the “lethal” yet nontrackable range (5mm to 10cm). A specific calculation for this risk will now be provided.

Doubling of the “Lethal” Debris Population

It is estimated by NASA that there are currently over 500,000 cm-size debris objects in LEO. [25] As stated earlier, collisions with objects of this size will likely terminate a satellite’s mission upon impact. Table 1 shows the results of an analysis of how long it would take the cm-size population to double due solely to collisions (i.e. to generate an additional 500,000 cm-size objects in LEO). [Note that this analysis is conservative because it only considers fragments down to 1cm whereas particles as small as 5mm will likely “kill” any satellite it strikes.]

A doubling of the hazard from cm-size debris was selected since nominally the annual risk to sun-synchronous satellites of 8E-3 being doubled would surpass the 1.5% (i.e. 1.5E-2) threshold described earlier for space insurance exposure after the first year of satellite operations. While only some LEO satellites are insured, this does provide a fairly reliable and relevant threshold for analysis.

It is assumed that about 40,000 fragments larger than 1cm will be created from each “significant” collision of two large intact objects such as payloads or rocket bodies (i.e. ~20,000 objects for each ~3,000kg object). [16] This analysis is very sensitive to the number of debris objects produced from the catastrophic breakup of two large objects which in turn is dependent on collision encounter geometry and physical makeup of each object. Most of the fragmentation data and modeling have focused on payloads and there is much less data available for the result of hypervelocity collisions involving rocket bodies.

Clearly, there will be other sources of cm-size debris but there will also be some reduction in cm-size debris due to atmospheric drag effects. These two factors are ignored here to provide a coarse examination of the population growth.

Trackable Collision Rate	“Significant” Collisions / Total Collisions	
	One Out of Two (50%)	One Out of Four (25%)
Every 1 Year	25 years	50 years
Every 2 Years	50 years	100 years
Every 4 Years	100 years	200 years

Table 1. The time it takes for collisions to create a doubling of “residual risk” shows that it will likely occur within the next few decades but possibly not for a century or longer. For example, if there is a trackable-on-trackable collision every 2 years and every other event is “significant”, then the “lethal” debris population will double within 50 years.

The examination of the hazard threshold provides a wide-variance result: 25-200 years with a 50-100 year range being most likely. These numbers are sufficiently large and variable to likely not be sufficient to motivate community action at this time on their own. As collisions become more common the statistics will provide a more reliable number with smaller error bars but until then, there is a wide range of potential scenarios of how the orbital population will evolve. These results are similar to other analyses. [1, 2, 7, 22, 23]

However, by examining the continued growth of only the cataloged population at historical levels and assuming a constant ratio of 1cm-to-trackable populations, the doubling of the hazard in the 650-1000km altitude band is found to likely double within 12-25 years as depicted in the figure below. If collisions occur every three or six years on top of the average growth rate over the last 50 years, the doubling point (1.5E-2) may be achieved much sooner.

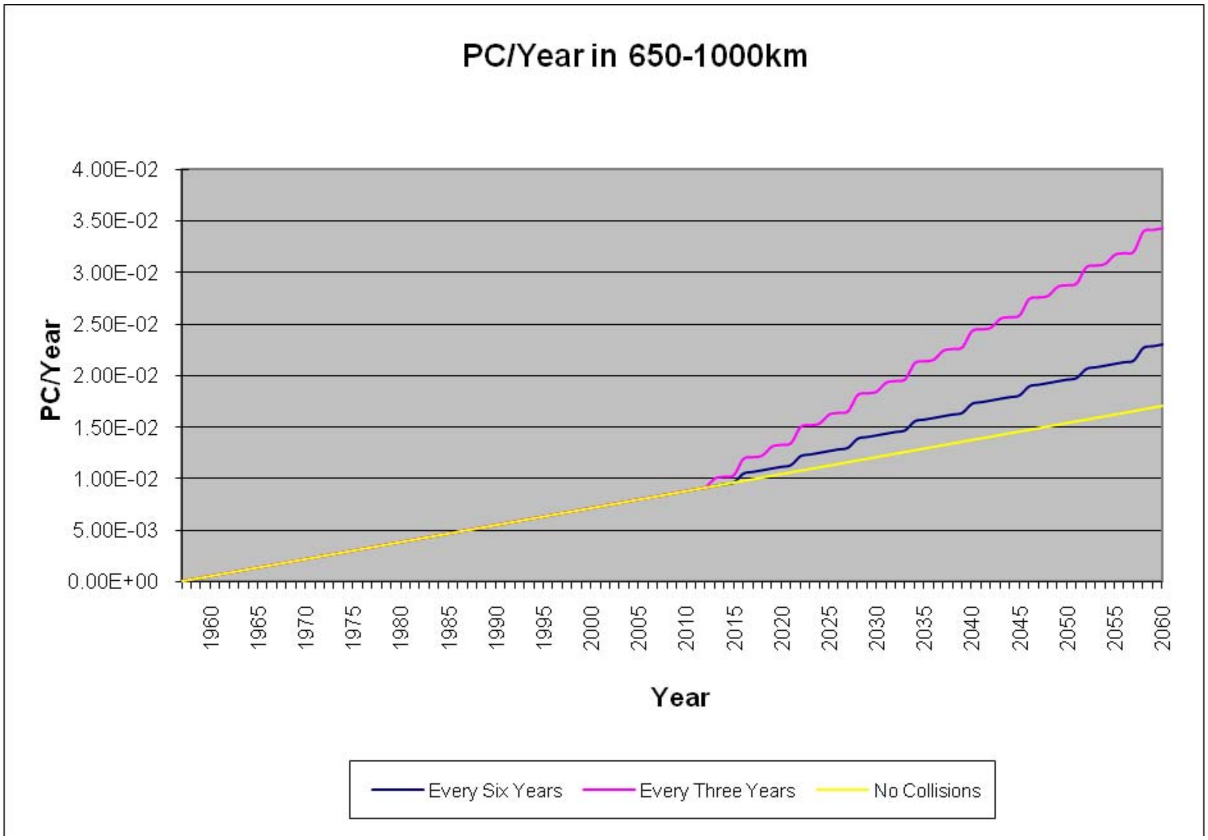


Fig. 3. If the satellite population down to 1cm continues to grow at historical levels, the hazard from cm-size debris will double in the next few decades in the 650-1000km altitude band. The actual catalog growth before 2010 in the figure above was replaced with the average growth rate from 1957 - 2010.

LEO vs GEO

The GEO orbit has not been discussed much since the current collision hazard in GEO is much smaller than in the LEO environment. As a result, the impetus to start active debris removal based on collision hazard will probably begin in LEO.

This observation could be altered if there are some major accidental breakup events or other operational issues that arise in GEO due to its unique characteristics:

- critical commercial and military payloads are being deployed in GEO;
- GEO region is much harder to access than LEO;
- GEO satellites are generally larger and more expensive than LEO satellites; and
- no secular orbit contraction perturbations exist in GEO (such as atmospheric drag).

While the need for debris removal in GEO is likely to lag behind LEO, the population of GEO objects is distributed such that the highest priority objects to remove are clearly identified. In geosynchronous orbit (GEO), the average annual probability of collision with the trackable population for a large stationkept communications satellite is 3E-7 to 3E-6 depending on its location relative to the stable points. [6]

The objects in GEO that are “trapped” (i.e. oscillate about stable points on the GEO arc) pose a disproportionately high percentage of the collision risk to operational satellites: about 15% of the objects pose 80% of the collision hazard in GEO. Therefore, the removal of around 150 objects can reduce overall GEO collision risk by a factor of five. [17]

Summary of Hazard Analysis

The hazard threshold analysis has not provided a precise answer on when to start active debris removal; results vary from 12-200 years until a relevant threshold will be crossed. However, it should be reinforced that these thresholds should not be considered as states that trigger action but rather states that should be avoided by the implementation of proactive measures.

While it seems logical that debris removal options ought to be developed before there is a decision to actually execute these missions, it is imperative that industry and government have a reasonable expectation that their efforts to develop debris removal solutions will be rewarded; otherwise, the investment of energy and resources will likely not occur in earnest. In addition, legal, political, and regulatory personnel need to be energized to quickly evolve and codify statutes and policies to support the deployment of active debris removal options and to ensure that lack of policy framework does not delay the use of needed debris removal operations in the future.

An economic analysis is now undertaken to identify some impetus for initiating the development and execution of debris control options with a focus on highlighting the difference between removing large derelict objects rather than medium-size lethal fragments.

4. COST EFFECTIVENESS OF ACTIVE DEBRIS REMOVAL

The December 2009 NASA-DARPA International Conference on Orbital Debris Removal provided a wide range of analyses proposing costs and effectiveness for debris removal options. [8-15] There are three general sizes of debris discussed for removal (debris risk regimes shown in Fig. 1):

- small: less than 5mm,
- medium: 5mm-10cm, nontrackable but still potentially lethal, and
- large: larger than 10 cm, all potentially lethal and includes intact derelict payloads and rocket bodies.

Small debris, as defined above, is not relevant to this analysis since it does not pose a significant hazard to operational spacecraft due to typical aerospace construction and shielding. In addition, the result of collisions with these objects will generally not be the source for any “lethal” fragments.

Medium-size debris are too small to be cataloged, so cannot be avoided yet have the potential to terminate the mission of an operational spacecraft. While these objects may terminate missions, collisions with them will not routinely create large numbers of additional “lethal” fragments.

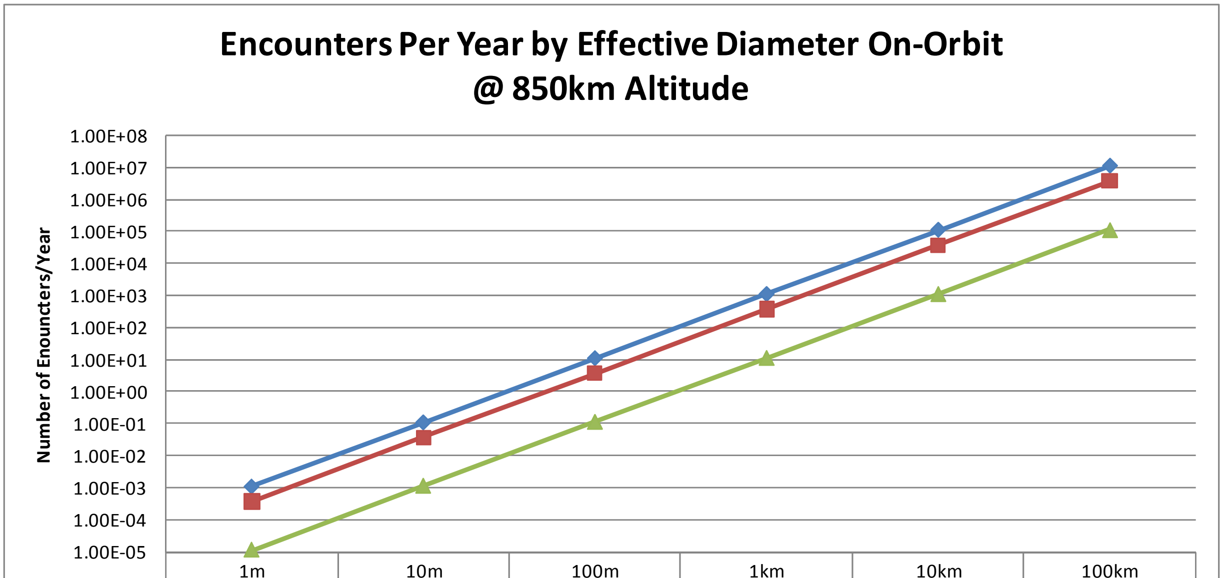
There are over 21,000 large objects being tracked in Earth orbit and collisions with these objects will almost always result in the termination of the mission of an operational craft and will also likely create hundreds or thousands of lethal fragments as the result of a collision.

Size	Lethal to Operational Spacecraft	Number in Orbit	Trackable (i.e. can be cataloged)	Produces Lethal Fragments When Impacting An Operational Spacecraft
Small < 5mm	(Usually) Not	Millions	No	No
Medium 5mm – 10 cm	Usually	~ 500,000 in LEO	No	Maybe
Large > 10 cm	(Almost) Always	~ 21,000	Yes	Yes – 100s to 10,000s

Table 2. Characteristics of the three size regimes of debris show that the medium-size is the most populous component of the debris population that can disrupt satellite operations. It will, therefore, eventually be the hazard that will drive future debris removal actions.

The cost and range of options to remove debris of each size is partially related to the ability to track the object since if you cannot track it, you can not actively rendezvous with it to intercept or capture it and then, possibly, apply a deorbit kit. To remove objects in the 5mm-10cm size range, there are two primary options under consideration – groundbased lasers and large orbiting "collection media." For these options, "clean up" is based on a statistical representation of the debris environment since the concepts act on an uncataloged population.

The removal of this uncataloged population will be estimated by an effect on a volume in space that probabilistically has a certain number of these fragments passing through which can be influenced by a groundbased laser or on-orbit "collection media." This "collection media" may be low-density capture material, rotating panels that absorb the momentum of incoming particles, or any of several approaches to physically remove small debris from orbit.



	1m	10m	100m	1km	10km	100km
5mm	1.09E-03	1.09E-01	10.90	1,089.60	108,960.03	1.09E+07
1cm	3.71E-04	3.71E-02	3.71	371.45	37,145.47	3.71E+06
10cm	1.11E-05	1.11E-03	0.11	11.14	1,114.36	1.11E+05

Fig. 4. The on-orbit manmade object population at 850 km is taken as an exemplar for congested regions in space, and the encounter rate of different size "sweepers" with varying sizes of debris is very instructive as to the efficacy of debris collection. For example, a 100m diameter collector would collide with about ten 5mm objects each year on average.

However, it is unlikely that energy dissipating mechanisms will be able to reliably remove cm-size objects although mm-size objects are more likely to be affected by these solutions. Removal of medium debris is difficult because of low flux from a "collect" perspective and the complexity of capturing hypervelocity fragments.

In addition, the spatial density of medium debris is ~1,000x trackable objects yet it is necessary to remove ~10,000s of medium-size debris to be considered effective. Yet, due to the only ~10x difference between these two ratios, any medium-size debris sweeping is likely to encounter large trackable objects, even potentially operational payloads, which render many sweeping approaches problematic. There is a significant amount of work needed to prove that any of these options will work.

In addition, an examination of the orbital lifetimes of trackable debris from LEO breakups shows that for breakups around 700 km and below all the debris will likely have reentered within 25 years. Similarly, for breakups with an average altitude of 900km about 50% of the trackable debris has historically reentered within 25 years.

It is anticipated that the nontrackable lethal debris will reenter in about the same time as the trackable debris since while the smaller debris is more affected by atmospheric drag it is also likely to be ejected into higher altitudes so the overall longevity is comparable. This observation makes the potential cost and difficulty of sweeping up medium debris even less compelling.

For large object removal, there are a wide variety of possibilities – electrodynamic tethers, inflatables, solar sails, and grappler/tugs. A new concept, called GLiDER, for contactless coupling of large objects in GEO based on the unique plasma environment in GEO, has recently been added to the large debris removal options. [9] The table below summarizes the general cost and viability for all of these options.

For this table, the analysis is normalized by assuming a 1cm fragment for the medium debris and ~3,000kg object for the large object removal. A large portion of *in situ* object removal cost comes from the launch cost. A launch cost for a 10,000lb payload to LEO is estimated to be about $30M while the same mass to GEO will cost about $120M. These costs have not changed much over a few decades but the introduction of a potentially "more affordable" launch provider, such as SpaceX, or a payload piggybacked on another mission, might provide cost savings.

Most debris removal options claim to be able to remove multiple objects with a single dedicated launch. This ratio (number of objects removed per launch) will drive the range of costs for debris removal options in both LEO and GEO. Another important factor regarding cost of mission may be the speed at which the removal maneuvers take place – generally, the faster the operations the more expensive the mission.

Economic Analysis

There are two ways in which the economic analysis could be accomplished – (1) simple and (2) time-sequenced. In the simple approach, a basic assertion is made that any large object that could be proactively removed will eventually have to be dealt with it after it has broken up into thousands of pieces.

So, in this approach there is no need to predict triggering events or thresholds for action but simply compare the cost of removing one large object to the removal of that one large object broken up into thousands of smaller, yet still lethal, pieces.

From the table above, to remove 20,000 cm-size debris from LEO (i.e. the debris produced from the catastrophic fragmentation of a 3,000kg satellite) rather than one large object (~3,000 kg) would cost about an order of magnitude more ($5-70M vs. $200M-500M) and likely take much longer to perform (weeks/months vs. years).

For GEO, the costs to deploy a large object removal mission will increase to about $180M but the efficacy of a medium debris removal mission to GEO has not been shown due to the lower relative velocities encountered in GEO and the small number of medium-size debris likely in GEO.

The requirement for large plane changes in LEO in order to perform multiple object retrievals may also add to the costs of LEO systems whereas total plane changes (for inclination) are limited to a maximum of 15 degrees in GEO.

Without any further analysis, it can be stated that "pay me now or pay me <u>more</u> later" can be supported by looking at the cost, technical risk, and time required to remove the same mass intact rather than in pieces following a collision. The time urgency is amplified when considering the potential number of large objects needed to be removed to effectively eliminate a future collision.

All of the cost figures in the table below are rough order of magnitude (ROM) estimates.

<table>
<tr><th>Debris Removal Option</th><th>Debris Size Removed</th><th>Costs</th><th>LEO or GEO or Both</th><th>Comments</th></tr>
<tr><td>Groundbased Lasers</td><td>1cm and below</td><td>$300M for one site so $1k per cm-size object if removing 300,000 objects and $15k per cm-size debris for removing 20,000 objects</td><td>LEO</td><td>Removal rate is very uncertain at this time but could take 5-10 years to remove any significant number of objects; more effective for mm-size debris [11]</td></tr>
<tr><td>Collection media sweeping out volume in space</td><td>Variable but better for the smallest debris (mm-size)</td><td>For 1-10cm LEO debris $20k/object for 5-year mission based on a $100M mission for a 100km^2 collector (for capture device); other concepts are too immature to estimate costs</td><td>Both</td><td>Others have estimated the cost to remove small debris by collection at near a $T [8] The physical efficacy of all approaches is questionable.</td></tr>
<tr><td>Electrodynamic Tether</td><td rowspan="5">Derelict R/Bs and P/Ls</td><td>$100M for single mission but the e-tether has the potential to execute multiple missions without other propulsive capabilities may reasonably approach $10M/object</td><td>LEO</td><td>EDDE proposed a drastically reduced rate to remove hundreds of large objects that would equate to about $100k-500k per large object removed from LEO but the conops have not yet been proven [12]</td></tr>
<tr><td>Grapple and Tug</td><td>$150M for 5 large objects resulting in $30M/object but may reduce the costs if you could do more missions</td><td>Both</td><td>OTV quoted removal rates about an
$8-27M/object [10]</td></tr>
<tr><td>Inflatables</td><td rowspan="2">$100M per object if doing them one at a time but with some autonomous vehicle it would be less per object but if you have a device to rendezvous with each object and then move why not just add a little more fuel and move the object impulsively?</td><td>LEO</td><td>Previous DARPA program has developed inflatable capability through technology demonstration [13]</td></tr>
<tr><td>Solar Sail</td><td>Both</td><td>They propose that they could use 2000m^2 sails for ~$1M each to move objects out of GEO but does not include launch costs [14]</td></tr>
<tr><td>GLiDER (contactless coupling)</td><td>$150M for 5 objects resulting in ~$35M/object</td><td>GEO</td><td>Developers claim about $12-15M per removal of a GEO object not including launch costs. Current technology is not proven [9]</td></tr>
</table>

Table 3. Debris removal options examined at the December 2009 NASA-DARPA International Conference on Orbital Debris Removal show that all *in situ* options have launch costs as a major cost factor. Electrodynamic tethers or propulsive tugs, however, offer a proven means to reduce the cost per object removed by being able to remove multiple objects per deorbit "system/kit".

Two operational issues that may impact the economic analysis over time are:

- Reduced launch costs will serve to enhance the economic viability for *in situ* solutions so will not further differentiate between these options but might make the *in situ* options more appealing relative to groundbased lasers. (Other technology advances might serve to reduce the cost of groundbased laser systems; however, over the last 20 years the cost efficiency has not changed significantly.)

- As the debris population worsens some of the removal options may not be as viable as currently depicted. For example, while the electrodynamic tether approach has some very positive supporting analytic calculations, the tethers do present a large collision cross-section for the on-orbit debris population. If deployment of this option is delayed until the mm- and cm-size population is significantly larger, mission success may be greatly reduced, resulting in much larger removal costs and potentially making the solution less reliable and less effective.

  Designs may be modified to correct for this increased hazard which may in turn increase the eventual cost of implementation. All these factors for tethers may also apply to inflatables and solar sail options. Propulsive tugs will not be affected as much by the increased debris population so their economics should not change as much over time.

Technology breakthroughs that might be considered to have an impact over time are listed below:

- Better space surveillance: Much of the analysis in this paper is based on the fact that the hazard from the "lethal risk" (i.e. cm-size debris) is the eventual concern that may trigger the need to remove orbital debris. If this regime of the debris population could be seen reliably and avoided by operational, maneuverable satellites then the entire situation might change.

  This, however, is only possible with new hardware and software. In addition, this may not be as much of a solution as one might expect. Just seeing an object is not sufficient to being able to avoid it. There must be good orbital element set information for the debris to produce data to create small covariance matrices that would permit accurate probability of collision values to be determined. This requires regular observations of smaller debris. However, smaller objects are generally more affected by atmospheric drag in LEO so it will be more difficult to maintain precise orbital elements on them (or at least it will require more frequent observations).

  The U.S.'s proposed S-band fence may contribute to both the ability to track and provide accurate element sets on smaller orbiting objects, if implemented as currently envisioned. [20]

  There are about 1,800 derelict rocket bodies and nearly 3,200 payloads in orbit. None of the abandoned rocket bodies have the capability to avoid collisions with other objects. Of the 3,200 payloads, only 1,000 are operational and nearly 800 of those are maneuverable with over half of those located in GEO. As a result, most of the mass in orbit (about 80%) cannot avoid disastrous collisions even if it was predicted and warned about in advance.

- New remote removal techniques: Debris removal options based on ballistic intercepts launched from the ground would generate a different set of economic and technical issues that might result in a much lower cost of object removal for LEO debris. There are significant issues to be addressed for the development of these "remote" options that have not yet been fully analyzed or scoped.

- General aerospace technologies: Many debris removal options depend on technologies for rendezvousing and grappling with uncooperative targets so any enhancements in these capabilities could assist many of the options.

The time-sequenced economic model will have the same deficiencies as the previous hazard threshold analysis - large uncertainties in the actual hazard and the timing of significant collisions will drive the results. Other issues that impact the time-sequenced economic model are the potential change to launch costs, the impact of worsening environmental conditions on debris removal options, and other technology breakthroughs. For these reasons, a time-sequenced economic analysis is not performed.

5. LARGE OBJECT REMOVAL

NASA analysis on the employment of active debris removal systems using their LEGEND model provides one snapshot of potential efficacy of large object removal. In the scenario, the removal of five large derelict objects was simulated each year over a 100-year timeframe. The derelict objects were selected for removal based on their product of probability of collision with the trackable population and their mass (i.e. PC*Mass). The resulting calculation showed that 14 of 40 predicted collision events would be prevented. Therefore, in collecting 500 large objects – in this Monte Carlo simulation – it is anticipated that 14 events would be averted: about 35 objects were removed for each collision prevented.

It is interesting to note that in advance of the Iridium 33 and Cosmos 2251 collision the potential conjunction of these two objects was not even one of the top 150 most likely that day and at worst was #11 on the most likely conjunction list a few days beforehand. [32] Further, it was not even the most likely collision of the operational Iridium constellation for that day.

In examining the U.S. space surveillance satellite catalog just prior to the Iridium/C2251 collision, the product of probability of collision and mass (PC*Mass) was calculated for all objects in orbit. [30] Iridium 33 and C2251 were rated #935 and #872, respectively, as most critical to be removed from Earth orbit. Clearly, Iridium was operational so would not have been considered for removal. By eliminating the operational payloads from this list, C2251 moved up to about #850.

The very largest objects, derelict payloads and rocket bodies, may collide with and terminate missions of operational systems when involved in a collision and the collision in turn will create tens of thousands of “lethal” fragments. As stated previously, it is these “lethal” fragments that will eventually be the hazard that will drive the need for active debris removal even though it may not be these objects that are the most critical, or advantageous, to remove first.

The efficacy of large object removal may be further increased by removing the objects with the largest collision threat and potential for debris creation first. As stated previously, in GEO 15% of the objects (~150) pose 80% of the collision hazard. Similarly, in LEO, 10% of the objects (~1,250) present 80% of the total collision cross-section. However, it is important to not overstate the benefits of this selective debris removal. The largest object in the most densely populated region in space will not necessarily be the first object involved in a collision even though it has greatest probability of collision. Therefore, it is important to get as many of the most likely collision objects removed in order to actually reduce the number of future impact events.

“Clumping” in LEO

An examination of the top 100 largest derelict objects in LEO shows a convenient clumping within inclination bands that might impact the strategy for large object collection.

Inclination Range	Number
20-30°	1
30-40°	3
40-50°	0
50-60°	4
60-70°	19
70-80°	38
80-90°	6
>90°	29

Table 4. Objects deemed “high priority for removal” are clustered at higher inclinations.

However, while the 70-80° range seems to be a highly populated region, a closer examination of the data provides more distinct spikes.

Inclination Range	Number	Number / Degree of Inclination
70.89-71.11°	37	~170
97.03-99.27°	19	~9

Table 5. A majority of the high priority objects are in a mere ~2.5° of inclination.

Clearly, the 70.89-71.11° inclination range is a viable location in which to first go after large derelict objects if fuel conservation is a significant part of the economic and operational model of large object retrieval. This class of objects mostly comprises Russian hardware placed in LEO. Based upon the probability of collision times mass metric (PC*Mass), these objects again are prominent. The table below lists the top 30 derelict objects in LEO by PC*Mass (largest first) from a special January 2009 satellite catalog provided by NASA with masses for most objects. [30] All but three of the entries are in one of the two inclination spikes identified above. The 70.89-71.11° band is represented well in the PC*Mass prioritized listing with ~ 70% of the objects being in that narrow inclination range.

PC*Mass	**International Designator**	**Satellite Number**	**Description**	**Inclination**	**Apogee**	**Perigee**
0.440	1998-043G	25400	SL-16 R/B	98.39	815	802
0.304	1990-046B	20625	SL-16 R/B	71.00	853	836
0.280	1993-016B	22566	SL-16 R/B	71.01	850	837
0.231	2002-056E	27601	H-2A R/B	98.58	842	737
0.226	1996-051B	24298	SL-16 R/B	70.89	861	841
0.217	1992-076B	22220	SL-16 R/B	71.00	849	828
0.192	1999-039B	25861	SL-16 R/B	97.69	651	630
0.189	1993-059B	22803	SL-16 R/B	70.99	849	825
0.168	2000-047B	26474	TITAN 4B R/B	68.00	644	558
0.168	1988-039B	19120	SL-16 R/B	71.01	848	813
0.135	2000-006B	26070	SL-16 R/B	71.00	854	829
0.131	1996-046A	24277	ADEOS S/C	98.34	797	796
0.128	1995-058B	23705	SL-16 R/B	71.02	853	832
0.127	1985-097B	16182	SL-16 R/B	71.00	843	835
0.122	1998-045B	25407	SL-16 R/B	71.01	847	834
0.121	1988-102B	19650	SL-16 R/B	71.00	851	830
0.120	1994-077B	23405	SL-16 R/B	71.00	846	839
0.116	1992-093B	22285	SL-16 R/B	71.02	846	841
0.115	1987-027B	17590	SL-16 R/B	71.00	842	832
0.113	1994-074B	23343	SL-16 R/B	98.01	651	640
0.111	2007-010B	31114	CZ-2C R/B	98.29	874	786
0.107	1994-023B	23088	SL-16 R/B	71.00	845	843
0.106	2007-029B	31793	SL-16 R/B	70.98	847	844
0.099	1987-041B	17974	SL-16 R/B	71.00	845	826
0.097	1988-039A	19119	COSMOS 1943 S/C	71.00	851	836
0.091	1991-050F	21610	ARIANE 40 R/B	98.62	764	759
0.089	1963-047A	694	ATLAS CENTAUR 2 R/B	30.37	1361	461
0.087	1991-063B	21701	UARS S/C	56.97	454	356
0.086	1987-041A	17973	COSMOS 1844 S/C	70.89	868	825
0.083	1994-023A	23087	COSMOS 2278 S/C	71.05	856	841

Table 6. The top 30 high priority objects are primarily of Soviet/Russian legacy.

Interestingly, within the top 300 objects by PC*Mass (vice just 30 or 100) a different clustering of inclination bands emerges. Almost all of the 70.89-71.11° band were in the top 100 objects but the low 80° and high 90° inclination ranges rise in importance when looking at a larger set of objects as can be seen in the table below. For the removal of up to 300 objects, these five bands contain the vast majority of all derelict objects (242/300).

Inclination Range	Number	Number / Degree of Inclination
70.89-71.11°	40	~180
81.08-81.28°	54	~270
82.47-82.56°	63	~700
96.94-98.07°	31	~25
98.15-99.04°	54	~60

Table 7. The five inclination bands that are most populated with "high priority for removal" objects represent only 1.5% of the entire US satellite catalog by number.

The propulsive resources needed to move/remove the five groups of large derelict debris objects clumped by inclination and altitude identified above is calculated. For the analysis it is assumed that all objects are in circular orbits and are evenly distributed within each altitude and inclination range but there is no correlation between altitude and inclination within each band.

Several types of delta-V calculations are made:

A. Moving between each of these objects only using either (i) two Hohmann transfers per maneuver or (ii) a low thrust maneuver;
B. Synchronize with each object by either (i) raising the apogee by 200 km and letting the object move underneath then returning to the circular orbit or (ii) executing a 10° plane change to synchronize with the next object.
C. Deorbit: Move each object to a perigee of 500 km (i.e. move to orbit with orbital lifetime of 10-15 years).

The table below summarizes the delta-V required for each band and removal type.

Group	Altitude Range (km)	Inclination Range	Number	A.Move Between		B.Synchronize		C.Deorbit	Total	
				i	ii	i	ii		i	ii
1	815-865	70.89-71.11°	40	0.039 km/s	0.050 km/s	2 km/s	50 km/s	3.6 km/s	6 km/s	54 km/s
2	750-900	81.08-81.28°	54	0.103 km/s	0.116 km/s	3.2 km/s	69 km/s	4.6 km/s	9 km/s	74 Km/s
3	1000-1500	82.47-82.56°	63	0.248 km/s	0.356 km/s	3.8 km/s	78 km/s	12 km/s	16 km/s	90 km/s
4	600-900	96.94-98.07°	31	0.394 km/s	0.193 km/s	1.8 km/s	39 km/s	1.8 km/s	4 km/s	41 km/s
5	700-1000	98.15-99.04°	54	0.270 km/s	0.231 km/s	3.2 km/s	69 km/s	5.0 km/s	9 km/s	74 km/s
Total # Total Mass Removed			242 1E6 kg	1 km/s	0.95 km/s	14 km/s	305 km/s	27 km/s	44 km/s	333 km/s

Table 8. These nearly 250 objects constitute about 1,000,000 kg of mass – about 4% of all mass in orbit.

Making contact with each object is provided simplistically in Column A and the Column B values add the requirement to synchronize with the objects that are randomly distributed by right ascension and true anomaly. The sum of Columns A and B would be the likely delta-V required if a propulsive tug was used to attach an inflatable device, electrodynamic tether, etc. Column C is total if the propulsive tug used to rendezvous with each object is used to execute a "deorbit" maneuver.

It can be seen that the largest delta-V requirements come from the synchronization initiated by a plane change (Column B.ii). This plane change is required if it is critical to make all of these maneuvers as fast as possible, whereas the synchronization by moving to a slower orbit (i.e. move to an elliptical orbit with a larger apogee) can be used if the removal of these objects can be done over weeks rather than hours.

Applying a less stringent movement threshold for "deorbiting" could also reduce the total delta-V requirement.

The time to execute any of these propulsive maneuvers depends on the mass being moved, and the I_{sp} of the propulsive system. The capability of other systems such as electrodynamic tethers or inflatables can be used to execute the Column C – deorbit activities. Additionally, some systems, such as electrodynamic tethers, may be used to move between the objects in each clump. In all of these scenarios, the delta-V to get the systems to the each clump from the ground is not included.

In summary, while the delta-V requirements shown in the table above are fairly daunting, if the maneuvers do not have to be done quickly and if there is a reasonable deorbit capability that does not require traditional propulsive capabilities then the removal of large objects does appear to be a legitimate means to manage the growth of orbital debris. However, this analysis may also be considered to reinforce the fact that the spacefaring community needs to rally and start to develop operational solutions to remove orbital debris immediately since it will take years to perfect these solutions and years for the benefits of active debris removal of large derelict objects to be realized via averted collisions.

6. CONCLUDING REMARKS

The management of the orbital debris risk is not unlike other general risk management problems (e.g. force protection, cyber security, nuclear safety, etc.). These are often examined by applying a layered approach to the options that might be used to manage the risk from a hazard (or threat) with the following categories nominally considered:

- Identify: note the existence of the hazardous phenomena,
- Characterize: study and represent the hazard in a repeatable manner,
- Deter: take actions to prevent the threat from manifesting itself, usually acts on the hazard,
- Deny: place assets in locations to avoid the hazard, usually acts on assets,
- Mitigate: take action to design assets or their operations to be less affected by the threat,
- Interdict: take action to reduce the impact of the hazard acting against assets,
- Recover: after the threat has been used against an asset, clean up the results and reconstitute assets that have been lost.

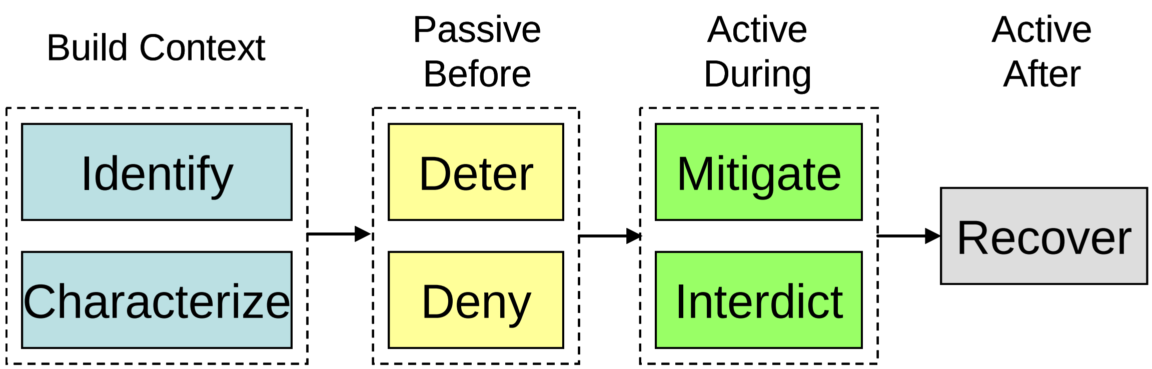


Fig. 5. The risk management process provides a framework for putting active debris removal into perspective.

Generally, identify and characterize provide a foundation for future active risk reduction options. For years, the aerospace community, largely led by NASA and industry visionaries, labored to highlight the importance of the orbital debris hazard and build the context for future analyses and actions.

The deter and deny phases focus on mostly passive means to reduce the threat. For orbital debris, this includes the formal presentations made by scientists and engineers about the potential future implications of the growth of orbital debris and the means to minimize the growth of the debris population. Moving satellites to orbits where there is little debris hazard would fit into "deny", but is normally not possible since the orbit of a satellite is usually selected carefully to support its mission.

The mitigate and interdict phases of risk management are active means to reduce the impact of the threat acting on a space asset. We are in this stage right now as mitigation measures applied in the 1990s are starting to have an impact in the last decade, but appear to be insufficient to manage the long-term growth of orbital debris. The question is whether to go after the large debris objects now or wait for some hazard threshold to be exceeded. Another form of "mitigation" is shielding. While this approach is effective against small debris (i.e. < 1 mm) it would be very expensive and operationally constraining to shield spacecraft to withstand impacts from debris greater than one centimeter in size.

Removing large derelict objects is considered an "interdict" response while the sweeping up of medium-size debris is a recover process.

If we get to the point of having to clean up the thousands of "lethal" fragments and launching satellites more often to compensate for debris-induced failures we will have migrated into the "recover" phase of the risk management continuum. At that point, we will be forced into the more expensive and slower medium-size debris cleanup.

While not completely analogous, this risk management paradigm is similar to some environmental health and maritime scenarios. For example, if a fully loaded oil tanker loses control, all efforts are made to secure the vessel before it ruptures and spills its contents into the sea. It is much preferred to control the vessel before an oil spill cleanup is needed.

In general, it has been found that risk management actions earlier in the sequence are more cost-effective to control the hazard. However, these marginal costs early in the life cycle of a threat are not always embraced by those who must incur them because the potential severity of the risk from the threat is not easily represented or understood. (See Endnote 24 on similarity to terrorism response.)

Current perceived and actual risks are below the threshold for immediate action. However, delaying action may cause us to go through a period of satellite failures due to collisions with debris. Eventually, the spacefaring community will expend more resources "recovering" from multiple collisions rather than proactively starting to remove large objects. This delay will cost the community 100's of millions of dollars to billions of dollars in debris cleanup and satellite replacement costs plus difficult-to-calculate impact due to termination of services supported by on-orbit assets.

While single object retrieval has been proven for selected missions such as the Long Duration Exposure Facility and repair of the Hubble Space Telescope, operationalizing this capability for uncooperative targets, not meant to be retrieved and potentially dangerous to handle, will be much more difficult. This capability will take significant engineering and testing to be made real for debris removal that will require many years, millions of dollars, and difficult associated policy/regulation evolution. The sobering fact is that this is the most mature of all technologies being considered so most or all other technologies will take even longer. The figure below depicts the general sequence of potential activities and their phasing, highlighting the need to start this process in earnest immediately.

A December 2009 survey [33] of fifty respondents at a technical debris removal conference provided the following results:

- 86% felt that action should be initiated in debris removal in the next 5 years;
- 70% said that debris affects their organizations; and
- 41% thought that debris removal actions should start immediately.

The figure below represents a semi-quantitative depiction of the environment evolution and the corresponding debris removal actions in order to keep the debris hazard from in the long-term getting much worse than it is now. This figure qualitatively addresses the actions required to field debris removal options against the growing hazard – as the crux of this paper has stated, the community can pay now in proactive actions and visionary efforts or pay later in the form of satellite replacements and forced removal option developments, deployment, and execution. The large object removal options are much closer to fielding so will take less time to move through the prototype stage but will take decades of operations to be effective. On the other hand, the medium debris sweeping possibilities are all very far from reality so it will take much longer to develop prototypes of these and then make them operational. However, once working it is anticipated that they should be able to perform their cleanup mission in less than a decade.

What the figure does not explicitly show is that if the growth of the lethal environment is misjudged it may be necessary to execute large object removal and lethal debris sweeping missions in addition to potentially having to replace some satellites "killed" by debris impacts.

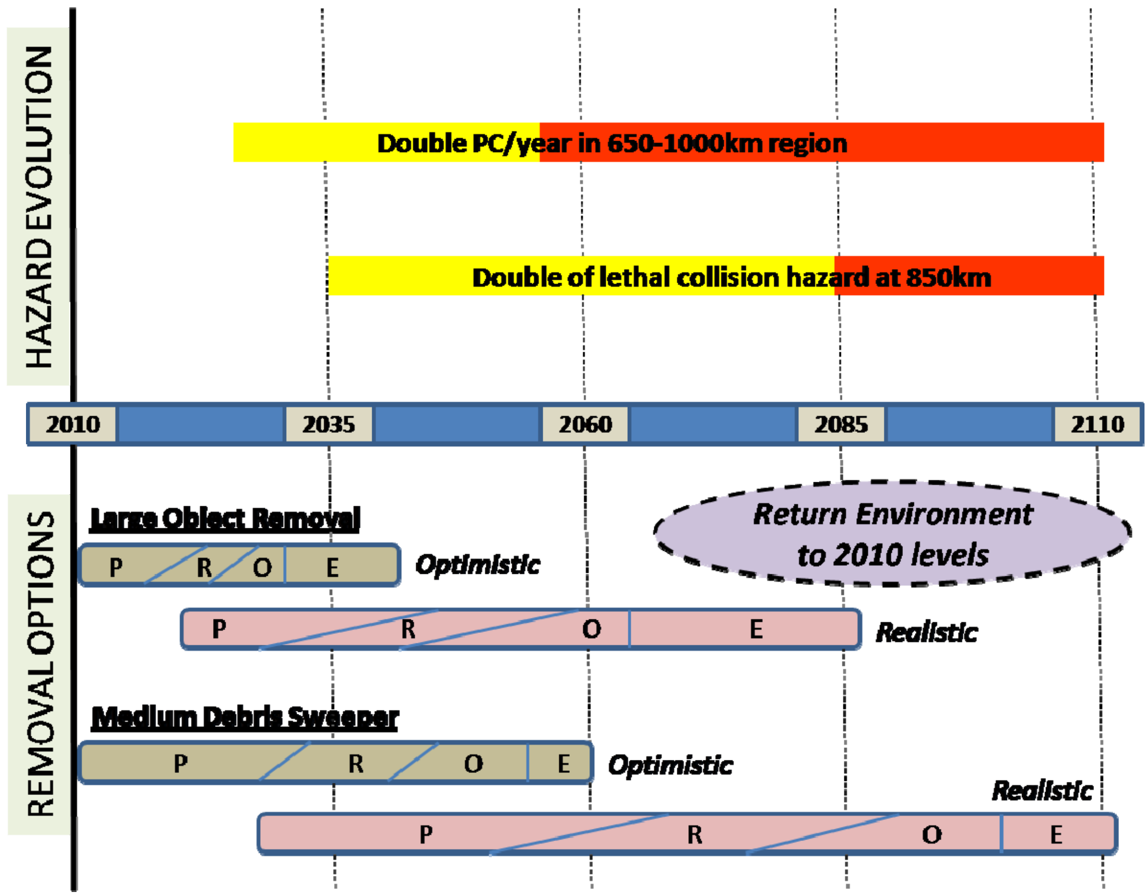


Fig. 6. The ability to control the growth of the orbital debris hazard requires a sequence of activities that amplifies the need to start this process now in order to minimize the chance that the response will be too late. In the Removal Options progression: P = prototype capability, R = regulations and policy development, O = operational capability development, and E = execution of the solutions on-orbit.

Only time will tell exactly when the debris hazard will cross into an untenable level and how much more we will end up paying to clean up tens to hundreds of thousands of medium-size "lethal" debris rather than tens to hundreds of large objects. It is also unclear if some single space mission loss (e.g. a space shuttle mission or a highly critical military satellite) will disrupt this process and be the catalyst for action. This is complicated by the fact that collision-induced fragmentations are highly deleterious to the environment and fairly rare, yet associated crucial variables are poorly known and there is little empirical background in order to reliably determine future event frequency.

Nassim Taleb, author of The Black Swan [18], describes the difficulty of dealing with highly improbable and highly unpredictable events that have severe repercussions. He accentuates the plight for those who try to prevent "Black Swans" because they are never appreciated if they are successful, since preventing something that was highly unlikely to begin with does not bring acclaim. Often, it is quite to the contrary; they actually get ridiculed for their attempts to prevent events that others have difficulty even imagining.

I hope that we do not have such a situation with active debris removal actions. While the calculus of delaying action is much clearer, it will still require some vision from policymakers and technologists to act now to start real programs for active debris removal.

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29. A similar phenomenon often occurs related to gambling. For example, the person who buys the most lottery tickets has the greatest probability of winning the lottery, however, it is almost always the single random purchase of a lottery ticket that is the winner. Again, the most probable event is hardly ever the next event to occur. The selective removal of large debris objects is not exactly random, as lottery ticket purchasing, yet it does still have the overarching issue of the most likely event usually not being the next event to occur.
30. Nicholas Johnson, NASA/JSC, provided a satellite catalog for January 2009 with the radar cross-section and mass included for all objects permitting this analysis.

31. Virgili, B.B. and Krag, H., Strategies for Active Removal in LEO, Proceedings of the 5th European Conference on Space Debris, Darmstadt, Germany, ESA SP-672, July 2009.
32. Kelso, T.S., Analysis of the Iridium 33-Cosmos 2251 Collision, AAS 09-368, presented at the 19th AIAA/AAS Astrodynamics Specialist Conference, Pittsburgh, PA, August 11, 2009.
33. During the December 2009 DARPA/NASA Conference on Orbital Debris Removal in Chantilly, VA, the Technical University at Delft distributed a survey to conference participants regarding space debris removal. The results were provided to the author in July 2010.