# Modeling Small Orbital Debris Remediation in Low Earth Orbit

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**CONFERENCE PAPER**

NASA's Orbital Debris Program Office estimates the population of small debris (particles between 1 and 10 cm) at approximately 500,000. The number of particles smaller than 1 cm exceeds 100 million. Although small, these objects can cause significant damage to operational satellites due to the orbital velocities and large transfer of kinetic energy in collisions. To protect our operational spacecraft, the best course of action is to prevent the unnecessary creation of debris. This has been the focus of the U.S. National Space Policy efforts and generally tends to focus on preventing large objects from colliding or exploding thus becoming small debris. It appears inevitable, given the proliferation of satellite constellations due to the lowered bar to entry into the space environment, that collisions will occur and significantly increase the number of small debris. This paper focuses on the modeling of various debris collection schemes using a predator-prey model with debris collection satellites as predators and debris as prey. This modeling effort explores a hypothetical aftermath of catastrophic collision events and a rapid increase to double the current debris population. The model computes the duration of debris abatement efforts for a variety of collection satellite schemes. Assumptions about the collection satellites include: the material technology for hypervelocity collision is sufficient for survival, collisions are with small debris only, the orbital trajectory of the collection satellite is maintained after a collision, all collisions result in the capture of the debris, and no extra debris is generated in the process. While these assumptions pose significant engineering problems, they are necessary conditions to explore the effectiveness of such an approach to debris abatement and determining measures of success. These engineering challenges may be overcome through dedicated investment in collision energy control technology for satellite systems. Collision rates for various orbital parameters are determined using the NASA Orbital Debris Engineering Model. Specifically, orbital inclination and altitude, which determines collision velocities, transferred kinetic energy, and survivability. The modeling effort also explores consolidation and disaggregation methodologies on mitigation. Initial modeling of a hypothetical collision that doubles the debris population, followed by deploying a predator platform with a 900 square meter collector at a 98-degree inclination angle at 950 km altitude, and using a rate of 4 collisions per square meter per year, would slow debris growth significantly but would be insufficient to return the population back to its original state. The model results indicate a total of 10 collectors would return the population back to original levels but would take decades. Also included is a discussion of the various assumptions in the model. The results show the importance of preventing disastrous collisions and unfortunately lay out the inevitability of the cost of rapid satellite proliferation.

## 1. INTRODUCTION

In this paper we investigate orbital debris specifically in the Low-Earth Orbit (LEO) regime. LEO has the highest concentration of orbital debris, trackable and otherwise. We discuss the source of this debris environment and how this debris affects space operations. We summarize remediation methodologies and their respective pros and cons. We then select a plow-class of satellite to investigate in more detail and perform modeling to show the effectiveness of debris remediation in this manner. We introduce a Predator-Prey model with a basis in Biology for analyzing the efficiency of the remediation methodology. Assumptions used for the development of the modeling as well as modeling results are discussed in detail.

## 2. ORBITAL DEBRIS PROBLEM

NASA's Orbital Debris Program Office (ODPO) states more than 25,000 objects larger than 10 cm are known to exist [1] . ODPO estimates the population of orbital debris between 1-10 cm to be in excess of 500,000 and the number of particles larger than 1 mm exceeds 100 million. Most of this debris is within 2,000 km of Earth in varying concentrations, with the greatest concentration near 750-1000 km. The source of this debris is primarily satellite explosions and collisions, either accidental or intentional. Objects less than 5 cm in size are difficult to track individually. Therefore, this population estimate relies on statistical sampling and modeling techniques [2]. These small-sized populations are termed Lethal Non-Trackable (LNT) debris since the particles are large enough to disable a satellite in a collision. The LNT population represents the largest quantity of orbital debris and poses significant risk [2] [3] [4]. All collisions, even with small debris, produce additional debris that increases the overall debris population that will eventually lead to a cascading effect. This effect, now known as the Kessler Syndrome, was suggested in the early decade of space capability development. Kessler theorized that as the population of space objects grew there was a finite probability of collisions between them [5]. He stated these collisions would create more fragments and subsequently more collisions. The result would be an exponential increase in the number of objects and eventually a belt of debris around Earth. The current debris situation demonstrates that we are now experiencing the effect of random collisions becoming the dominant source for debris population growth [4] [6].

Significant attention by NASA has been placed on controlling the creation of debris during launch and during post mission deactivation activities [7]. Removing large bodies from the space environment and thus preventing them from becoming smaller debris is a very efficient way to prevent a rapid increase in the small debris population. However, very little attention has been focused on the remediation of the small debris population that exists and will continue to grow. Partially because protecting spacecraft using debris shields can be quite effective against small particles 0.1-1 cm in size [8]. However, on-orbit shielding is insufficient for protection from debris 1-10 cm in size. Instead, impact mitigation is achieved by redundancy with maximum physical separation of redundant components, which may be sufficient for some missions while reasonable collision rates exist. Physical protection against particles greater than 10 cm is not yet technically feasible, therefore the remainder of this paper will focus on the debris population less than 10 cm in size.

Natural processes act to remove debris from orbit, giving objects an orbital lifetime. The primary influence on the lifetime in LEO is atmospheric drag, which will act to first circularize an orbit, then cause the altitude to decay into the increasing atmospheric density until the object becomes aerodynamic or incinerates. This process works at a rate that is proportional to the area to mass ratio of the object and the atmospheric density at a given altitude [5]. These effects on this population have been computed by [5], [9], and [10] using assumptions for the calculations that include a 1 cm radius sphere of mass density 2 g/cm$^3$ (mass of 8.4 g) to change its altitude by 100 km for circular orbits of 800 km and 1200 km. These predictions are shown in Table 2.1.

*Table 2.1. Estimates to reduce altitude of 1 cm radius sphere of mass density 2 g/cm$^3$ (mass 8.4 g) by 100 km.*

| Initial Orbit Altitude | 800 km | 1200 km | Source |
|---|---|---|---|
| Years required to reduce altitude by 100 km | 32 years | 455 years | [5] Kessler |
| | 110 years | 2000 years | [9] Martin |
| | 20 years | 100 years | [10] Brooks |

The large range in values results from uncertainties in the atmospheric models and drag coefficients used. However, one can ascertain from this data (even with the most optimistic estimate) that this small debris will not be removed from orbit for more than a century…far too long to wait out a post collision environment that makes an orbit unusable or impenetrable. Considering the human dependence on space capabilities, this highlights the need for an active debris remediation concept targeted at this population. A number of ideas have surfaced for the removal of this portion of the debris population which will be discussed in the next section.

## 3. ACTIVE ORBITAL DEBRIS CONCEPTS FOR LEO

Ideas that get significant attention such as spears, nets, and grappling hooks are directed at large bodies that are at least mostly intact, with the aim of deorbiting the object by some means. These ideas should be considered for removal of large bodies to prevent them from becoming a source for smaller sized populations. However, this is not the focus of the modeling effort in this paper. For the population of debris less than 10 cm in size, alternative methods must be employed.

Drag augmentation via on-orbit disbursement of dusts [11], foams [12], mists, or liquids present potential solutions for removal of small debris. The concept is to release a large quantity of material on orbit that would increase drag on any debris encountering the cloud of material. After repeated encounters with the cloud, the debris would amass a sufficient reduction in momentum and reenter the atmosphere, removing it from the population. A concern for this approach is the material rapidly dispersing to a point that is no longer effective. Containment of the materials by balloons would avoid dispersal but only until the first collisions, at which point the material would begin to disperse.

An extension of this idea is the spider web concept, where large segments of foam are extruded from a satellite placed in orbit. The Foam Debris Catcher (FDC) is a concept by a Russian company Start Rocket [13] to use extruded foam to form a large surface area to attach to or collect debris. While not explicitly stated in their marketing documents, this concept could be used to collect small debris with strategies to reduce impact velocities. However, while the overall bulk surface area may be quite large, the nature of the extrusions results in the effective surface area substantially smaller.

A more kinetic solution exists in the plow or shield [14] [15] concepts. This method requires interception of the targeted debris; during which the debris may pass through successive layers of a shield structure and thus dispersing its kinetic energy as the particles become smaller and spread over a larger area. However, the forces endured during the collision would be immense. With additional development of hypervelocity materials and structures, this concept could be a worthy candidate for a debris remediation mission. It is this class of debris removal we intend to investigate in the remainder of this paper.

## 4. MODELING OF SMALL DEBRIS

NASA's ODPO developed and is responsible for the distribution of the Orbital Debris Engineering Model (ORDEM). The purpose of ORDEM is to compute orbital debris flux – the yearly rate from a given direction that debris from a given population and of a given size and larger would strike an equivalent spherical spacecraft with unit cross sectional area [16]. It is this flux that provides the collision rates for the modeling of the plow-class debris remediation concept. The modeling in the remainder of this paper utilized the ORDEM 3.1 version. It is acknowledged that ORDEM 3.2 is the most current version of the debris model, but the timing of its release in March 2022 [17] precluded its use in this study.

ORDEM was used to simulate a circular polar orbit at 950 km altitude and a 98-degree inclination angle. The following figure shows the debris flux for this orbit.

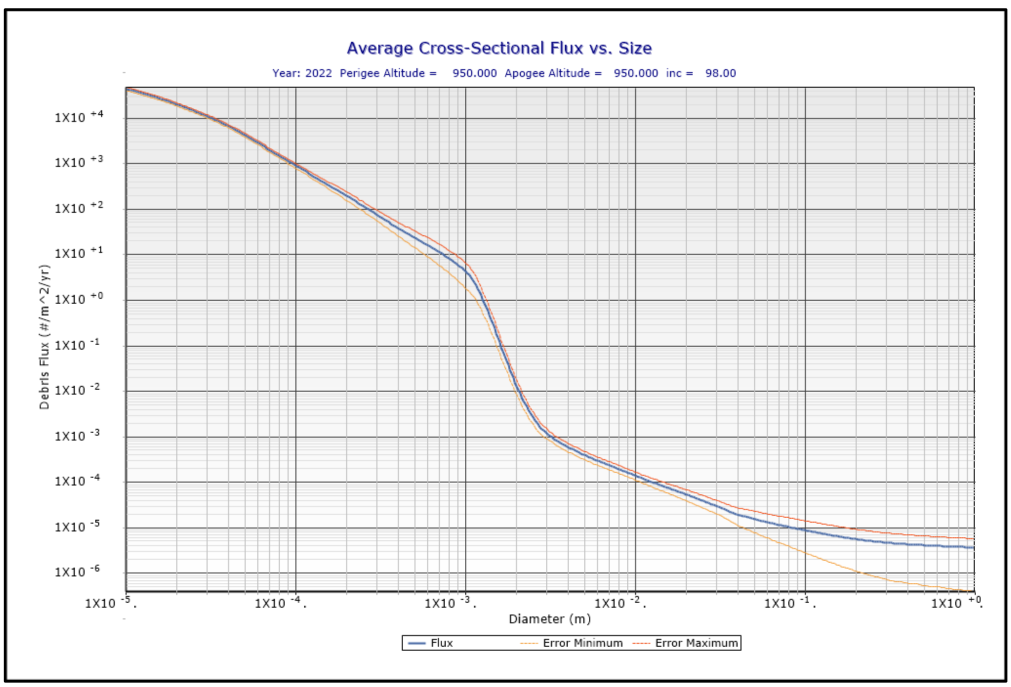


*Figure 4.1. Output of ORDEM for an orbit at 950 km altitude and a 98-degree inclination angle.*

This output of ORDEM allows for selection of various collision rates by size threshold. For the purpose of this modeling effort, the 1 mm and larger debris population with a collision rate of 4 collisions per square meter per year will be used as the baseline. Collision rates with larger debris (greater than 10 cm) are on the order of $10^{-5}$ or less, which bodes well for avoiding collisions with these objects as it would be catastrophic to the health of the debris collector.

Figure 4.2 shows the direction the debris will encounter a spacecraft for this orbit. In this case, the overwhelming majority of collisions will be in the direction of travel, implying a spacecraft design with the plow surface perpendicular to the direction of travel. This has implications of increasing atmospheric drag which could be useful for a shorter mission lifetime and potential deorbiting mechanism.

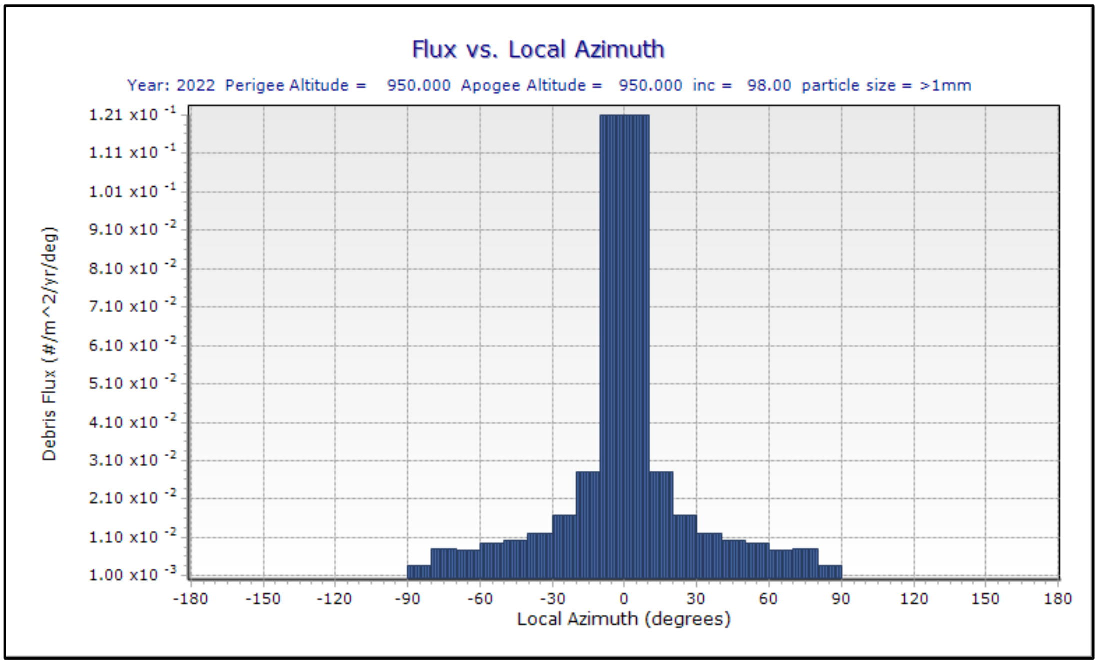

*Figure 4.2. ORDEM Debris Flux vs Local Azimuth for an orbit at 950 km altitude and a 98-degree inclination angle.*

Collisions from the direction of travel also has consequences on the collision velocities. Since most of the collisions are head on, the velocities of those collisions will be quite high. Figure 4.3 shows the ORDEM results for the velocity of collisions in this orbit.

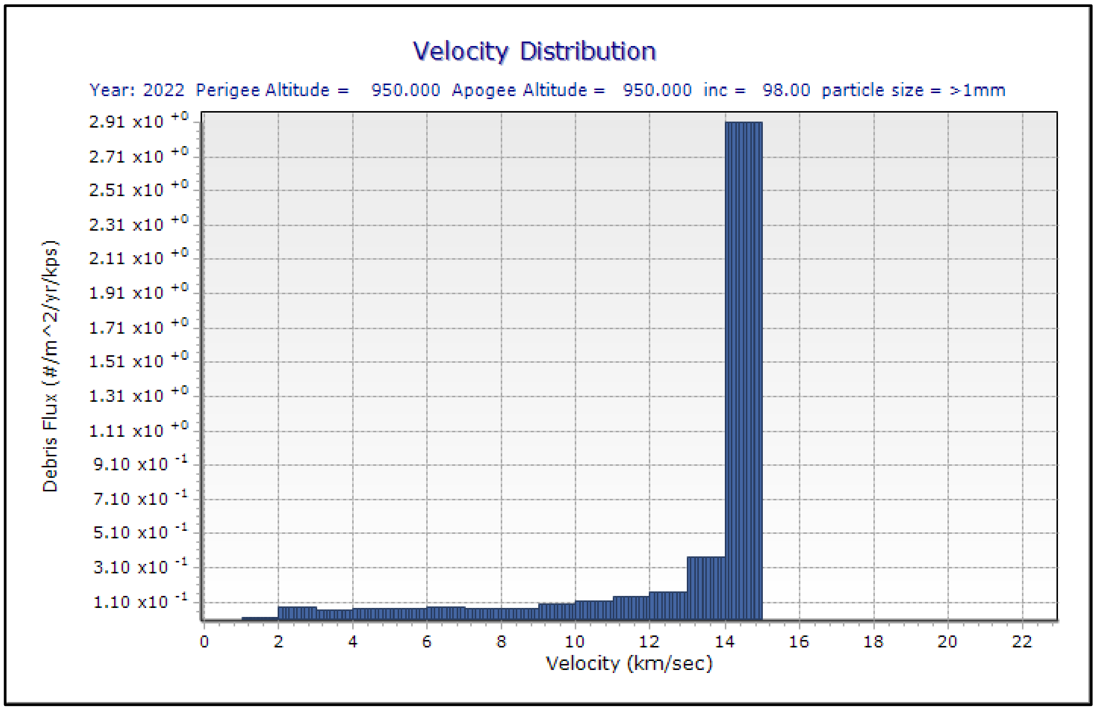


*Figure 4.3. ORDEM Collision Velocity for an orbit at 950 km altitude and a 98-degree inclination angle.*

A majority of the collisions fall in the 14 km/sec bin. This is quite a large energy exchange which might be challenging to overcome. An alternative orbit to address this would be at a low inclination angle, the tradeoffs of which are described below.

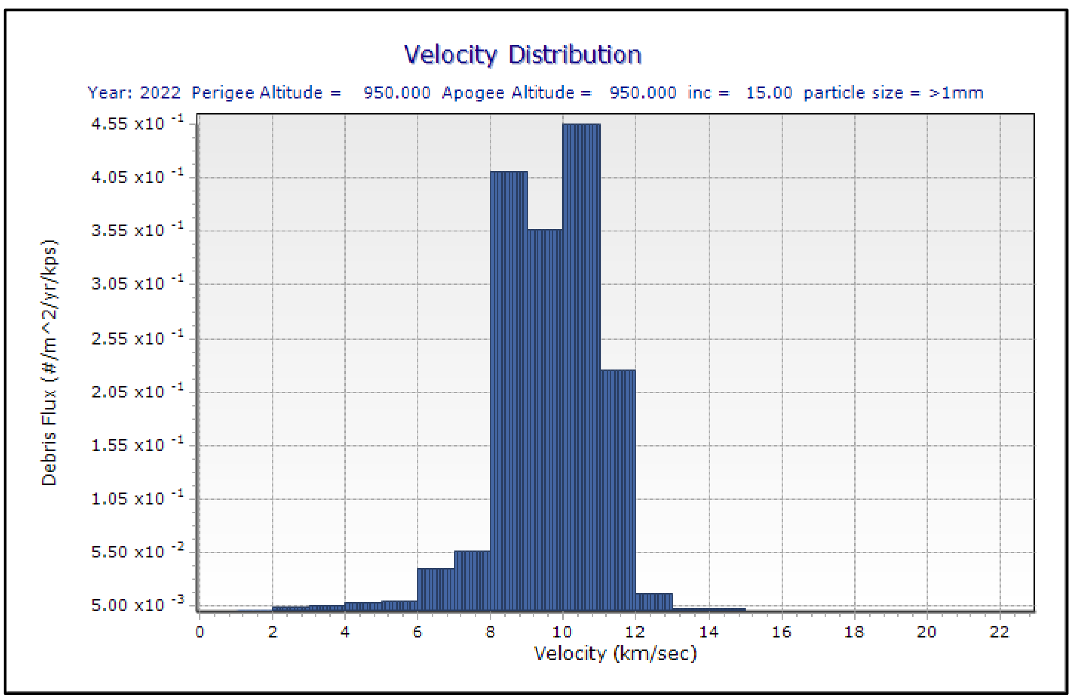


*Figure 4.4. ORDEM Collision Velocity for an orbit at 950 km altitude and a 15-degree inclination angle.*

Figure 4.4 shows the collision velocities of the 950 km altitude orbit but with a 15-degree inclination angle. By changing only this one orbital element, the collision velocities are reduced significantly to values in the 8-11 km/sec range. However, the tradeoff in energy exchange comes at a price in the number of actual collisions.

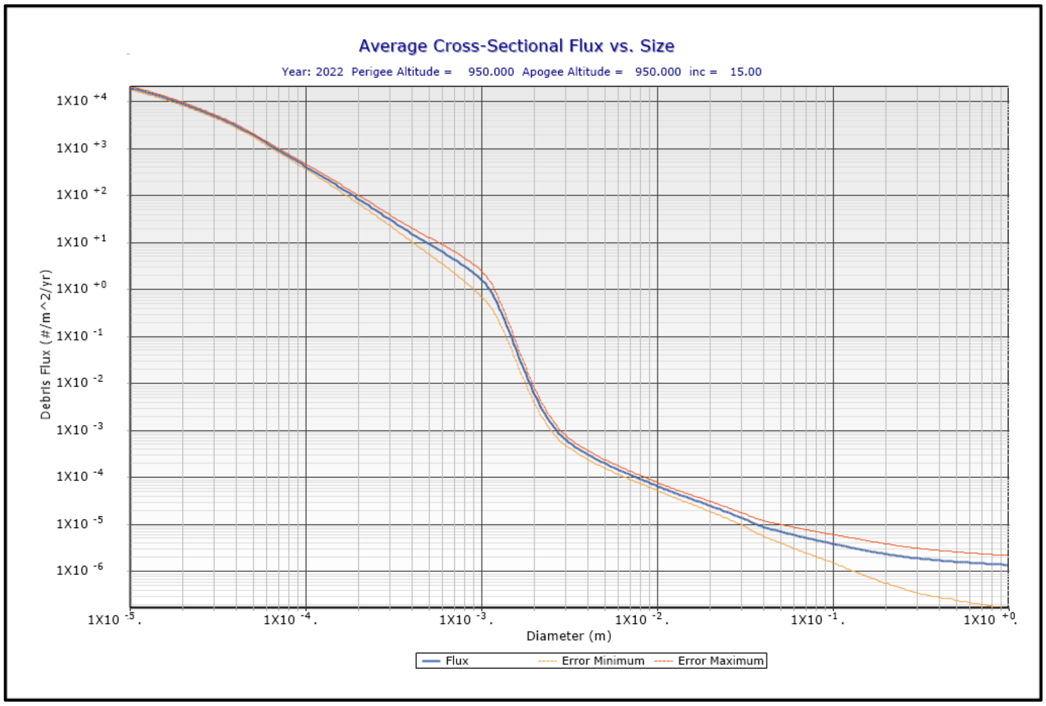


*Figure 4.5. Output of ORDEM for an orbit at 950 km altitude and a 15-degree inclination angle*

Figure 4.5 shows a graph similar to Figure 4.1, but with the inclination angle changed to 15-degrees. The debris flux of particles 1 mm and larger is about 4 times smaller than the polar orbit. This means that fewer collisions occur in the equatorial orbit, making the plow less efficient at collecting debris.

This orbital selection offers an improvement to atmospheric drag concerns. Figure 4.6 shows the histogram of debris flux by local azimuth. This distribution implies collisions are from +/- 60 degrees in local azimuth…the debris is not head on but from the side. This explains the reduction in collision velocity as well. No collisions are from the front suggesting a change in plow orientation from perpendicular to parallel to the direction of travel. This has the effect of reducing atmospheric drag and potentially extending the orbital lifetime of the plow.

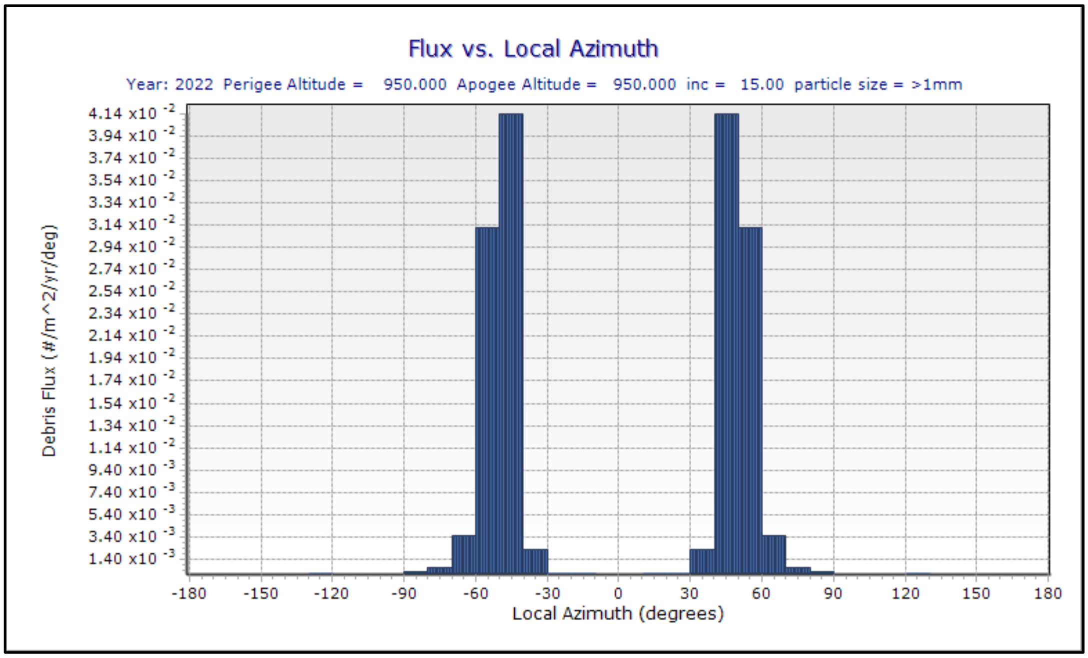


*Figure 4.6. ORDEM Debris Flux vs Local Azimuth for an orbit at 950 km altitude and a 15-degree inclination angle.*

To keep this paper a manageable size, the remainder of this paper will investigate the plow-class concept in the polar orbit (98-degree inclination angle) at 950 km. This investigation will need a collection efficiency model to quantify how well the chosen design performs in this orbital regime. That model is described in the next section.

## 5. SMALL DEBRIS REMEDIATION MODELING AND RESULTS

In this section, a model is developed to explore the effectiveness of a plow-class debris remediation concept for LEO. The plow spacecraft is inserted into orbit and unfurled to present a surface area orthogonal to the debris collisions. The plow is envisioned to collide with the debris, survive the collisions, and remove the debris by collecting or imparting a sufficient change in velocity to deorbit the debris. To perform this mission, a plow-like satellite will need to maximize effective surface area and use materials designed for hypervelocity collisions. There are myriad technical challenges to overcome; however, for now we assume all these challenges are achievable to determine the effectiveness of relying on collisions to remove small orbital debris. For this concept to be considered successful, it must be able to remove debris in sufficient numbers to alter the growth rate of the debris population. The degree of alteration can be argued and will vary depending on the situation such as minor slowing of the growth rate, maintaining population at current levels, or cleaning an orbit after a catastrophic event such as another intentional anti-satellite weapon deployment.

For the purpose of determining the effect on the growth rate, we developed the following model based on a predator-prey relationship borrowed from the field of Biology. In our model the plow spacecraft are the predators, and the debris are the prey. The prey population, $P$, starts at some initial population, $P_{\text{initial}}$, and changes over time depending on the growth rate, $k$, of the debris from new launches and collisions. The prey population is also reduced according to a reduction rate, $h$, which is dependent on the properties of the predator constellation. An additional reduction term related to the solar cycle and the resultant atmospheric drag could be added but is ignored in this investigation. This is not unreasonable since the focus of the debris abatement in this example is at 850-1000 km altitude and reduction in population due to this effect is very small. Additionally, it is assumed that all predator satellites remain functional for the duration of the simulation or are immediately replaced once sufficient damage is incurred and the satellite deorbited. This predator population term is found in many predator-prey models since typically in nature the prey is a food source for the predators. However, in our situation the prey could damage the predator and force it from the predator population. This term could be considered in future modeling efforts, but for now we stick with the assumption of survival or replacement, maintaining a constant predator population with the consequence of the result being a best-case scenario.

The model takes the form,

$$P = P_{\text{initial}} + \int k - h\frac{P}{P_{\text{initial}}}dt \tag{1}$$

where:

$P$ = orbital debris population (prey)
$P_{\text{initial}}$ = initial debris population at the beginning of the simulation
$k$ = growth rate of small debris
$h$ = reduction rate = number of predators * surface area * collision rate
$t$ = time

To use this model, several assumptions must be made to reduce the complexity of the orbital debris problem. First, the initial population of a particular orbit must be established. As shown previously, there are many sources for debris populations but generally these numbers are the size of debris in bulk, throughout the near-Earth environment. This model is for a particular orbital regime or at least altitude. In the modeling that follows we chose a circular, polar orbit (98-degree inclination angle) at 950 km altitude. This allows for collisions at any point along the orbital plane of the plow spacecraft, but also at the poles where numerous orbital planes (at the same altitude) intersect. Since we are modeling the removal of small debris, the model needs an estimate of the initial small debris population. We intend to vary this value to explore the effectiveness of the plow-like constellations under various scenarios. But first we need an estimate of the current situation. To find this, estimates of the initial population of large objects (greater than 10 cm) in this orbital regime were obtained from Liou and Johnson, who used the LEO-to-GEO Environment Debris (LEGEND) model to estimate there are approximately 1300 objects at 900-1000 km orbital regime [18]. Assuming no new launches into our scenarios, these bodies are the parent population for the small debris which will grow at a linearly proportional rate. To obtain our small debris population we computed the bulk space estimates of small to large debris and scaled this orbit's large debris estimate by the ratio of small to large debris which resulted in about 500,000 particles.

Next, we make assumptions about the growth rate, *k*, of the small debris. A linear growth rate of 320 new objects per year has been commonly used since Kessler and Cour-Palais [5]. However, this is the value for all large objects in space. In this simulation we need just the growth rate for one particular orbital regime for both large debris and small debris. Again, we source the Liou and Johnson work with LEGEND [18] to find an orbital regime growth rate of 10 large objects per year. This value is also scaled to achieve a modest growth rate of 400 objects per year.

The collision rate used in our simulation was selected from the ORDEM. The ORDEM was run in spacecraft mode for a circular orbit at 950 km and a 98-degree inclination angle, resulting in the corresponding collision rate of 4 collisions/m$^2$/year. This value remains constant during our simulation but could be scaled by population size to include effects of harvesting debris. This is a feature we defer for future work. Another assumption related to collisions is the harvest rate, *h*. We assume every collision results in a removal from orbit and no new debris is created. This assumption is very generous and results in a best-case scenario for this concept as a debris abatement solution. For now, we are interested in determining if this concept is even feasible, so we leave this assumption as is.

Also affecting the harvest rate is the surface area of the collector array. The surface area of one predator collector array was determined by using the interior dimensions of current payload shrouds as a limiting factor. We imagine a collector array with dimensions 12 m by 75 m by 20 cm thick rolled about a central axis. This mass should fit within the space of the 5 m by 19.8 m payload shroud of the Delta IV [19]. An array this size presents an achievable surface area ~900 square meters. To increase the effective surface area on orbit, more predator spacecraft are necessary. We show results for up to 10 predators in the following simulations.

With these assumptions we ran our predator-prey model to achieve the results in Figure 5.1. The charts show the simulation over a 100-year period. The number of objects in orbit starts at about a half million in this specific orbit. The blue line indicates the growth rate of the debris population with no attempt at remediation. The number of predator spacecraft was varied as indicated by the family of curves with green labels on the right side.

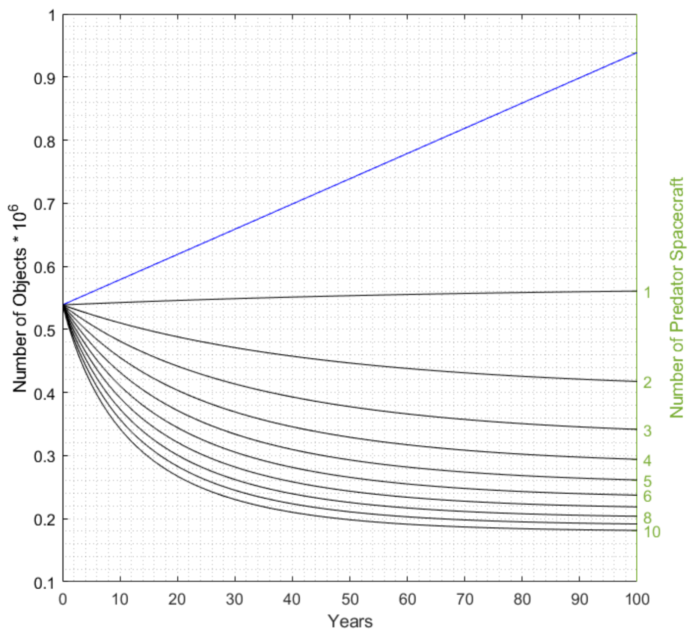


*Figure 5.1. Results of Predator-Prey Model for Initial Conditions.*

The model results indicate a sustained constellation of a sufficient number of predators can reduce the growth rate of orbital debris. With enough spacecraft in the constellation, the debris population could be reduced to half the initial population in about 20 years. Considering the assumptions that went into this model, it emphasizes the necessity to control the debris population with discipline on new launches and by removal of large debris objects to prevent them from adding to the small debris population.

With a baseline model in hand, we can investigate additional scenarios. Increasing the surface area of the collector array may be possible with more advanced materials or more clever engineering. If the size of the collector array was doubled to 1800 square meters, much more can be done with regards to cleaning an orbit as shown in Figure 5.2. As you would expect the timeframe to reduce the debris population is 10 years, about half the time of the original conditions.

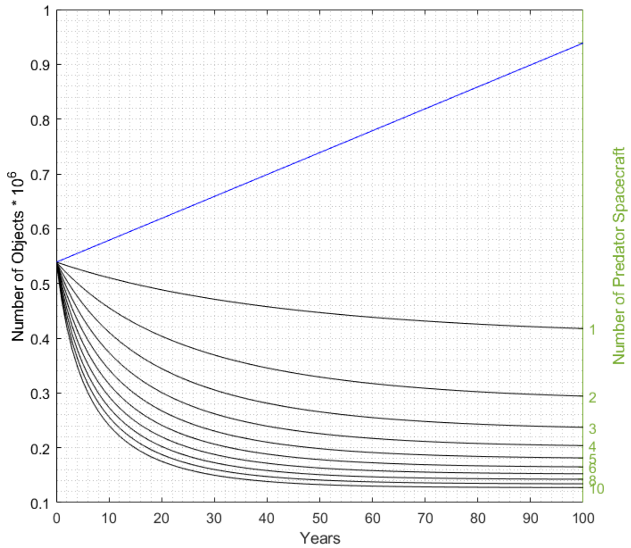


*Figure 5.2. Results of Predator-Prey Model with collector array of 1800 m$^2$.*

Another scenario that could be modeled is to assume a collision in this orbit resulting in a doubling of the small debris population. Figure 5.3 shows the results of starting with a debris population of one million with an associated doubling of the collision rate. The model indicates a count of 10 predator spacecraft would be required to reduce the population back to pre-collision size over 15-20 years.

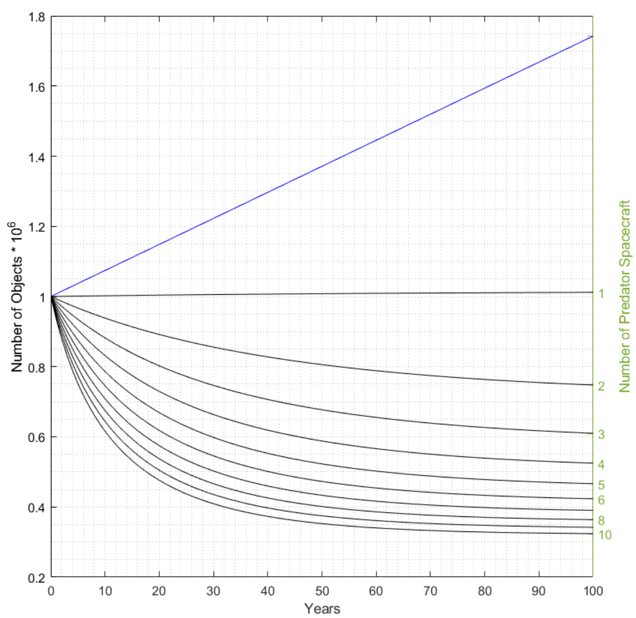


*Figure 5.3. Results of Predator-Prey model after a collision resulting in a doubling of the initial debris population.*

This example shows the ability of a predator constellation to reduce the orbital debris population to nearly half the original size in a matter of a few decades. But what is not modeled here is the cost; the cost of the abatement program would be significant. Additionally, there are tangible and intangible costs associated with the loss of space capabilities during this time. It is conceivable that the risk of launch through LEO to replenish aging geostationary communications satellites would be too great and the loss of critical nodes for global communications would start to affect industries required for modern society. The pressures to remediate the debris would be enormous.

## 6. CONCLUSION

In this paper we summarized the orbital debris problem and challenges associated with remediation of small orbital debris (1 mm – 10 cm). We introduced a predator-prey model derived from biology examples to characterize the effectiveness of a plow-class remediation satellite. We discussed the simplifying assumptions we used during the development of the model and its simulations of the debris environment. We also showed results for various debris environments and showed that the plow-class debris remediation concept may be a feasible methodology to remove small orbital debris from LEO. However, the challenge of designing collector arrays that survive hypervelocity collisions is not a trivial matter. For now, using the predator-prey model to characterize the environment and ability to remediate small debris appears to validate the concept.

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