SPACE DEBRIS MITIGATION CONOPS DEVELOPMENT

THESIS

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Abstract

Space debris remains an unsolved hazard for space operators and astronomers alike. From the nascent stages of space programs, space debris began accumulating in near-Earth orbit. Passive debris mitigation techniques have been enumerated and codified by the UNCOPUOS and IADC and several proposals for actively mitigating space debris have been presented.

However, the space debris problem requires reframing. This study aims to redirect the focus of solving the space debris problem by allocating weight of effort to target prioritization, appointment of a leading international agency that rallies nations toward the cause of solving the space debris problem, enrichment of binding relevant law and policy and development of collaborative agreements between countries in developing and enacting solutions to the space debris problem. Using meta-analysis, this study intends to reveal consensus among experts concerning the direction of a space debris mitigation program. 120 documents were compared and contrasted across data points germane to the data points mentioned above. Also included in the documentation found were laws and policies currently in place which outline conduct in space operations.

On the way to developing a viable CONOPS with associated courses of action, a multi-disciplinary construct for building solution sets to tackle the space debris problem must be created. The construct must be shaped by building blocks of active and passive space debris mitigation techniques, space debris characterization and space law. Within these building blocks, central considerations must be taken. First, targeting of space debris for removal must be prioritized to unite effort and to make significant reductions in the space debris threat. Next, a leading agent must be identified and empowered to act as an executor for a space debris mitigation program, be it passive or active. Also necessary is the enactment of enforcement measures to ensure space faring nations comply with binding regulations. Lastly, active space debris mitigation programs must be urged along by the international community with contributions from all nations able to provide any help. Aside from monetary contributions, aid can be rendered via intellectual space and manpower. We must seek the right questions to effectively solve the space debris problem.

Acknowledgments

I'd like to thank my wife first and foremost for having the patience when I locked myself away to focus on my graduate study especially in preparing my thesis and the grace to tackle our day-to-day responsibilities, at times singlehandedly, to allow me to concentrate while motivating me along the way. To my boys, I'll never regret not doing more work, but I'll always regret not playing with you more. Lastly, I'm extremely grateful and indebted to Lt Col Brent Langhals, my thesis advisor, for his patience, guidance and thought provoking discussions steering me to the right direction during the research.

Earl B. Alejandro

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I. Introduction

Background

For as long as man has realized the dream of space travel, he has left evidence of his achievement floating in the new frontier. There was a time when space debris was considered a necessary evil requisite of space exploration. “Plenty of space” used to be the phrase that went with the outlook with respect to space operations “wiggle room.” Looking back, the perspective on space debris has been altered to that of a nearly perpetual cluttering of humanity’s unreserved new territory.

Space debris poses an ever growing threat to space operations. At current count, there are more than 16,000 space debris objects in space; those are only the objects that measure 10 cm in diameter or larger that can be tracked by present day optical and radar instrument technology. A depiction of the number of space objects in Earth orbit is shown in figure 1 (Liou, 2011).

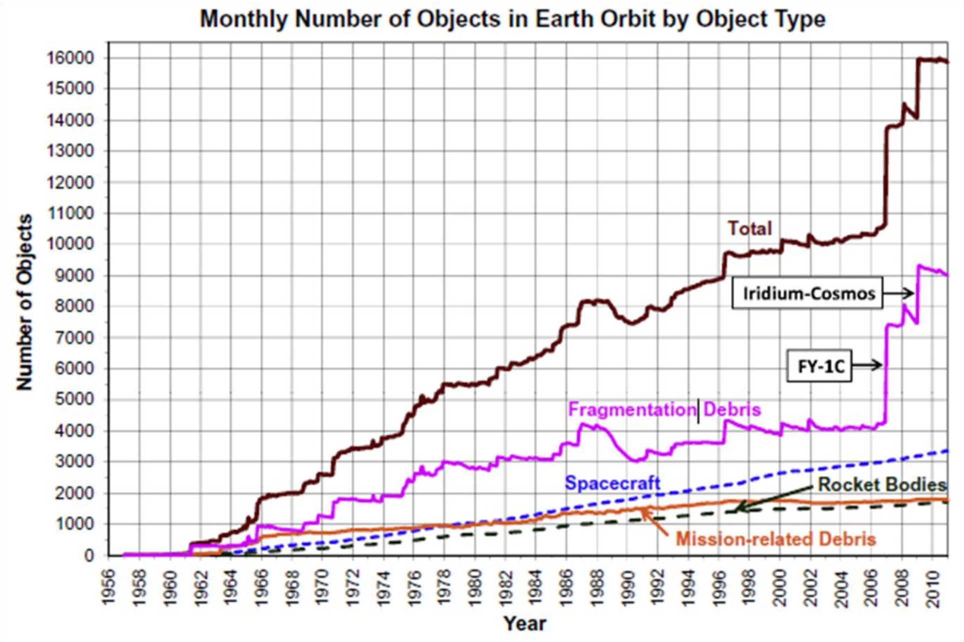
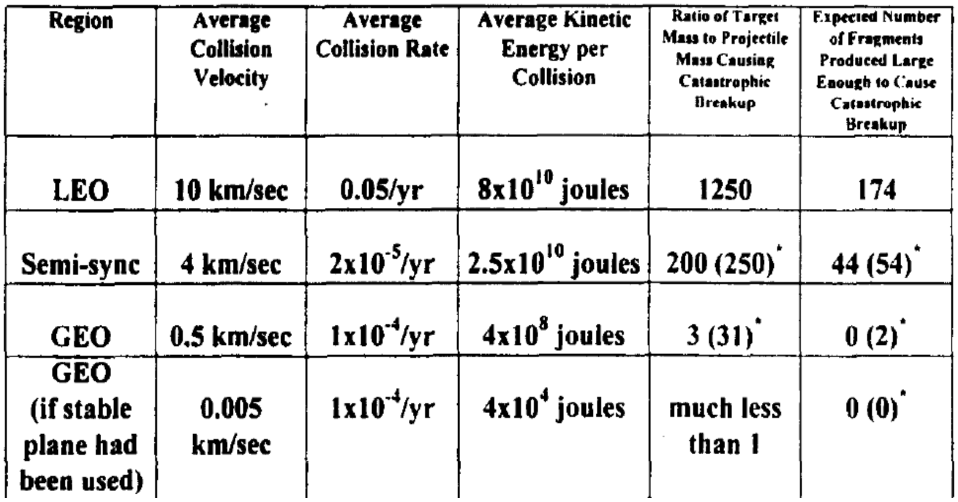


Figure 1 Number of objects in Earth orbit as cataloged by the US Space Surveillance Network (SSN). (Liou, 2011)

An additional innumerable amount, possibly in the millions, are also orbiting the Earth at sizes one centimeter or larger (Shrogl, 2010). Both size categories travelling at an assumed 10 km per second by expert estimations have the potential to harm operational space assets and humans in manned space flight (Valsecchi, Rossi, and Farinella, 2000). Figure 2 shows the kinetic energy characteristics for different orbits. The examples listed in Figure 2 are in joule units. As a point of reference a joule in everyday life is the equivalent of the kinetic energy of a tennis ball moving at 14 mph. The average speed of a professional tennis player's serve is 120-130 mph.



Region	Average Collision Velocity	Average Collision Rate	Average Kinetic Energy per Collision	Ratio of Target Mass to Projectile Mass Causing Catastrophic Breakup	Expected Number of Fragments Produced Large Enough to Cause Catastrophic Breakup
LEO	10 km/sec	0.05/yr	$8x10^{10}$ joules	1250	174
Semi-sync	4 km/sec	$2x10^{-5}$/yr	$2.5x10^{10}$ joules	200 (250)*	44 (54)*
GEO	0.5 km/sec	$1x10^{-4}$/yr	$4x10^{8}$ joules	3 (31)*	0 (2)*
GEO (if stable plane had been used)	0.005 km/sec	$1x10^{-4}$/yr	$4x10^{4}$ joules	much less than 1	0 (0)*

Figure 2 Kinetic Energy Characteristics in Earth orbit using 1993 US Space Command Catalogue. (Kessler, 1995)

Other manifestations of the space debris problem are intermittent interruption of RF paths (McKnight et al., 1993) and interference in sensor observations (Mulholland and Veillet, 2004). Small space debris in clusters and large space debris can move in front of RF communication transmission paths, radar and optical sensors and effectively obscure line of sight. It’s analogous to trying to speak or see through a wall. Lastly, space debris, if left unmitigated, has the potential to start a cascading collision event known as the “Kessler Syndrome” (Walker and Martin, 2004; Kessler, 1991). The “Kessler Syndrome” is a theoretical condition in which space debris generated from a collision event triggers another collision and in turn debris from that collision triggers another and so on. The ramifications are a near endless chain of collisions from generated space debris and a resulting copious pollution of space debris.

Space debris can be produced in a variety of ways. The most catastrophic example is breakup of an orbiting space object due to its collision with another orbiting space object. Some of these are unintentional as in the case of free floating pieces of detritus crashing into operational satellites: Iridium 33 collided with a Russian satellite no longer in operation. While some are operationally carried out by space faring nations with deliberate intentions (e.g. Chinese ASAT test (Barbee et al., 2011)), routine space operations carried out during the lifetime of a space asset also contribute to pollution in space. They are considered "operational debris"; examples are separation bolts, upper stages, tankage from the launch vehicle and protective coverings (Walker and Martin, 2004). Other operational sources of debris come from on board solid propellant rockets used for attitude and orbit modifications, which can produce particles that can agglomerate into slag (Mulholland and Veillet, 2004). Experts and space operators recognize the apparent threat of space debris to space operations and the obvious need for mitigation which logically follows.

Purposeful debris control can be illustrated in two categories of methods: active and passive debris mitigation (McKnight et al., 1993). Debris can be *passively mitigated* through better design and operations, expulsion of any remaining energy potential such as battery charge or remainder fuel in satellites that approach their operational end of life (most recently termed as "passivation" (Mulholland and Veillet, 2004)), retention of covers and separation devices and maneuvers of non-operational satellites to disposal orbits (McKnight et al., 1993). *Active debris removal* methods consist of retrieval, maneuvers, drag augmentation to include solar sails, tethering, sweeping and lasers (McKnight et al., 1993). Most of these options are still in the conceptual stage of their development with feasibility analysis limited to mathematical models thus far. Others are still immature in their development and, as is customary with space-borne systems, prototype testing in the actual operational environment is nonexistent. While these options exist, the only natural and least expensive way of removing space debris is its orbital decay eventually taking it down to lower altitudes for drag forces to finally allow space debris to de-orbit; passive or active space debris mitigation methods can speed up this process (McKnight et al., 1993).

In order to model the space debris densities floating above us and consequently successfully control pieces of debris, a space debris removal method must be able to "see" its target. Suites of tracking sensors are available. Both ground and space based sensors (impact, radar and optical) have been used to track pieces of space objects and characterize the near-Earth space environment. Most belong to the US Space Surveillance Network (SSN) and the Russian Space Surveillance System (SSS). Examples of Earth-based installations are the US Millstone, TRADEX, Ground-based Electro-Optical Space Surveillance (GEODSS), CCD Debris Telescope (CDT) and Liquid Mirror Telescope (LMT); ESA's Geostationary Orbit Impact Detector (GORID); the German Tracking and Imaging Radar (TIRA); and Japan's Middle and Upper Atmosphere (MU) radar (Johnson, 2004). Among the first space borne assets to measure space debris were NASA's Long Duration Exposure Facility (LDEF) and the ESA's EUropean REcoverable CArrier (EURECA). LDEF had a 69 month mission life ending in 1990 and resulted in 15,000 recorded "ram" impacts from a single year. After further analysis of these hits, it was determined that they were not from interplanetary dust but from manmade orbital debris and that they existed in cloud clusters sometimes 1000 km along track (Mulholland and Veillet, 2004).

Although many sensors are available, there are limitations to their detection capabilities and as a result, limitations in modeling and characterization. In general, anything between one centimeter and 10 centimeter is too small to be sensed by tracking assets. Worse yet, particles one millimeter to one centimeter in diameter, while also being too small for sensors to detect, will still have mission-degrading effects on spacecraft (McKnight et al., 1993). For these particles, a probabilistic distribution function must be modeled based on other characteristics such as albedo from a sample of the population of spatial densities (Kessler and Jarvis, 2004). Albedo is the property of an object to reflect radiation; given known or historical albedo values in the background of cosmic space and spacecraft materials, researchers can discern manmade space objects against naturally occurring orbiting bodies. Although based on a simple model resulting in two-line Element Sets (ELSETs), the US Strategic Command's Satellite Catalog is the most complete (Johnson, 2004; Shrogl, 2010).

Problem Statement

While there is an abundance of studies on the subject with respect to the space debris threat, its detection/tracking, modeling, and characterization and mitigation, discussion of clear objectives, command relationships, functional requirements, or sustainable states for space debris in the near-Earth space environment have not been advanced. We currently do not have a CONOPS to guide space debris mitigation efforts which start with clear objectives. Moreover, such objectives need to reflect the views from the consensus of space faring nations and nations that are developing their own space programs. The attainment of these objectives should also be through international concerted efforts with equitable apportionment of cost and risk. As the International Academy of Astronautics (IAA) so eloquently states, “Space is a ‘commons’ used by many for their individual and collective benefit” (McKnight et al., 1993).

Numerous institutions have taken initiatives to advocate for space debris awareness and its cleanup. Examples of these agencies are the IAA, the International Space University (ISU), the UN Committee On the Peaceful Uses of Outer Space (UNCOPUOS), the European Space Policy Institute (ESPI) and the Center for Defense Information (CDI). Along with the effort to raise awareness, there have been committees established that have taken leading roles on the issue of space debris mitigation. Among them are the International Association for the Advancement of Space Safety (IAASS), UNCOPUOS, the Inter-Agency Space Debris Coordination Committee (IADC) and the Committee on Earth Observation Satellites (CEOS) (Shrogl, 2010); unfortunately, just as many have failed to proceed with decisive action to draft and ultimately implement space policy that addresses space debris, limited to technical advisor positions (Shrogl, 2010). International cooperation with respect to the system level management of the space debris environment begins with constructing a concept of operations and a clear set of objectives.

When the space faring community develops well framed objectives for the mitigation of space debris, it will provide clear direction and focused effort globally with regard to the task at hand. Given desired effects, the space faring community can decompose strategy to specific tasks and requirements. In this case, the desired effects to be achieved are mitigation of space debris, reversal of the progression of the Kessler syndrome, and prioritization of target sets based on a space object’s potential to add to the aggregate population of space debris and its probability for collision with other space objects. These desired effects and well framed objectives are realized by developing a concept of operations for space debris mitigation

A concept of operations in turn will aid a future established space policy maker in guiding application of a preponderance of the collective international energy toward those specific samples of the population of space debris which can be detected, modeled, characterized, and controlled. Standards will also need to be established for space operations regarding curtailing manmade space debris production in the course of space operations. Acceptable thresholds for space debris levels can be instituted as a target for active removal utilizing current proven methods and tools. These objectives then can aid in the formulation of a basis of measures of effectiveness of space debris mitigation.

Not only do the desired effects or clear objectives require a concept of operations, establishment of a command and control relationship is also necessary. A definitive leader in this case lends aid to the solution by demonstrating an unambiguous chain of command from which space debris mitigation operations take unmistakable guidance. Also, this enables accountability by space faring nations to some form of leadership. Of course, the chain of command would be subject to various constraints such as space and terrestrial legal language.

Research Objectives

The purposes of this study are to expose objectives in space environment regulation with regard to controlling the space debris environment for space operators internationally, reveal the prime authoritative body to act as the command and control element per the collective opinions of space professionals worldwide, and advocate prioritization in space debris mitigation targeting. At this stage in the research, space debris will be generally defined as manmade space debris. Orbital debris is herein defined as “any man-made Earth-orbiting object which is non-functional with no reasonable expectation of assuming or resuming its intended function or any other function for which it is or can be expected to be authorized, including fragments and parts thereof” (McKnight et al., 1993). Central questions that will be explored are:

1. What are the objectives that are desired for space debris mitigation?
2. Is there a global trend that calls for a champion for the issue of space debris mitigation operations and if so which agency is identified?
3. How do we prioritize target sets in space debris mitigation operations?
4. What is the current state of space debris characterization?
5. What are current passive and active space debris mitigation methods?
6. What is the current legal framework concerning the space environment; how is it applied to the space debris problem and how can nations be legally bound to it?

Methodology

The intended methodology to be employed is meta-analysis. 120 documents comprised the literature review for this research. They focused on active and passive space debris mitigation methods, space debris characterization technologies and models, and space legal subject matters. Derivations of objectives and requirements will come from initiatives by globally recognized space centric technical and political professional societies and agencies such as NASA, ESA, UNCOPUOS, ISU, ESPI, CDI, IAASS, IADC, CEOS, IAA, Committee for Space Research (COSPAR), International Astronautical Federation (IAF) and International Institute for Space Law (IISL) (Shrogl, 2010; McKnight et al., 1993). A tendency for regulation definition to include limits in scope and hints of proper command authority will be drawn from these agencies. Consequently, strategies of comparing emerging methods, samples, observation data, document data, text analysis and software simulations will be used to gather defined bounds of space debris measurement, space debris control effectiveness and command and control operations.

This study focuses on finding key nodal gaps in solving the space debris problem. To make optimal use of limited resources, the space faring community needs to define the objectives of a space debris mitigation program and to prioritize the targeting of space debris for reduction in orbital lifetime. Another essential data point is the identification of a leading agency in space debris mitigation which would make major decisions, provide policy and guidance and set standards. This study also surveys current technologies and modeling for characterization of the space debris environment. Additionally, an exploration of active and passive space debris mitigation methods is conducted to enumerate options considering feasibility, cost and effectiveness. Lastly, the current legal framework is illustrated while analyzing deficiencies that hinder the progress of space debris mitigation execution.

Focus Areas

To tackle the investigation of space debris mitigation CONOPS development, we add to the definition of our solution space some focus areas. Our first focus area is passive mitigation by itself is not sufficient to stabilize the space debris environment. In the article “An Active Debris Removal Parametric Study for LEO Environment Remediation”, J.-C. Liou of NASA’s Astromaterials Research and Exploration Science Directorate (ARES) examines the results of a simulation forecasting the growth of the historical debris population. This simulation was re-accomplished after two new catastrophic fragmentation events. Namely, these were the 2007 Fengyun-1C ASAT test performed by China and the collision between Iridium 33 and Cosmos 2251 in 2009; for which the resultant debris clouds are illustrated in an AGI simulation shown in figure 3 (Liou, 2011).

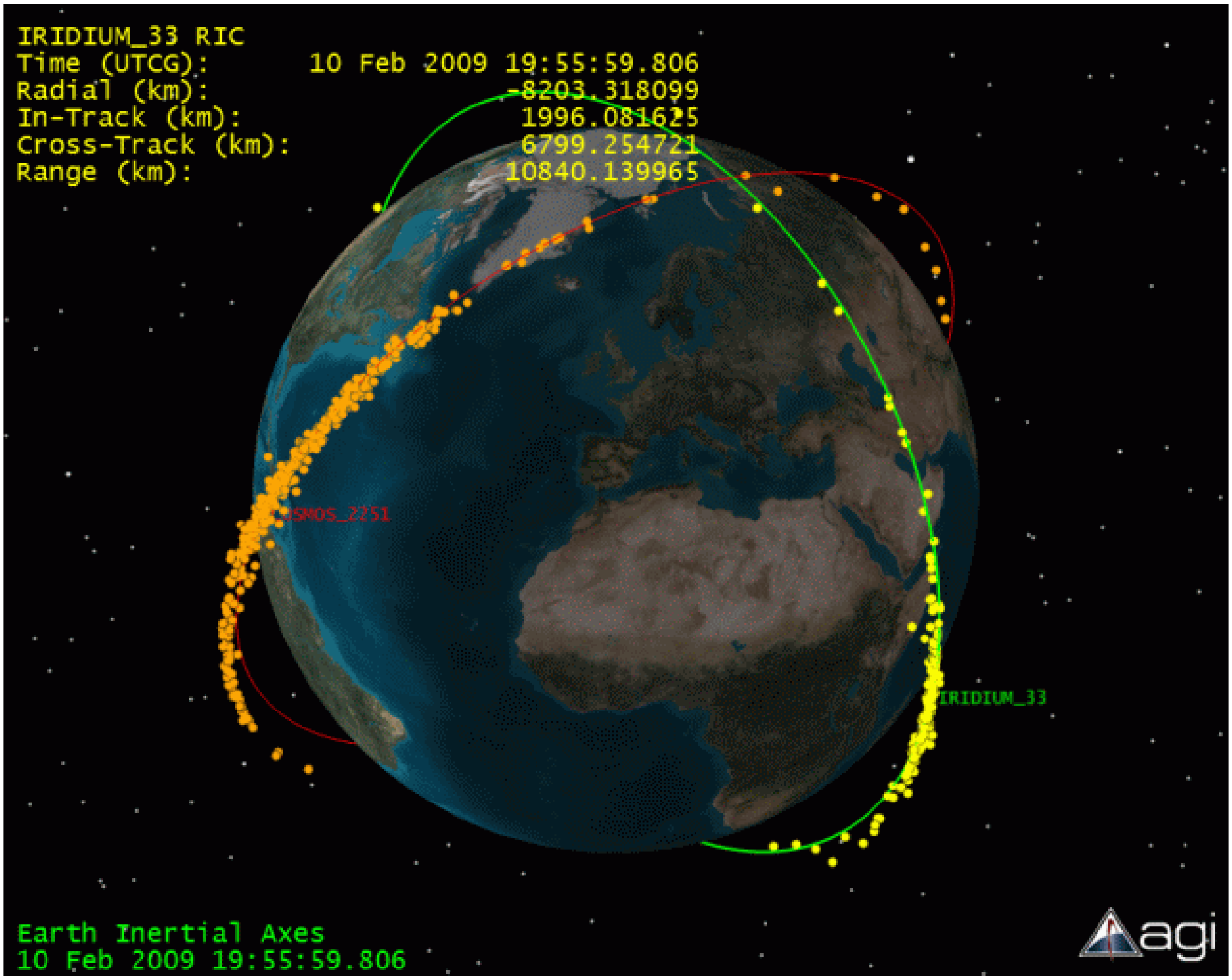


Figure 3 A map of the debris clouds just after the Iridium 33/Cosmos 2251 collision. (Listner, 2012)

The latter was an event involving a nonoperational satellite (Cosmos 2251) and an operational one (Iridium 33). This event is notable for two reasons. First, as Liou notes, "[the] event signaled a well-accepted trend that the future environment will be dominated by fragments generated via similar accidental collisions, not explosions" from non-passivated decommissioned satellites (Liou, 2011). Second, after an attempt at invoking written laws under the Liability Convention, neither party involved in this incident was found liable for the breakup and consequently not liable to each other in terms of compensation for the loss of either satellite. It is worth noting that the government of Russia (owner of the defunct Cosmos 2251) had no ability to perform a collision avoidance maneuver because of its defunct state while the United States based Iridium LLC (owner of Iridium 33) was an active satellite and had the opportunity to perform such a maneuver (Listner, 2012). The second outcome has the significance of showing the pitfall attributed to current space law that the current framework lack enforcement. In addition to prior debris levels and previous significant events, a "no future launches" scenario was added to the space debris environment model while current passive debris mitigation measures are observed. The plot of this simulation is shown in figure 4.

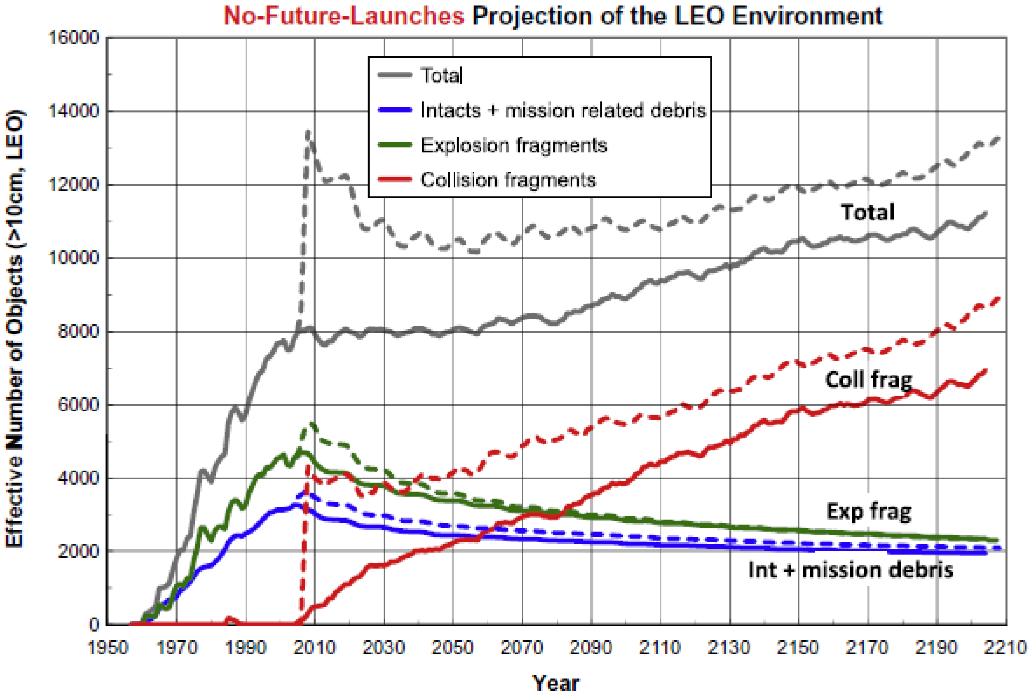


Figure 4 LEO population growth based on the no-future-launches scenario. Solid curves are from a simulation where the historical component ended in 2006. Dashed curves are from another simulation where the historical component ended in 2009. (Liou, 2011)

As seen on this graph, the total debris population will not decrease even with the absence of future launches and the sustained practice of passive debris mitigation; "fragments generated from mutual collisions among existing objects will force the population to increase over time" (Liou, 2011). These findings demonstrate that passive mitigation routines by themselves are not sufficient to reverse the progression of the Kessler syndrome or as Liou puts it, they are "insufficient to prevent the debris self-generating phenomenon from happening" (Liou, 2011)

The next focus area made in this study, to the effect of forming a design for the space debris mitigation CONOPS, is that there is no authoritative executive agency addressing space debris, taking the lead in these matters and holding States to mitigation standards. At most, the international community has at its service consultative bodies such as the IADC or the IAASS which prescribe mitigation methods. There exist advocates but not a decision making authority; no agency has decisively taken the charge in planning, funding, organizing, executing and controlling space debris mitigation operations. A hint of the sentiment to define a leader has been articulated by Carl Q. Christol, *the* pioneer of the field of Space Law and former President of the International Institute of Space Law American branch: "as has been generally assumed, the United Nations…[assumes] the lead policy and legal roles in [space debris]" (Christol, 1994).

Surprisingly, UNCOPUOS, as the assumed frontrunner to take on this responsibility, has treaded lightly on being the enforcer and creating relevant space law that is legally binding as applied to the international community. This is reflected in the language of their master space debris mitigation document "Space Debris Mitigation Guidelines of the Committee On the Peaceful Uses of Outer Space" which states:

> “Member States and international organizations should *voluntarily take measures*, through national mechanisms or through their own applicable mechanisms, to ensure that these guidelines are implemented, to the greatest extent feasible, through space debris mitigation practices and procedures.
>
> These guidelines are applicable to mission planning and the operation of newly designed spacecraft and orbital stages and, if possible, to existing ones. They are *not legally binding under international law*.
>
> It is also recognized that exceptions to the implementation of individual guidelines or elements thereof may be justified, for example, by the provisions of the United Nations treaties and principles on outer space.”

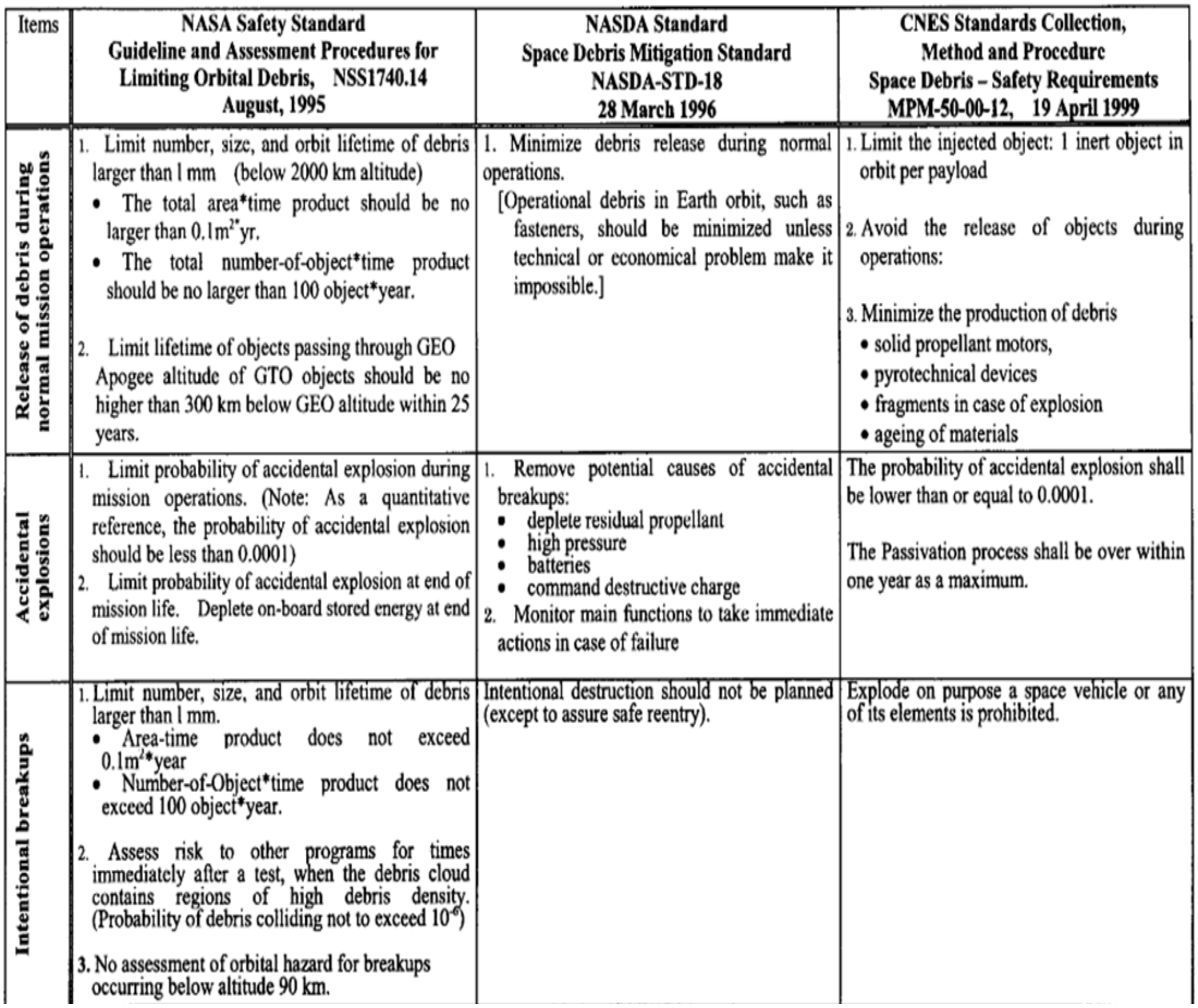
Just as a lack of an executive chair hinders the advancement of space debris mitigation operations by depriving it of clear direction, there is also a vacuum with respect to auditing mitigation practices.

This brings about the next focus area that there is no inspection agency that certifies compliance with prescribed passive space debris mitigation practices. As mentioned above, it’s specified that member nations of the UNCOPUOS are free to bend the guidelines as they are proposed. At its most lenient requirement, the Space Debris Mitigation Guidelines allow nations to voluntarily observe mitigation practices. To reiterate, the language explicitly states that “[space debris mitigation guidelines] are not legally binding under international law.” This license is extended to non-governmental actors such as contractors and commercial entities as illustrated in Article VI of the Outer Space Treaty:

> *States Parties* to the Treaty shall *bear international responsibility for national activities* in outer space, including the Moon and other celestial bodies, *whether* such activities are *carried on* by governmental agencies or *by non-governmental entities,* and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty.

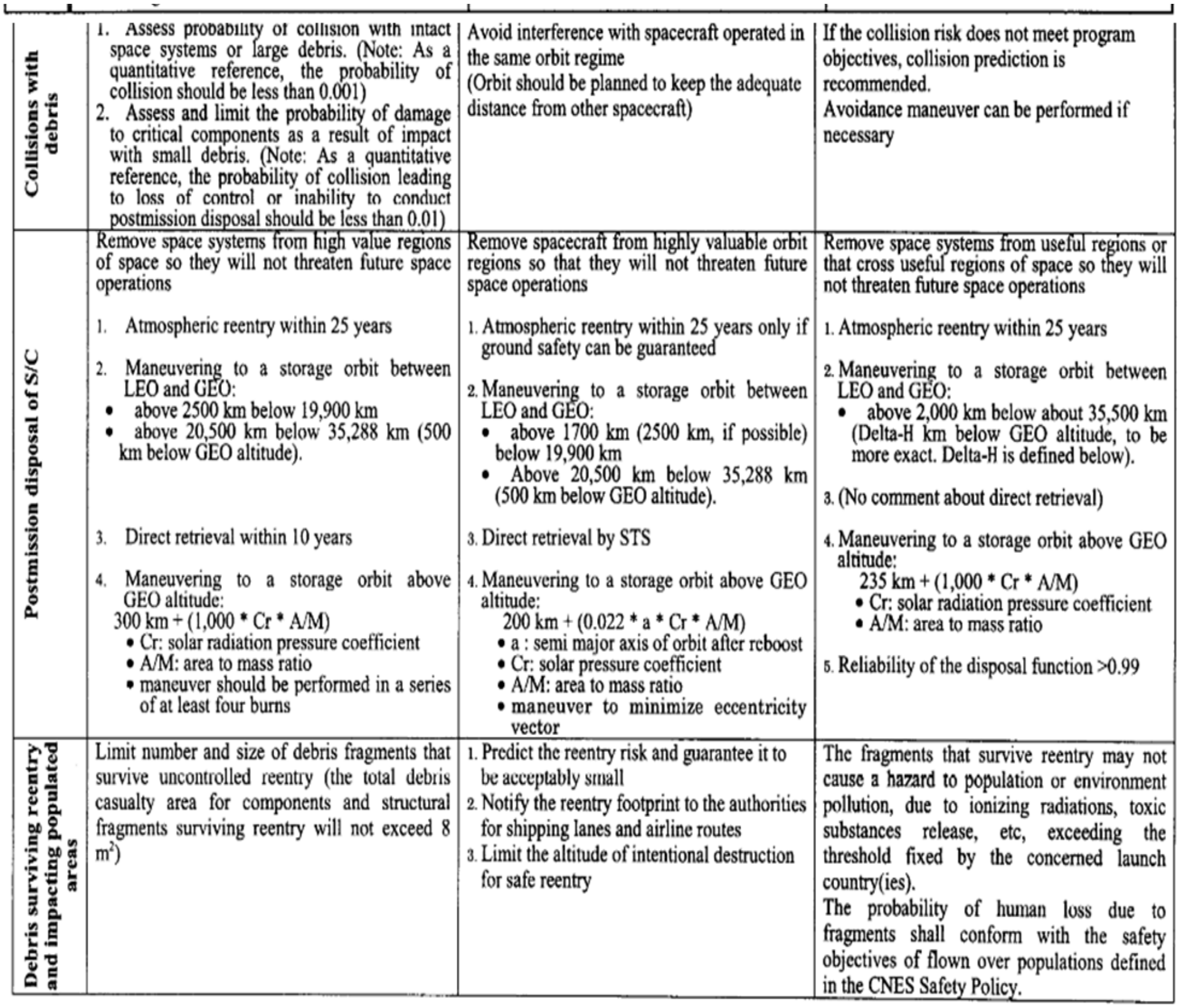
Therefore, if a State party to the OST is freed from the obligation to observe the Space Debris Mitigation Guidelines, then other citizens belonging to that State is free of such obligation also.

It is clear then that another focus area can be made which is that there is no legislative language binding State actors to adhere to prescribed passive space debris mitigation practices. Evidence of this is shown in the variation of implementation in space debris mitigation practices worldwide. Figure 5 and 6 below communicates this reality. Although this snapshot of the comparison of national space debris mitigation standards as set by different State actors was made in 2001, the phenomenon still rings true that left to their own devices, separate States will have a separate implementation of guidelines. This evolution is due to divergent definitions or descriptions of mission requirements and contrasting fidelity on how to meet the requirement set in addition to dissimilar cultures which have inherently dissimilar cognitive framing of the problem and solution sets.



Items	**NASA Safety Standard** **Guideline and Assessment Procedures for Limiting Orbital Debris, NSS1740.14** **August, 1995**	**NASDA Standard** **Space Debris Mitigation Standard** **NASDA-STD-18** **28 March 1996**	**CNES Standards Collection, Method and Procedure** **Space Debris – Safety Requirements** **MPM-50-00-12, 19 April 1999**
Release of debris during normal mission operations	1. Limit number, size, and orbit lifetime of debris larger than 1 mm (below 2000 km altitude) • The total area*time product should be no larger than $0.1 m^{2*}$yr. • The total number-of-object*time product should be no larger than 100 object*year. 2. Limit lifetime of objects passing through GEO Apogee altitude of GTO objects should be no higher than 300 km below GEO altitude within 25 years.	1. Minimize debris release during normal operations. [Operational debris in Earth orbit, such as fasteners, should be minimized unless technical or economical problem make it impossible.]	1. Limit the injected object: 1 inert object in orbit per payload 2. Avoid the release of objects during operations: 3. Minimize the production of debris • solid propellant motors, • pyrotechnical devices • fragments in case of explosion • ageing of materials
Accidental explosions	1. Limit probability of accidental explosion during mission operations. (Note: As a quantitative reference, the probability of accidental explosion should be less than 0.0001) 2. Limit probability of accidental explosion at end of mission life. Deplete on-board stored energy at end of mission life.	1. Remove potential causes of accidental breakups: • deplete residual propellant • high pressure • batteries • command destructive charge 2. Monitor main functions to take immediate actions in case of failure	The probability of accidental explosion shall be lower than or equal to 0.0001. The Passivation process shall be over within one year as a maximum.
Intentional breakups	1. Limit number, size, and orbit lifetime of debris larger than 1 mm. • Area-time product does not exceed $0.1 m^{2}$*year • Number-of-Object*time product does not exceed 100 object*year. 2. Assess risk to other programs for times immediately after a test, when the debris cloud contains regions of high debris density. (Probability of debris colliding not to exceed 10^{-6}) 3. No assessment of orbital hazard for breakups occurring below altitude 90 km.	Intentional destruction should not be planned (except to assure safe reentry).	Explode on purpose a space vehicle or any of its elements is prohibited.

Figure 5 Comparison of national space debris mitigation standards (Kato, 2001)



Collisions with debris	1. Assess probability of collision with intact space systems or large debris. (Note: As a quantitative reference, the probability of collision should be less than 0.001) 2. Assess and limit the probability of damage to critical components as a result of impact with small debris. (Note: As a quantitative reference, the probability of collision leading to loss of control or inability to conduct postmission disposal should be less than 0.01)	Avoid interference with spacecraft operated in the same orbit regime (Orbit should be planned to keep the adequate distance from other spacecraft)	If the collision risk does not meet program objectives, collision prediction is recommended. Avoidance maneuver can be performed if necessary
Postmission disposal of S/C	Remove space systems from high value regions of space so they will not threaten future space operations 1. Atmospheric reentry within 25 years 2. Maneuvering to a storage orbit between LEO and GEO: • above 2500 km below 19,900 km • above 20,500 km below 35,288 km (500 km below GEO altitude). 3. Direct retrieval within 10 years 4. Maneuvering to a storage orbit above GEO altitude: 300 km + (1,000 * Cr * A/M) • Cr: solar radiation pressure coefficient • A/M: area to mass ratio • maneuver should be performed in a series of at least four burns	Remove spacecraft from highly valuable orbit regions so that they will not threaten future space operations 1. Atmospheric reentry within 25 years only if ground safety can be guaranteed 2. Maneuvering to a storage orbit between LEO and GEO: • above 1700 km (2500 km, if possible) below 19,900 km • Above 20,500 km below 35,288 km (500 km below GEO altitude). 3. Direct retrieval by STS 4. Maneuvering to a storage orbit above GEO altitude: 200 km + (0.022 * a * Cr * A/M) • a : semi major axis of orbit after reboost • Cr: solar pressure coefficient • A/M: area to mass ratio • maneuver to minimize eccentricity vector	Remove space systems from useful regions or that cross useful regions of space so they will not threaten future space operations 1. Atmospheric reentry within 25 years 2. Maneuvering to a storage orbit between LEO and GEO: • above 2,000 km below about 35,500 km (Delta-H km below GEO altitude, to be more exact. Delta-H is defined below). 3. (No comment about direct retrieval) 4. Maneuvering to a storage orbit above GEO altitude: 235 km + (1,000 * Cr * A/M) • Cr: solar radiation pressure coefficient • A/M: area to mass ratio 5. Reliability of the disposal function >0.99
Debris surviving reentry and impacting populated areas	Limit number and size of debris fragments that survive uncontrolled reentry (the total debris casualty area for components and structural fragments surviving reentry will not exceed 8 m^2)	1. Predict the reentry risk and guarantee it to be acceptably small 2. Notify the reentry footprint to the authorities for shipping lanes and airline routes 3. Limit the altitude of intentional destruction for safe reentry	The fragments that survive reentry may not cause a hazard to population or environment pollution, due to ionizing radiations, toxic substances release, etc, exceeding the threshold fixed by the concerned launch country(ies). The probability of human loss due to fragments shall conform with the safety objectives of flown over populations defined in the CNES Safety Policy.

Figure 6 Comparison of national space debris mitigation standards (continued) (Kato, 2001)

The last focus area made in the research is that there is no operational system actively removing debris from orbit. Conceptual systems have been proposed but haven't been realized due to the nonexistence of funding sources for such projects. While many envisage notional space or ground assets that actively remove non-operational objects from earth orbit, no organizations have risen to the occasion of collaborating in making them come to fruition. At the 27th National Space Symposium, General William Shelton, Commander of United States Air Force Space Command, delivered some remarks and answered some questions. When asked “if the Air Force plans on funding [active] space debris mitigation capability”, he offered the following answer:

> “*We haven't found a way yet that is affordable and gives us any hope for mitigating space debris*. The *best we can do*, we believe, *is to minimize debris* as we go forward with our operations. As we think about how we launch things, as we deploy satellites, minimizing debris is absolutely essential and we're trying to convince other nations of that imperative as well.” (Anonymous, 2011)

Keying in on some salient points from his comment, it can be inferred that such systems are in their research and development stage and haven’t proven the concept of actively removing debris. On the other hand, existing techniques in passive mitigation are comparatively lower in cost while minimizing debris production to some degree, thus, they are more attractive when performing a cursory cost-benefit analysis.

The table below summarizes the key focus areas made in this study. These focus areas are relevant to the study because they drive the progress of developing active debris mitigation measures, identifying leading agencies that take charge of key functions necessary for debris mitigation and designing binding legal language to facilitate compliance with debris mitigation measures and international collaboration with a focus on solving the space debris problem.

Table 1 Focus Areas

Focus Areas
Passive mitigation by itself is not sufficient to stabilize the space debris environment
There is no authoritative executive agency addressing space debris
There is no inspection agency certifying compliance with prescribed passive space debris mitigation practices
There is no legislative language binding state actors to adhere to prescribed passive space debris mitigation practices
There is no operational system actively removing debris from orbit

Summary

Chapter II of this study catalogs pertinent literature in the legal, policy, and technical, to include passive and active space debris mitigation methods, realms found during research. Chapter III explains the methodology used to find answers to the questions listed above. Chapter IV is the culmination of the analysis performed from the literature review using the methodology discussed in Chapter IV against the questions posed earlier in this chapter. Finally, Chapter V suggests further research and technical and legal recommendations for solving the space debris problem.

II. Literature Review

Chapter Overview

Literature review for the research began with searches for the terms “space debris mitigation”, “space debris removal”, “active space debris removal”, “space debris”, “space law”, “space debris characterization”, and “Kessler Syndrome”. Documents were recovered from space policy journals, space law professional association articles, space safety academic journals, various national space agency debris mitigation guidelines, governmental and non-governmental policy documents, and UN space debris mitigation guidelines. 120 documents were reviewed, categorized into “space debris mitigation”, “space debris characterization” and “space law” bins, which is sufficient and appropriate for the meta-analysis method used. Generally speaking, the topic demanded exploration of technical and legal aspects of space debris.

Technical in this sense consisted of passive debris mitigation techniques available to mission control stations commanding and controlling spacecraft. On the other hand, it also entails conceptual active debris mitigation systems proposed to solve the problem. Additionally, it includes characterization techniques. Literature review for this subject matter yielded an abundance of documentation on remote and in situ sensing of space debris and the results of the data gathered. Other academic research focused on mathematical models of space debris clustering, fragmentation and post collision breakup.

It’s equally important in this research to delve into the legal side of the space debris problem. Space, as the “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies" or Outer Space Treaty (OST) explicitly states, is "the province of all mankind". The declaration enhances the argument for space debris mitigation as it will preserve mankind's "province". However, with respect to space debris mitigation operations, especially active mitigation, it is complicated by the need to define the proper level of authority to begin to manipulate and maneuver space objects that are a nation State's property. Another contentious subject is the issue of how to attribute a space debris fragment to its launching State to consequently determine liability or responsibility to remove the object from orbit and its potential for collision with other objects.

Space Law

The practice of law isn't a new foray in space operations. Past and present leaders on the international stage have long recognized the extraordinary feature of space as being a global "commons" which does not lend itself to a claim of sovereignty by any single nation. It is unlike air, land or naval territories which are marked with distinguishable boundaries. What's important in this distinction is that it compels States to cooperate on an international level because each nation has equal stake. In the infancy of space exploration, when man's reach of space was becoming more of a reality than a dream, legal language in the form of UN treaties were defined to protect equal interest. The benchmark of UN space treaties is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies or more familiarly known as Outer Space Treaty (OST) or the Principles Treaty.

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

Entered into force on 10 October 1967, the OST forms the basis for international law with regard to space. As of 1 January 2012, 101 countries were parties to the treaty with 26 signatories awaiting ratification. It is comprised of 17 articles, and bears the central idea of "*Recognizing* the common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes." The study selectively focuses on a number of articles of interest to international cooperation as it relates to space debris.

The first paragraph of Article I of the OST states:

> The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the *benefit and in the interests of all countries*, irrespective of their degree of economic or scientific development, and shall be the *province of all mankind*.

This all important paragraph establishes with international accord that outer space and all celestial bodies are to be shared equitably by all mankind. Furthermore, the sole paragraph of Article II expands Article I's declaration:

> Outer space, including the Moon and other celestial bodies, is *not subject to national appropriation* by claim of sovereignty, by means of use or occupation, or by any other means.

While the above promise is noble, mankind has found itself constricted by the prognostication of a suffocating space environment riddled with space debris. Those States or agents that have yet to explore space due to their limited economic or scientific scope, unfortunately, are subject to being a late comer into the space domain, must vie for position for optimal operational orbital slots against more endowed State and non-State actors, and find themselves thrust into an environment already filling up with debris in the form of fragments, or whole spacecraft or whole upper stages. For space to be truly the *province of all mankind*, international cooperation in work effort and financial support must be focused on cleanup actions in near Earth orbit in order to make room for all nations with shallower pockets and reduced scientific development.

As Articles I and II institutes the idea that space is a global commons, Articles III, VI, VII and VIII associates legal language with the conduct of States in space operations. Article III states:

> States Parties to the Treaty shall *carry on activities* in the exploration and use of outer space, including the Moon and other celestial bodies, *in accordance with international law*, including the Charter of the United Nations, *in the interest of maintaining international peace and security and promoting international cooperation and understanding*.

The more relevant implication made by this passage is with respect to property, damages and environmental mindfulness, connoting consideration for space operations' impact on the environment and its effects on other space operators. Article VI advances the scope of international law:

> States Parties to the Treaty shall *bear international responsibility for national activities* in outer space, including the Moon and other celestial bodies, *whether such activities are carried on by governmental agencies or by non-governmental entities*...The *activities of non-governmental entities* in outer space, including the Moon and other celestial bodies, *shall require authorization and continuing supervision by the appropriate State* Party to the Treaty.

Because of this provision, States' governments assume accountability for agents' space activities within the purview of their national territory with the exception of those sponsored by external States, as will be explained later in this section. Even as non-governmental agencies are called on for to reimburse governmental agents at a later time, the initial dispensation is still a burden to the State actors. Article VII continues this line of argument:

> *Each State Party to the Treaty that launches or procures the launching of an object* into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, *is internationally liable for damage* to another State Party to the Treaty…

Naturally, the progression to the above is to create a system which supports attribution of liability should damage occur; specifically speaking a system of registration for launched objects. Article VIII of the Principles Treaty asserts:

> *A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body*.

By suggestion, registries of launched objects are to be maintained for the purpose of tracing objects launched into orbit back to the launching State for attribution of responsibility, assumption of command and control, resolution of damages, and, when objects or parts thereof are found outside of the launching State's territories, the return of the objects to the rightful owner. The principles defined in Articles III, VI, VII, and VIII are later codified in the following conventions: Convention on International Liability for Damage Caused by Space Objects and Convention on Registration of Objects Launched into Outer Space.

Article IX of the OST shows the precursor to the current space debris mitigation guidelines from the IADC and UNCOPUOS and an indication of the concern for space safety, to include the safety of manned space missions:

> *…conduct exploration of [the Moon and other celestial bodies] so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose*.

The italicized text emphasizes avoidance of harmful contamination and adverse environmental changes, however, this clause failed to foresee the necessity for more active debris removal caused by the growth of humanity's space programs, the resultant space debris and the persistence of said space debris.

The aforementioned articles support Active Debris Removal (ADR) in that operations in this mission area when executed have legal structure. These should be sufficient to persuade States internationally to cooperate and equitably share the cost of such operations as the OST has been ratified by a majority of nations worldwide. Articles I and II clearly affirm that space belongs to all mankind making all States responsible for stewardship of the space environment. Articles III, VI, VII, and VIII make the connection to international law and opens up possible avenues for grievances with respect to attributing liability. ADR not only needs to encompass the actual implementation of ADR measures, but, it also needs the legal and executive organization in order to protect the interests of space debris mitigation and of space operators. Article IX calls out to space faring States to preserve the space environment which by implication, given the evolution of space debris conditions, could involve developing and growing operations for more direct debris mitigation measures to include ADR.

Articles X and XI are articulated respectively:

> In order *to promote international cooperation* in the exploration and use of outer space, including the Moon and other celestial bodies, *in conformity with the purposes of this Treaty*, the States Parties to the Treaty shall consider on a basis of equality any requests by other States Parties to the Treaty to be *afforded an opportunity to observe the flight of space objects launched by those States*.
>
> In order *to promote international cooperation* in the peaceful exploration and use of outer space, States Parties to the Treaty conducting activities in outer

> space, including the Moon and other celestial bodies, agree to *inform the Secretary-General of the United Nations as well as the public and the international scientific community*, to the greatest extent feasible and practicable, *of the nature, conduct, locations and results of such activities*. On receiving the said information, the Secretary-General of the United Nations should be prepared to disseminate it immediately and effectively.

These principles are germane to the study and advancement of ADR in that they encourage the quelling of the fear that ADR operations may be conducted in error and with collateral damage to unauthorized and non-approved targets. As will be discussed in later sections, there's a healthy anxiety in the international space-faring community of violating property laws, specifically, the targeting of a launching State's respective space asset. On a national security note, the retrieval of space objects belonging to another government presents the risk of extracting intelligence which can be used for political and military advantage. On a similar note with regard to proprietary technology, intellectual property can be reverse engineered if the space asset is exposed to competitors.

Convention on Registration of Objects Launched into Outer Space

Another body of legal language of note is the Convention on Registration of Objects Launched Into Outer Space; it was entered into force on 15 September 1976. As the title suggests, it compels States signatory to the convention to register space objects launched into orbit. It builds on Article VIII of the Outer Space Treaty. The foremost spirit and intent of the convention are:

> *Desiring*, in the light of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, to make provision for the national registration by launching States of space objects launched into outer space,

> *Desiring* further that a central register of objects launched into outer space be established and maintained, on a mandatory basis, by the Secretary-General of the United Nations,
>
> *Desiring* also to provide for States Parties additional means and procedures to assist in the identification of space objects,
>
> *Believing* that a mandatory system of registering objects launched into outer space would, in particular, assist in their identification and would contribute to the application and development of international law governing the exploration and use of outer space,

Language in the articles of the document mainly focuses on roles, responsibilities and procedures with respect to launched space objects. As of 1 January 2012, the convention has been ratified by 56 nations, signed by an additional two and adopted by two international intergovernmental organizations.

Article I defines the terms "launching State", "space object" and "State of registry". Article II inculcates to signatories procedures on communicating to the Secretary-General of the UN entries in space objects registries, registration, jurisdiction and control of launched space objects in a joint venture, and each State's latitude on maintaining its own registry. Article III obliges the Secretary-General of the UN to maintain a registry of space objects launched which are furnished to the office by launching States and accessibility to the registry. Article IV lists the required information for registry:

1. Name of launching State or States;
2. An appropriate designator of the space object or its registration number;
3. Date and territory or location of launch;
4. Basic orbital parameters, including:
    i. Nodal period;

    ii. Inclination;

    iii. Apogee;

    iv. Perigee;

5. General function of the space object.

Also included in this section of the directive are provisions for furnishing additional space objects and updates to the registry. Article V presents terms on providing information on markings stamped on a space object.

Article VI is intuitively the most outstanding in the study:

> Where the application of the provisions of this Convention has *not enabled* a State Party *to identify a space object which has caused damage to it or to any of its natural or juridical persons, or which may be of a hazardous or deleterious nature, other States Parties…shall respond* to the greatest extent feasible to a request by that State Party, or transmitted through the Secretary-General on its behalf, *for assistance* under equitable and reasonable conditions *in the identification of the object*.

The paragraph is of import because it makes possible the attribution of damages to a responsible State party by associating identification with space object registration. While the above condition sounds promising, the evolution of the debris problem has rendered it and Article V of the Registration Convention lacking. As Article V discusses having markings on launched space objects, the current space debris environment consists of fragmented debris unidentifiable by any means. Markings on non integer space objects are essentially absent; a tagging system allowing the identification of fragments of space objects needs to be developed. Furthermore, attribution of damages caused by micro-sized debris is nearly impossible without being able to associate the piece of debris with the registered object and consequently the launching State.

Convention on International Liability for Damage Caused by Space Objects

Entered into force on 1 September 1972, the Convention on International Liability for Damage Caused by Space Objects, or Liability Convention, is designed with the chief principles below:

> *Taking* into consideration that, notwithstanding the precautionary measures to be taken by States and international intergovernmental organizations involved in the launching of space objects, *damage may on occasion be caused by such objects*,
>
> *Recognizing* the need to *elaborate effective international rules and procedures concerning liability for damage caused by space objects* and to ensure, in particular, the *prompt payment* under the terms of this Convention of a full and equitable measure of *compensation to victims* of such damage,
>
> *Believing* that the establishment of such rules and procedures will contribute to the *strengthening of international cooperation* in the field of the exploration and use of outer space for peaceful purposes,

At the heart of the subject examined by the convention is restitution for damages caused by space objects and the avenue through which States settle such disputes. It is an extension of Article VII of the OST and furnishes scenarios and procedures for redress expressed through its own articles. The Liability Convention has been ratified by 88 nations, signed by 23 others, and adopted by three international intergovernmental organizations as of 1 January 2012 and has yet to be invoked successfully.

Article I of the Liability Convention sets definitions of terms:

a. The term “damage” means *loss of life, personal injury or other impairment of health; or loss of or damage to property* of States or of persons, natural or juridical, or property of international intergovernmental organizations;

b. The term “launching” *includes attempted launching*;

c. The term “launching State” means:

    i. A State *which launches or procures the launching* of a space object;

    ii. A State from *whose territory or facility a space object is launched*;

d. The term “space object” includes *component parts of a space object as well as its launch vehicle and parts thereof*.

Articles II and III communicate attribution of liability; each of their paragraphs is listed respectively:

> A launching State shall be *absolutely liable* to pay compensation for damage caused by its space object *on the surface of the Earth or to aircraft in flight*.
>
> In the event of *damage* being caused *elsewhere than on the surface of the Earth* to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be *liable only if the damage is due to its fault or the fault of persons for whom it is responsible*.

The impression in Article II is liability to a State which has suffered damage for impacts not occurring in the space environment. On another note, Article III addresses mishaps in the space environment and goes a step further by adding the clause “liable only if the damage is due to its fault or the fault of persons for whom it is responsible.” Article II then implies that a State whose space object causes damage to terrestrial assets automatically establishes fault with the State owning the space object. Article III illustrates that space flight characteristics are not fully controlled by a launching State and there are many factors not accounted for in catastrophic scenarios. Nothing is truer now in the present space environment which has borne accumulated debris levels from routine space operations or catastrophic events. Recall that the Liability Convention was unsuccessfully invoked after the Iridium 33 and Cosmos 2251 collision event. These two space objects were clearly identified and attributed to their responsible States, but, the fault was not found decisively to assign compensation. Also recall that fragmented debris has a low certainty of identification due to its broken up state which makes it even more difficult to determine fault as identification of the responsible State is improbable.

Articles IV through VII categorize States that are liable and those that suffer damages. Articles VIII through XIII offer a process for claims between States while Articles XIV to XX establishes recourse in the form of a Claims Commission when State to State negotiations fail. Article XXI gives provision to aid provided by a launching State to the claimant State in cases when damage produced by the launching State's space object "presents a large-scale danger to human life or seriously interferes with the living conditions of the population or the functioning of vital centres." Article XXII characterizes the roles and liabilities of international intergovernmental organizations and Article XXIII affirms that no provisions of the Liability Convention shall affect any other international agreements with respect to the subject matter.

The aforementioned treaties and conventions are in need of amending. Evolution of the international political stage, space operating capabilities, participants in the space race and debris environment have rendered most of the above provisions ineffective and invocation of them weak. The OST, Registration Convention and Liability Convention are but pieces of the space debris problem. They must be observed with current

UNCOPUOS and IADC Space Debris Mitigation Guidelines as well since the above treaties and conventions offer support in terms of enforcing the idea of ADR. Internationally cooperative enforcement in addition to powers the UN's executive abilities have not been summoned. In the next section, the study examines cooperation between nations and the level required to tackle the space debris mitigation problem.

International cooperation

Because space is a global commons and the heritage of all mankind, all nations have a stake in dealing with the space debris problem. It is reasonable to conclude that tackling space debris mitigation requires international cooperation. We look to Game Theory to "understand the dynamics and logic of cooperation, conflict and competition" and its application to the space debris problem. The study progresses through the distinction between non-cooperative and cooperative game theories.

In non-cooperative game theory, actors act independently in their own best interests and advancing toward their best response in accordance with other actors' strategies. This category of game arises in the absence of a third party that enforces cooperation and agreements among parties are self-enforcing. There are varying degrees of participation depending on how actors assess the operational environment and the benefit reaped from entering into a coalition. A "null coalition" exists when all parties' mutual best response is to not enter into a coalition. In contrast, when all parties profit optimally by engaging in full membership into a coalition, a "full coalition" is achieved. Halfway between the two is a "partial coalition", a condition achieved when it's in some actors' best interest to join while the remainder refuses after determining that non-participation is the best answer. "Null" and "Partial" coalitions fail to realize mutually optimal global profit while a “Full” coalition is the most efficient. Figures 7 and 8 illustrate relative efficiencies of each type of coalition and show the results of a simulation wherein “null”, “best partial” and “full” coalitions are compared according to their abatement levels (Q) and profit attained (Π) respectively.

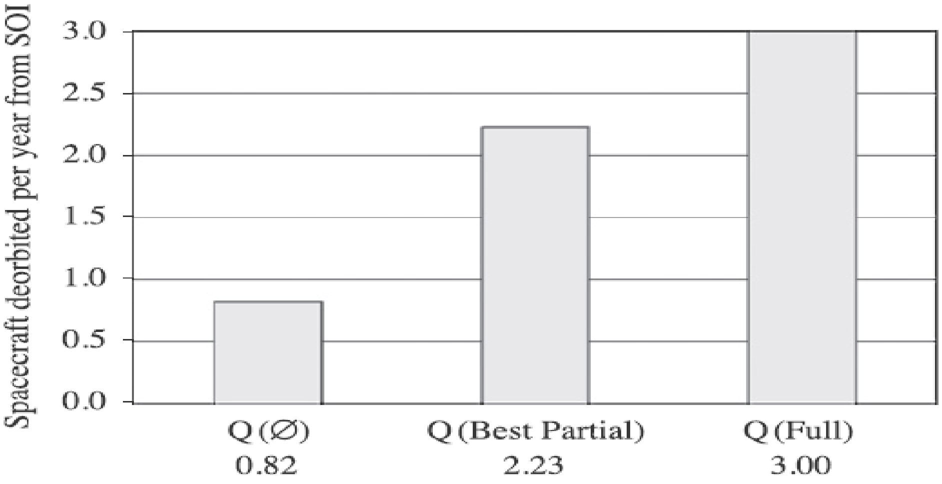


Figure 7 Global abatement for null, best partial, and full coalitions. (Singer, 2011)

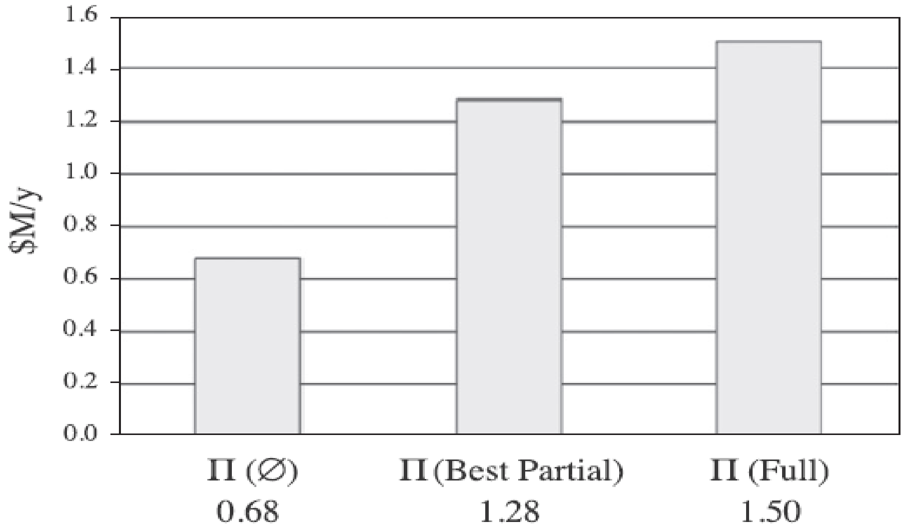


Figure 8 Global profit for null, best partial, and full coalitions. (Singer, 2011)

A challenge in non-cooperative game theory where there is a lack of a third party for enforcement is keeping costs and benefit to all participants equitable. Cooperative game theory provides a means for fairness to abound.

A cooperative game is arrived at when a binding agreement between parties is enforced by a third party. For purposes of space operations and the world's shared inheritance of it, the cooperative game theory is supported by the UN's involvement and the States' acceptance of the UN as the arbitrating forum and the medium for vetting binding agreements, especially since this relationship has been in effect since the inception of space operations. With this in mind, the position of the UNCOPUOS and present legal literature is lacking in enforcement merit. What's necessary is the examination of an ideal structure favorable to advancement and enforcement with respect to space debris mitigation. An article exploring discourse over the prohibition of the use of force in space, "Keeping the peace in outer space: a legal framework for the prohibition of the use of force", proposes an organizational structure with the UN, namely the UNCOPUOS and the UN Office of Outer Space Activities (OOSA), as a focal point and sub organizations that are charged with enforcement, surveillance, and inspection functions.

For enforcement, an International Tribunal for Outer Space (ITOS) is proposed. It would be charged with attributing fault to a party for damages caused by space objects. Also, it would arbitrate space related disputes, seeing them through resolution. Additionally, it would appraise reparations necessary in cases of determined fault. The composition of the tribunal would need to be a fair mix of representation internationally. This would further space debris mitigation in that it asserts consequences for inaction and abandon of the cause to keep the space environment conducive to availability and safety of space operations for the utilization of all mankind. The enforcement mechanism would in turn need to be buttressed by processes verifying compliance to space debris mitigation, specifically with respect to passive techniques (Goh, 2004).

Verification of compliance to the passive mitigation regimen requires three processes:

1. Monitoring of the observance of space debris mitigating techniques and mission profiles
2. Evaluation of conformity of the above actions to the set standards
3. Assessment of the above actions' effectiveness in the space environment and to the advancement of stabilizing the debris population to trend positively over time where large space debris are outnumbered by operational space assets

To these ends, two other sub organizations are proposed: International Space Surveillance Agency (ISSA) and International Space Inspection Agency (ISIA). The ISSA owns the charge of monitoring space activities with respect to space debris mitigation and the ISIA handles the job of auditing space agencies' actions and assaying effectiveness of such actions (Goh, 2004). While the proposed agencies were offered by an external source, their functions have been modified to be of relevance to space debris mitigation.

Monitoring the space environment obviously requires sensors positioned globally to acquire a comprehensive picture. As previously mentioned, surveillance would also need to be continuous to create an accurate model of orbiting bodies. To spread the cost function and for the sake of efficiency, the ISSA's monitoring sensors would be composed of those owned by States party to the OST and which own assets on-orbit. This alignment is only meant to organize the efforts of States under the mission of the ISSA and not to designate any command and control or transfer ownership of assets to the ISSA. States desiring to contribute to solving the space debris problem but are less endowed with space assets may contribute in other ways such as either allowing other States to construct sensors in their territory or allocating intellectual resources to the cause such as operators, engineers or analysts. Data gathered by the surveillance function would in turn be scrutinized by the ISIA.

The role of the ISIA would be to make inquiries on the space debris mitigation activities of space faring States. Resulting reports would illustrate the effectiveness of an audited State. They would be objective and, in cases when reparation for damages caused by space debris is sought, would recreate the sequence of events leading up to the impact event. The ISIA would also act as a certifying authority akin to the International Organization for Standardization; it would certify that a space program complies with passive space debris mitigation standards concerning techniques and mission planning. Noncompliant space programs would be unable to launch another space object until violations have been resolved. In cases when a space program is involved in ITOS proceedings which have yet to be resolved, grounding would also apply until no fault is found or, if fault is found, until the violations have been rectified.

Membership in the three sub organizations mentioned above would be comprised of equitable international representation. Permitting the views of the developing space faring States is of importance. For such a protocol and structure to exist, a treaty must be put into force by the UN through its normal channels of having a treaty or convention adopted. Figure 9 shows the relational diagram of the aforementioned structure.

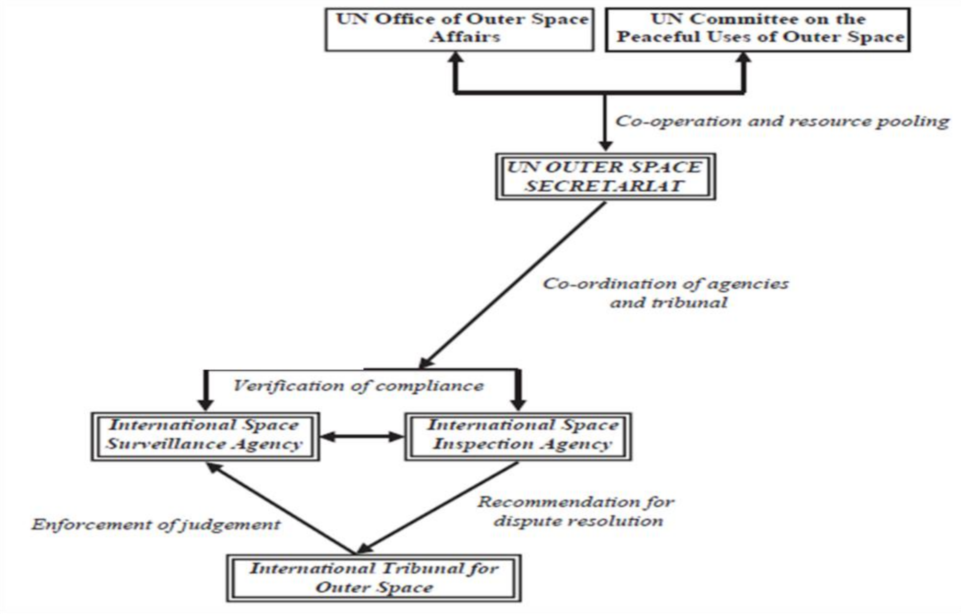


Figure 9 Proposed framework and enforcement mechanism. (Goh, 2004)

The ISIA would only be able to certify compliance to passive space debris mitigation standards. The addressing of active mitigation techniques requires a modified approach.

While passive mitigation techniques are implemented on a per country basis, development and employment of active debris removal necessitates equitable international investment contributions in varying resources beyond supplying money. The above structure would obviously still apply; however, added terms would have to be agreed upon. An additional treaty or convention would be essential to unite States to the cause of developing an active debris removal program. Legal provisions conferring authority in good faith to engage debris targets would have to be outlined. Targets would have to be prioritized according to their relative potential for fragmentation and increase in the probability of crossing the Kessler Syndrome threshold. Data sharing protocols for the space debris environment characterization would have to be enumerated as well. Lastly, an organizational rallying point would have to be named as above so as to exercise effective command and control of the program.

Inter-Agency Space Debris Coordination Committee Space Debris Mitigation Guidelines

While the effort to clean up space debris has no clear and designated commanding authority, it is not absent an advocate for the cause. The foremost agency addressing the issue of space debris is the Inter-Agency Space Debris Coordination Committee (IADC). It is an international governmental forum made up of several agencies: ASI (Agenzia Spaziale Italiana), CNES (Centre National d'Etudes Spatiales), CNSA (China National Space Administration), CSA (Canadian Space Agency), DLR (German Aerospace Center), ESA (European Space Agency) ISRO (Indian Space Research Organisation), JAXA (Japan Aerospace Exploration Agency), NASA (National Aeronautics and Space Administration), NSAU (National Space Agency of Ukraine), ROSCOSMOS (Russian Federal Space Agency), and UKSpace (UK Space Agency). The collective's mission is to "[coordinate] activities related to the issues of man-made and natural debris in space." The committee's purposes are to "exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options."

In this spirit, IADC presents its findings and recommendations to the United Nations Committee on the Peaceful Uses of Space (UNCOPUOS) Scientific Technical Subcommittee (STSC) on an annual basis following its own annual meetings for facilitation of research activities. In addition to these appraisals, the organization has published its Space Debris Mitigation Guidelines in 2007 which has garnered acceptance by UNCOPUOS which consequently issued its own guidelines that parallel those of the IADC. IADC's guidelines are widely recognized by space agencies worldwide, implementing their own adaptations of mitigation measures to meet the guidelines.

The following is an abridged version of the IADC Space Debris Mitigation Guidelines which is found in Chapter 5 in the document of the same name:

1. Limit Debris Released during Normal Operations
2. Minimise the Potential for On-Orbit Break-ups
    a) Minimise the potential for post mission break-ups resulting from stored energy
    b) Minimise the potential for break-ups during operational phases
    c) Avoidance of intentional destruction and other harmful activities
3. Post Mission Disposal
    a) Geosynchronous Region
    b) Objects Passing Through the LEO Region
    c) Other Orbits
4. Prevention of On-Orbit Collisions

Forms of these guidelines were presented at the fortieth session of the Scientific and Technical Subcommittee (STSC) of UNCOPUOS in 2003.

UNCOPUOS Space Debris Mitigation Guidelines

As previously mentioned, IADC guidelines were presented to the UNCOPUOS STSC and eventually adopted into the UNCOPUOS' version of space debris mitigation guidelines. It is the conclusion of many years of work by the STSC in coordination with the space faring community and UNCOPUOS. It started in 1994 with an entry of the space debris issue into its agenda. The vision then was to perform scientific research to characterize the space debris environment. From consideration of the threat and analysis, STSC prepared a technical report during the period 1996-1998, carried forward and updated each year. Thereafter, the technical report was adopted by the Subcommittee in 1999 and widely distributed internationally to include the UN Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) in 2000. 2001 through 2005 marked developmental stages for the goal of international adoption of voluntary space debris mitigation measures during which, as noted earlier, in 2003 the IADC proposed its debris mitigation guidelines to the Subcommittee. Subsequently, cultivation of the utilization of previous research and mitigation recommendations for adoption by UNCOPUOS occurred in 2005 through 2007 and finally endorsement by the UN General Assembly.

The document carries with it authenticity and genuine concern for the cleanup of the debris environment, however, the authority is obviously lacking by way of language. As previously stated, the legality of the UNCOPUOS Space Debris Mitigation Guidelines is explicit in its non-binding nature as evidenced by the statement that the guidelines "are not legally binding under international law." In addition, the document acknowledges that the space faring nation States may make exceptions to individual guidelines or elements thereof.

UNCOPUOS makes a distinction between its guidelines and the IADC's. IADC guidelines are meant to serve as "high-level qualitative guidelines, having wider acceptance among the global space community", whereas, UNCOPUOS guidelines "are based on the technical content and the basic definitions of the IADC space debris mitigation guidelines, and taking into consideration the United Nations treaties and principles on outer space." The list below displays condensed versions of UNCOPUOS Space Debris Mitigation Guidelines which are contained in chapter 4 of the document:

1. Limit debris released during normal operations
2. Minimize the potential for break-ups during operational phases
3. Limit the probability of accidental collision in orbit
4. Avoid intentional destruction and other harmful activities
5. Minimize potential for post-mission break-ups resulting from stored energy
6. Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission
7. Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission

It's important to note that the UNCOPUOS document encourages consideration of these guidelines during "mission planning, design, manufacture and operational (launch, mission and disposal) phases of spacecraft and launch vehicle orbital stages" in order for a system level application of the principles of debris mitigation.

Characterization of the Space Debris Threat

We now turn to characterizing the space debris threat. The discussion continues here with respect to technical capabilities and availability of models more so than a comparison of the validity of models. Techniques are reliant on present day sensor capabilities. Sensor types, examples, and capabilities will be now enumerated. Characterization of the space debris environment begins with sensing of the near Earth orbit. After all, description of objects in space and their activities cannot be performed without first seeing the objects themselves. Sensor types utilized presently are radar, optical or electro-optical, and impact detection.

Radar sensors detect a space object's position, range, velocity and trajectory. The primary providers of this technology are the US Space Surveillance Network and the Russian Space Surveillance System. Collectively, they share approximately 30 sites operating in the VHF, UHF, C, L, and X bands. Sites bolstering remote radar measurements of the space debris population are "Millstone, TRADEX, Millimeter Wave, and Have Stare radars in the US; the German Research Establishment for Applied Science's (FGAN's) Tracking and Imaging Radar (TIRA); and Japan's Middle and Upper Atmosphere (MU) radar", to include Goldstone, Haystack, and the new Haystack Auxiliary (HAX) (Johnson, 2004).

They have the advantage of not being hampered by cloud cover and differing sun angles. Conversely, they have the disadvantage of requiring the application of more power to detect objects of greater range. Also, when detecting objects at greater altitudes, signal return attenuates by a greater amount due to the signal from a radar beam reflected from a satellite falling off as the fourth power of the altitude. This denotes that the space debris mitigation community is limited to radar operations in relatively shorter altitudes most appropriately to the LEO environment; some radar measurements are undertaken for GEO, but, limited in effectiveness. Another drawback of radars is the limits to which objects can be detected due to a trait of an object to reflect radar signals. Individual space objects differ in their ability to reflect radar. Contributing factors to this characteristic are object size, shape or material composition. Radar methods have come a long way, however, statistical sampling of objects as small as two millimeters in diameter in LEO have been developed (Johnson, 2004).

Optical and electro-optical sensors have the opposite advantages and disadvantages attributed to radar. Optical and electro-optical sensors are limited in performance when faced with cloud cover and differing sun angles. Line of sight limitations come into play when it comes to this type of sensing. On the other hand, given clear line of sight, optical and electro-optical platforms are less hampered by attenuation when an object's reflection of the sun is returned to the sensor. "The signal from sunlight reflected by the satellite falls off only as the square of the altitude of the satellite"; this is two orders of magnitude more signal strength versus radar. Similar to radar, effective detection by optical sensing relies on a space object's size and material composition; some objects may not be visible by this method because an object is too small or that it doesn't reflect light sufficiently for it to be sensed.

It is also notable that optical sensors are less effective in detecting LEO objects due to the long integration times required to optically sense objects and the higher relative velocities in LEO (Potter, 1995). With these factors, optical sensors are more apt for utilization for higher altitude remote sensing of the debris environment and less so for LEO. While radar's nominal detection size is two millimeters at LEO, optical sensors are only able to see down to one centimeter in LEO and 10 centimeters at GEO (Schildknecht, 2004; Africano, 2004).

However, limited implementation of in situ electro-optical measurements can yield flux characterization of debris particles less than one millimeter in diameter; electro-optical sensors are orbited on spacecraft like the Infrared Astronomical Satellite (IRAS) and the Midcourse Sensor Experiment (MSX). In situ electro-optical measurements of the debris environment is still in its infancy with future development foreseen (Johnson, 2004). Still, optical sensors add much to the characterization of the space debris environment as shown in figures 10 and 11; exhibited in these figures is the detection of GEO and GTO objects not correlated to objects in the US Space Catalog.

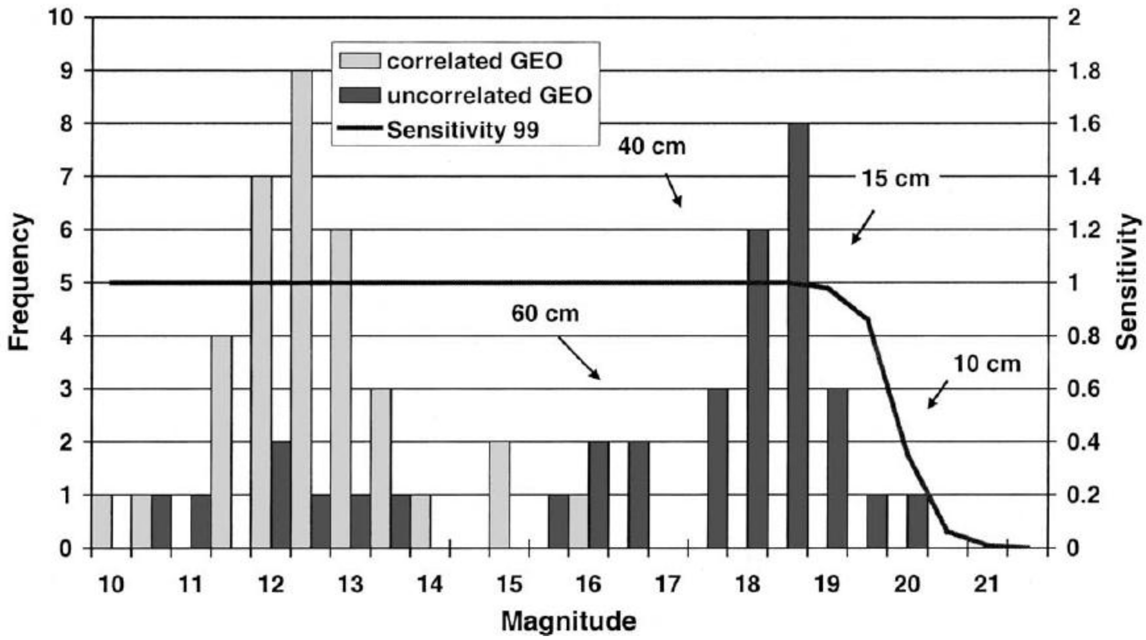


Figure 10 GEO objects detected in a June/August 2002 optical survey (Schildknecht, 2004)

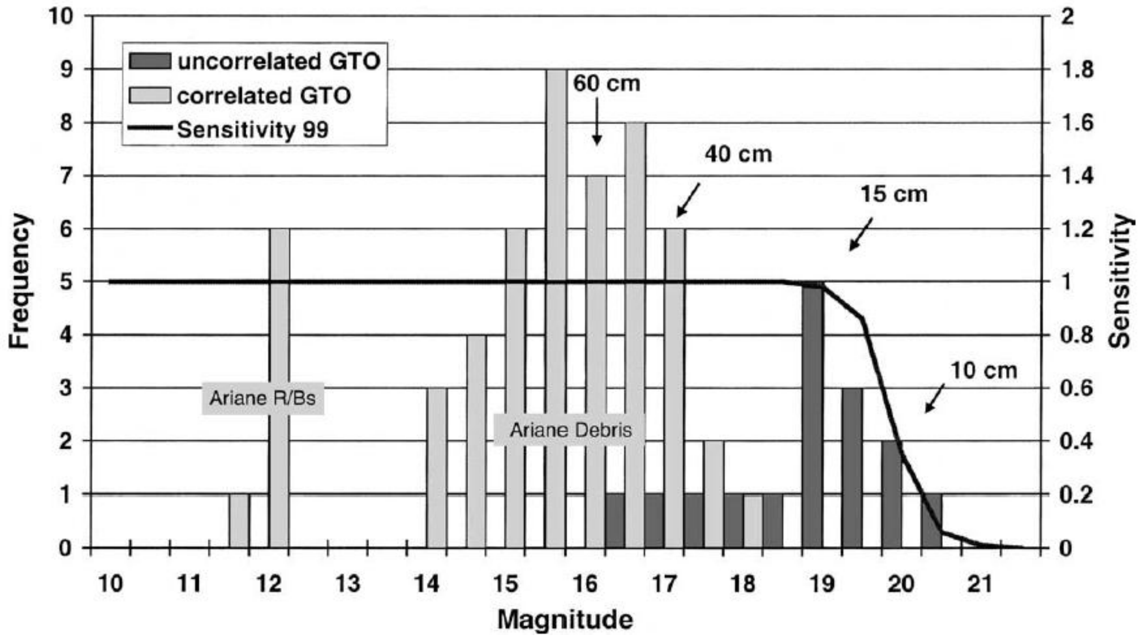


Figure 11 GTO objects detected in a June/August 2002 optical survey (Schildknecht, 2004)

Installations with electro-optical sensors are the U.S. Ground-based Electro-Optical Space Surveillance (GEODSS), U.S. Air Force Maui Optical Station (AMOS), the Maui Optical Tracking and Identification Facility (MOTIF), and the new Advanced Electro-Optical System (AEOS) (all located atop Mt. Haleakala on Maui, Hawaii), NASA's CCD Debris Telescope (CDT) and Liquid Mirror Telescope (LMT), University of Berne's Zimmerwald Laser and Astrometry Telescope (1:0 m diameter), a similar telescope owned by the European Space Agency at Tenerife, a 0.9 meter diameter telescope operated by the Observatorie de la Cote d'Azur (OCA) 0:9 m diameter telescope near Grasse, France, and the Japanese 0.75 m diameter telescope at Kita-Karuizawa (Johnson, 2004).

The final method of detecting space debris is through direct destructive sensing also known as impact sensing. Impact sensors are attached to and launched with spacecraft to experience impact collisions with objects less than one millimeter. This is because spacecraft that impact sensors are attached to are limited to LEO orbits either due to their primary missions (some impact sensing was performed even on manned spacecraft like the Shuttle or Mir) or due to the necessity for the sensors to be retrieved for analysis (Johnson, 2004). Of historic note, it was an accidental technique discovered with lower orbit manned and unmanned missions in the early evolutionary stages of space exploration when components from launched assets returned to land and were available for analysis.

Because impact sensors must be retrievable for analysis, GEO campaigns for this type of sensing are not practiced. This of course is a disadvantage of the method. On the other hand, an advantage is that the impact sensors can loiter in orbit for long time exposures allowing "flux mass distribution of impacting particles [to be] derived with an increasing accuracy." Impact craters provide useful information on particle geometry, as well as the chemical identification of particle remnants, in order to determine the origin of the particles (Mandeville, 1997). Figure 12 shows a sample crater from the EUROMIR experiment. Impact sensing measurements have been performed by “Long Duration Exposure Facility (LDEF), the European Retrievable Carrier (EURECA), and the Japanese Space Flyer Unit (SFU) as well as components from the Solar Maximum Mission (SMM or Solar Max) and the Hubble Space Telescope (HST)…[and] Orbital Debris Collector (ODC) and the Momentum Stage Impact Detector (MOM)” (Johnson, 2004).

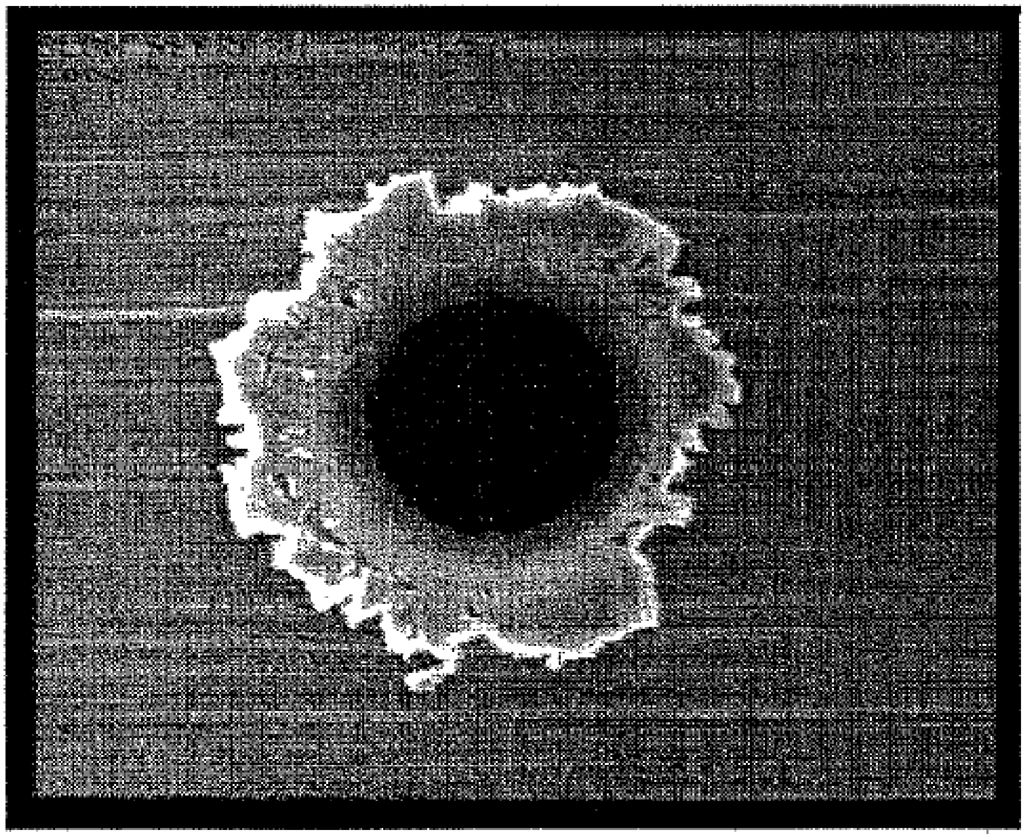


Figure 12 Perforation of an aluminium sample (diameter of crater is 70 µm) (Mandeville, 1997)

Radar, optical and impact sensing methods are employed in concert to develop more robust models and characterization of the space debris environment in high and low altitude environments. Information provided by models can be applied to the execution of debris mitigation measures such as collision avoidance maneuvers and active retrieval of space debris which will be covered in the next sections.

Space Debris Mitigation

Space debris mitigation consists of measures that minimize sources of debris that add to the current population already in orbit and that reduce the current population by actively influencing a space debris object's structure. The former includes methods that are coupled with a spacecraft's existing design and mission profile that abate the creation of debris. These techniques are categorized as *passive space debris mitigation*. The latter refers to measures that involve an external system applying force to a piece of detritus with the intent to manipulate and maneuver or destroy completely; these technologies are currently not operational and are in the conceptual or development phase. These systems are categorized as *active space debris mitigation.*

Passive space debris mitigation methods are relatively less costly than active space debris mitigation. This is because passive techniques do not require extensive technology development. Consequently, they require minimal operations which incur fewer costs from employing personnel, establishing and occupying a command and control architecture, and, launch operations, in the case of space borne systems. In the next subsections, these techniques will be enumerated and the processes explained. Impact to the primary operating environment (i.e. space) and external environments (i.e.

air, land, and sea) will be discussed. The literature review also reveals limited effectiveness of passive space debris mitigation methods which give way to the argument that active space debris mitigation is necessary to positively influence the reduction of the current population.

Passive Space Debris Mitigation

Passivation

Passivation or safing is a collection of techniques which aims to eliminate any potential energy from a spacecraft. It addresses guideline 5 of the UNCOPUOS Space Debris Mitigation Guidelines which recommends to "[m]inimize potential for post-mission break-ups resulting from stored energy." The idea of passivation is to effuse energy sources from the spacecraft which can cause it to explode due to thermal heating of those energy sources such as batteries or which can cause it to gain any momentum causing the spacecraft to either spin on an axis or maneuver uncontrollably in orbit. The excerpt below is from the guideline and identifies passivation as the technique to meet the objective.

> In order to limit the risk to other spacecraft and launch vehicle orbital stages from accidental break-ups, all on-board sources of stored energy should be depleted or made safe when they are no longer required for mission operations or post-mission disposal.
>
> By far the largest percentage of the catalogued space debris population originated from the fragmentation of spacecraft and launch vehicle orbital stages. The majority of those break-ups were unintentional, many arising from the abandonment of spacecraft and launch vehicle orbital stages with significant amounts of stored energy. The *most effective mitigation* measures have been the *passivation* of spacecraft and launch vehicle orbital stages at the end of their mission. Passivation requires the removal of all forms of stored energy, including residual propellants and compressed fluids and the discharge of electrical storage devices.

The following examples of ways to passivate are taken from the NASA Standard NASA-STD-8719.14A:

- Burning residual propellants to depletion
- Venting propellant lines and tanks
- Venting pressurized systems
- Preventing recharging of batteries or other energy storage systems
- Deactivating range safety systems; and
- De-energizing control moment gyroscopes.

It’s important to note that NASA’s guidance includes the consideration that “[t]he design of these depletion burns and ventings should minimize the probability of accidental collision with known objects in space” (Anonymous 2012).

De-orbiting/Re-orbiting of Upper Stages

De-orbiting and Re-orbiting of upper stages “minimize[s] the growth rate of the large objects that contain most of the mass and area which could be involved in future collisions” (Walker, 2004). De-orbiting requires an upper stage to be left in an orbit that allows it to decay and re-enter the earth’s atmosphere. At its most active and operations intensive, de-orbiting has been proposed to involve the maneuvering of the upper stage for direct descent; obviously, this technique would require designing the launch vehicle and flight profile so as to include extra propellant to commit to maneuvering and additional subsystems to track, command and control the upper stage.

On the other hand, re-orbiting centers on the idea of displacing upper stages to designated orbits where derelict space objects of large mass are disposed; these orbits are referred to as disposal orbits. As with de-orbiting for a direct descent, re-orbiting by implication would require taxes to operations by way of extra mass and propellant, and subsystems. Of course, LEO and GEO differ in their disposal orbit requirements. Per NASA-STD-8719.14A, GEO disposal is 300 km above GEO and LEO disposal for structures is between 1400 km and 2000 km. LEO's disposal orbit has potential for collision hazards especially when the disposal orbit reaches saturation from repeated disposals of nonoperational space objects. To the contrary, GEO's disposal orbit touts less of a collision threat due to the vast expanse of space in the orbital regime. However, it introduces a collision risk to interplanetary missions. In any case, the current *de facto* international convention for orbital lifetime of upper stages transient in LEO and Geosynchronous Transfer Orbit (GTO) is 25 years as recommended by the IADC and UNCOPUOS (Johnson, 2005). De-orbiting and re-orbiting both tackle the following UNCOPUOS guidelines:

> Guideline 6: Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission
>
> Guideline 7: Limit the long-term interference of spacecraft and launch vehicle orbital stages with the Geosynchronous Earth Orbit (GEO) region after the end of their mission

While the subset of the debris population comprising of larger objects with respective masses is smaller in terms of quantities and therefore collision probabilities, it is the subset that encompasses the most mass and most breakup potential, and, hence, results in the most catastrophic impact events which increase the total debris population precipitously.

De-orbiting/Re-orbiting of Spacecraft at End-of-Life

Akin to the aforementioned method of de-orbiting or re-orbiting upper stages is the same method applied to spacecraft when it reaches the end of its mission. It is clear that the application of this method to spacecraft resolves the same UNCOPUOS guidelines 6 and 7. Additionally, it observes the IADC's space debris mitigation guideline 5.3: Post Mission Disposal. Subsections of this recommendation differentiate between approaches in separate orbital regimes.

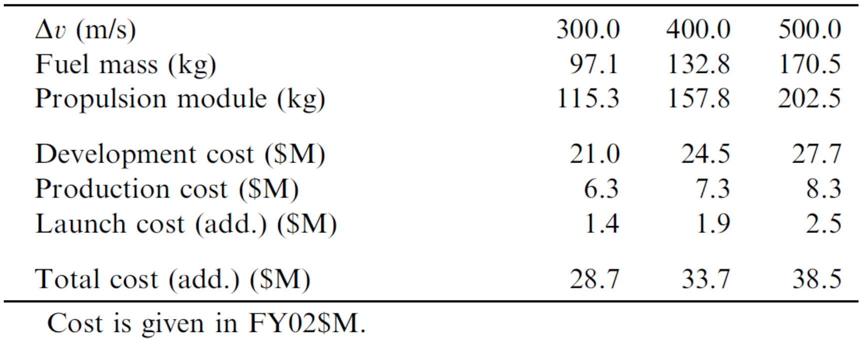
Spacecraft in GEO orbit are treated to re-orbiting operations. According to the IADC principle and NASA's approach, a spacecraft that has reached the end of its operational life is either raised to at least 200 kilometers above GEO into a super-synchronous orbit or descended to 200 kilometers below GEO. Unfortunately, spacecraft in GEO is not afforded the concession of a direct or expedient atmospheric reentry by way of de-orbiting as LEO spacecraft are able due to the obvious altitude differential relative to Earth.

In comparison, within the bounds of NASA's mitigation standards, LEO spacecraft are presented more alternatives: atmospheric reentry, storage or disposal orbit, and direct retrieval by a capture device. Atmospheric reentry can be executed by leaving the spacecraft in an orbit where natural drag forces can de-orbit it into the Earth's atmosphere within 25 years of End-of-Mission but no more than 30 years after launch. A substitute for this is to maneuver the spacecraft into a controlled reentry trajectory as soon as practical after End-of-Mission. The storage orbit option entails maneuvering spacecraft into to an orbit with perigee altitude greater than 2000 km and apogee less than

GEO minus 500 km. Lastly, direct retrieval, when possible, intends to remove spacecraft within 10 years of mission completion.

Spacecraft traversing between GEO and LEO orbits such as those in MEO or GTO are also considered in the guidelines set forth by the IADC. Subsection 5.3.3 of the Post Mission Disposal, Guideline 5.5, asserts that spacecraft reaching the end of their operational life is to be “manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions.” NASA’s technical standard responds to this by calling for spacecraft to be “left in an orbit with a perigee greater than 2000 km above the Earth’s surface and apogee less than 500 km below GEO” and for spacecraft “not [to] use nearly circular disposal orbits near regions of high value operational space structures.” Motivation for the second clause is to preserve the introduction of decay in the orbit, reducing the orbital lifetime of the defunct spacecraft, thereby enhancing the probability of atmospheric reentry.

As with de-orbiting or re-orbiting of upper stages, several levies on the spacecraft design and mission profile are a matter of consequence. These result in incurring costs for development and operations. The associated cost and mass allowances for de-orbiting and re-orbiting operations are shown in figure 13.



Δv (m/s)	300.0	400.0	500.0
Fuel mass (kg)	97.1	132.8	170.5
Propulsion module (kg)	115.3	157.8	202.5
Development cost ($M)	21.0	24.5	27.7
Production cost ($M)	6.3	7.3	8.3
Launch cost (add.) ($M)	1.4	1.9	2.5
Total cost (add.) ($M)	28.7	33.7	38.5

Cost is given in FY02$M.

Figure 13 Cost and mass estimation of an additional bipropellant propulsion module for a given velocity requirement Δv (Wiedemann, 2004)

It’s important to note that these costs do not reflect the “high reliability of the propulsion and attitude control systems at end-of-life,” which would themselves tack on additional costs (Walker, 2004).

The technique is highly effective due to its effect of lessening large masses of space objects from orbit, thereby, reducing the breakup potential responsible for future debris flux. As with all designs for limiting space object lifetimes in orbit, the target timeline is 25 years. The figures below display effectiveness of the technique’s application to meet the target timeline vice other target timelines such as 0, 10, 50 and 100 year de-orbit schemes. Figures 14 to 16 exhibit effectiveness in a nominal launch traffic scenario which assumes “continuation in activity at the same constant average rates and orbit distributions determined from historical events during the period 1991 to 1999, and add[s] 330 launch and mission related objects per year and generate fragments from 5.5 explosions per year on average.” These figures are resultant of Monte Carlo simulations by the European Space Agency’s (ESA) Debris Environment Long-Term Analysis (DELTA) tool which models debris evolution. The model used as inputs data from the Meteoroid and Space Debris Terrestrial Environment Reference Model (MASTER) 2001.

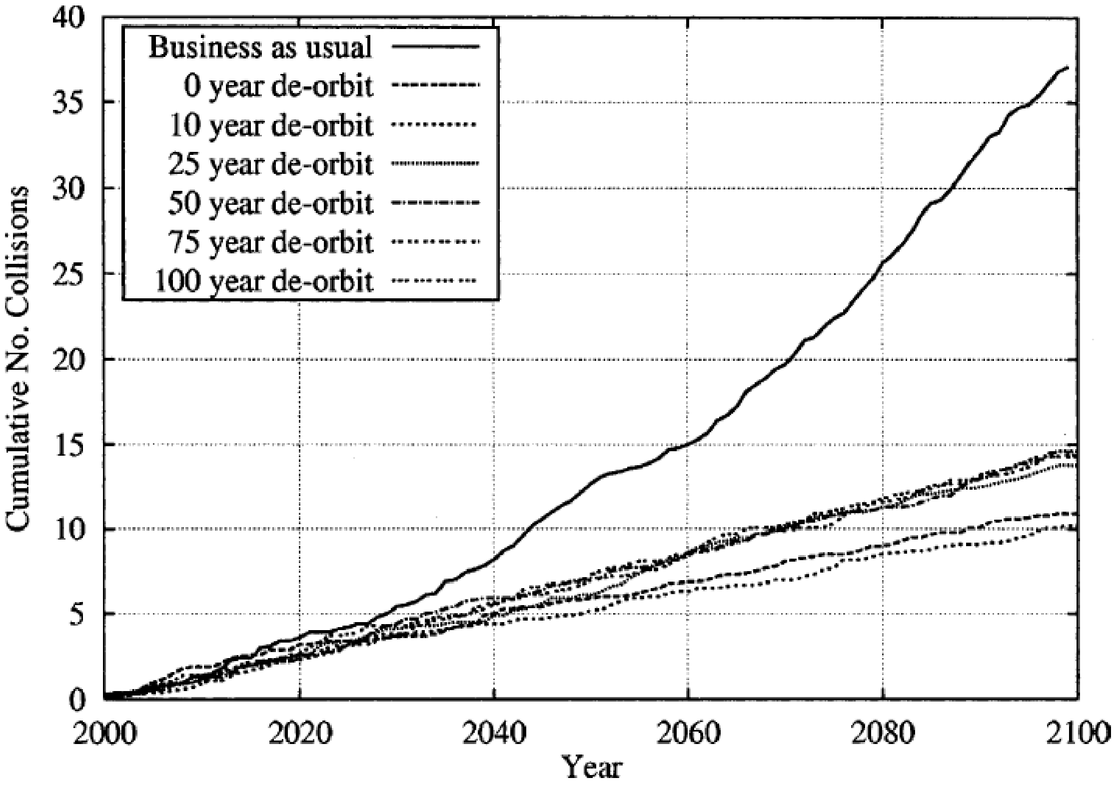


Figure 14 Future collision activity in LEO as predicted by the DELTA model for different post-mission de-orbit lifetime scenarios under the assumption of nominal future launch traffic (Walker, 2004)

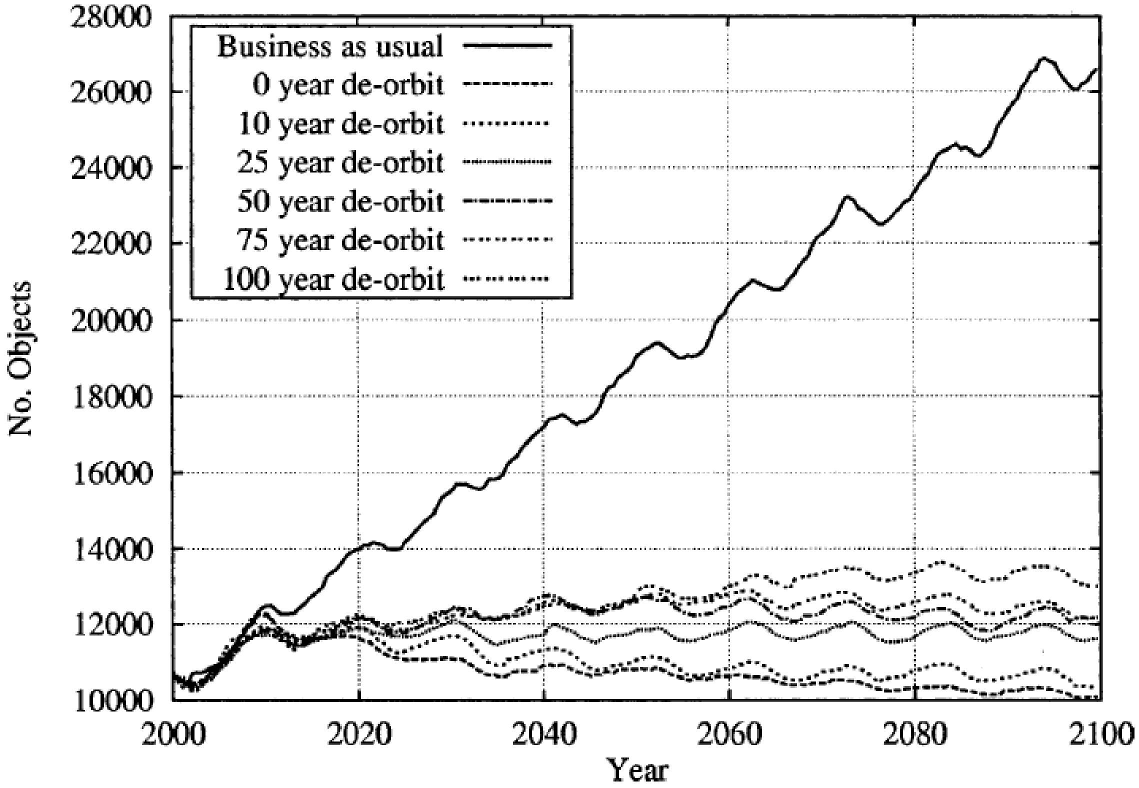


Figure 15 Future evolution of objects >10 cm in LEO as predicted by the DELTA model for different post-mission de-orbit lifetime scenarios under the assumption of nominal future launch traffic (Walker, 2004)

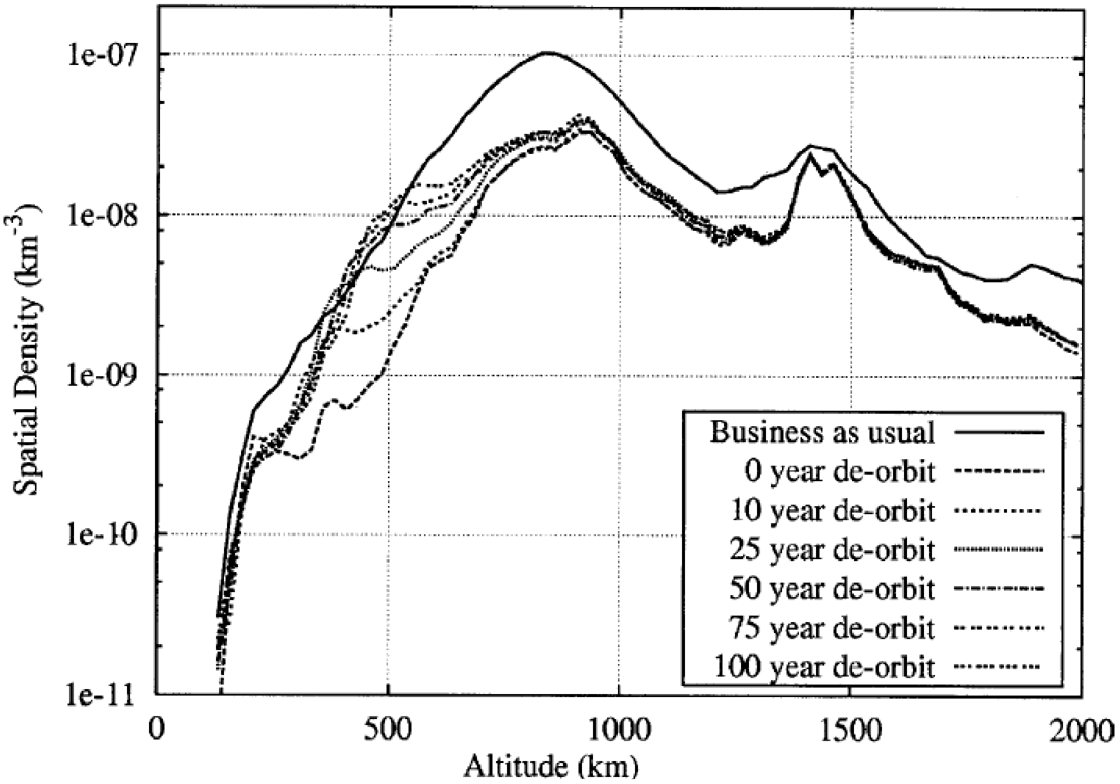


Figure 16 Spatial density of objects >10 cm in LEO after 100 years as predicted by the DELTA model for different post-mission de-orbit lifetime scenarios under the assumption of nominal future launch traffic (Walker, 2004)

Prevention of the Release of Mission Related Objects

Historically, a steady source of space debris has been the release of mission related objects. An outdated perception of the release of mission related objects is of its acceptance, that of it being a “necessary evil” for space operations. Examples of mission related objects released are “sensor covers, tie-down straps, explosive bolt fragments, attitude control devices, and dual payload attachment fittings” (Anonymous, 2012). Contrastingly, the UNCOPUOS guideline for the prevention of the release of mission related object is as follows:

> Guideline 1: Limit debris released during normal operations. Space systems should be designed not to release debris during normal operations. If this

> is not feasible, the effect of any release of debris on the outer space environment should be minimized.

The requirement for space system design that does not release debris during normal operations is accommodated by using tethers to keep sensor covers or explosive bolts attached to the spacecraft. Alternative designs or flight profiles can also be implemented; an example of this is to release attitude control devices at lower altitudes to abate debris buildup in operational regions, to decrease the probability of collision with other objects and to advance de-orbiting of debris when possible. In the case that the release of mission related objects is not preventable, “[a]ll debris released…shall be limited to a maximum orbital lifetime of 25 years from the date of release” (Anonymous, 2012).

The charts below illustrate the effectiveness of preventing the release of mission related objects when compared to the business as usual case reference of historical launch and on-orbit explosion trending from the years 1991-2001 and not implementing any debris mitigation measures. On each of the charts, the legend is as follows:

1. BAU – Business as Usual; the reference traffic scenario includes 80 launches per year, 5 constellations and 5.5 explosions per year (4.25 low intensity, 1.25 high intensity).
2. NOEX_MRO – Explosion prevention; as BAU, but with the suppression of explosions (i.e. prevention of on-orbit breakups during flight, operations and post-mission) in orbit after 2010.

3. NOEX – Suppression of mission related objects; in addition to the explosion prevention after 2010, mission-related objects are eliminated after 2005.
4. MIT – Full mitigation; in addition to explosion prevention and mission-related objects suppression, the new upper stages are immediately de-orbited after 2005 and the satellites below 2000 km are immediately de-orbited at the end-of-life after 2015 (Anselmo, 2001).

Figures 17 to 21 below are results shown from simulations conducted to investigate the effectiveness of mitigation measures on the long-term evolution of the orbital debris population. Twenty Monte Carlo runs were performed for each aforementioned scenario.

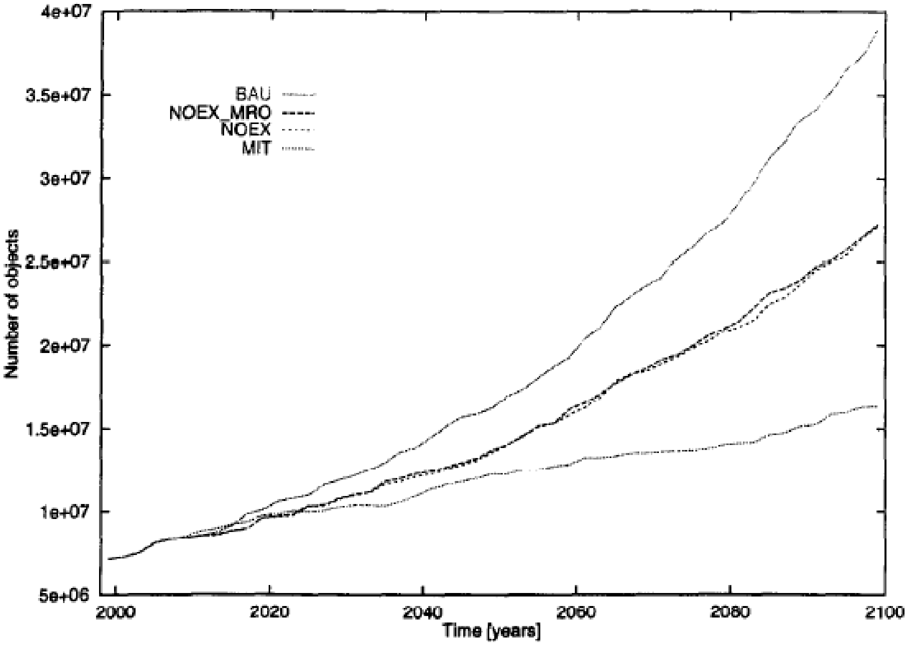


Figure 17 Number of objects larger than 1 mm (Anselmo, 2001)

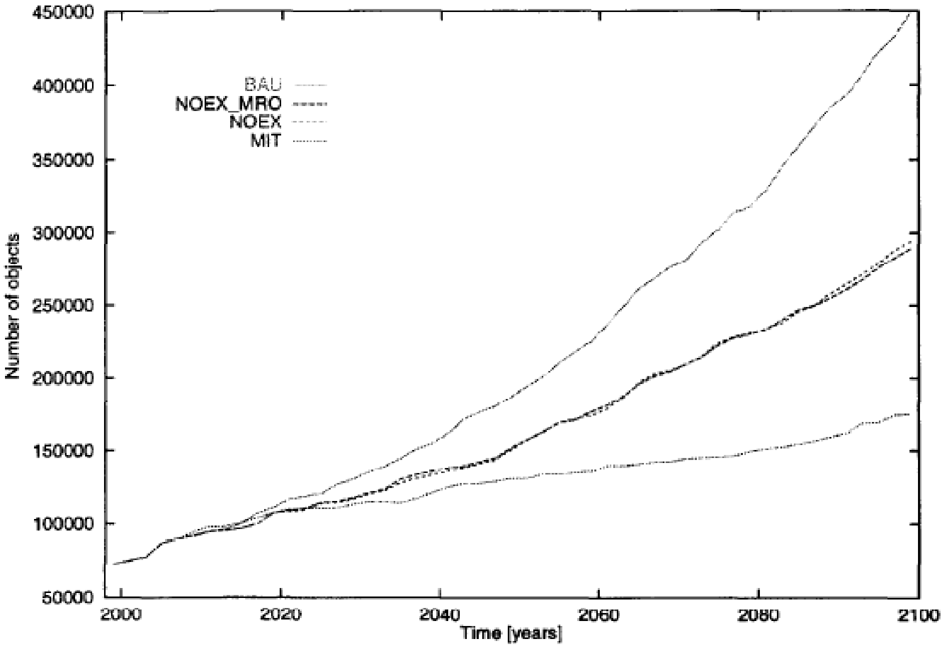


Figure 18 Number of objects larger than 1 cm (Anselmo, 2001)

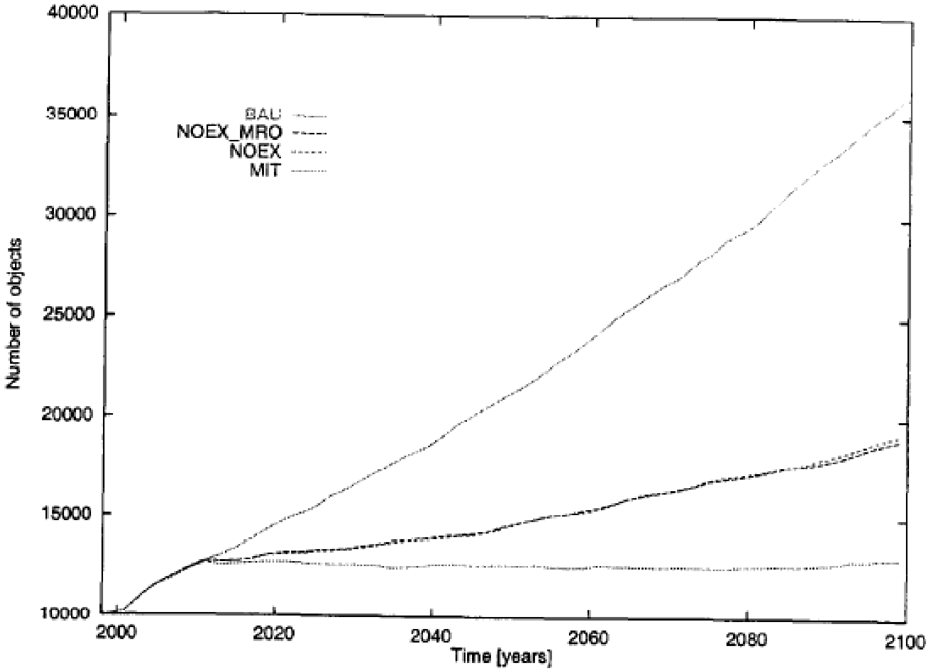


Figure 19 Number of objects larger than 10 cm (Anselmo, 2001)

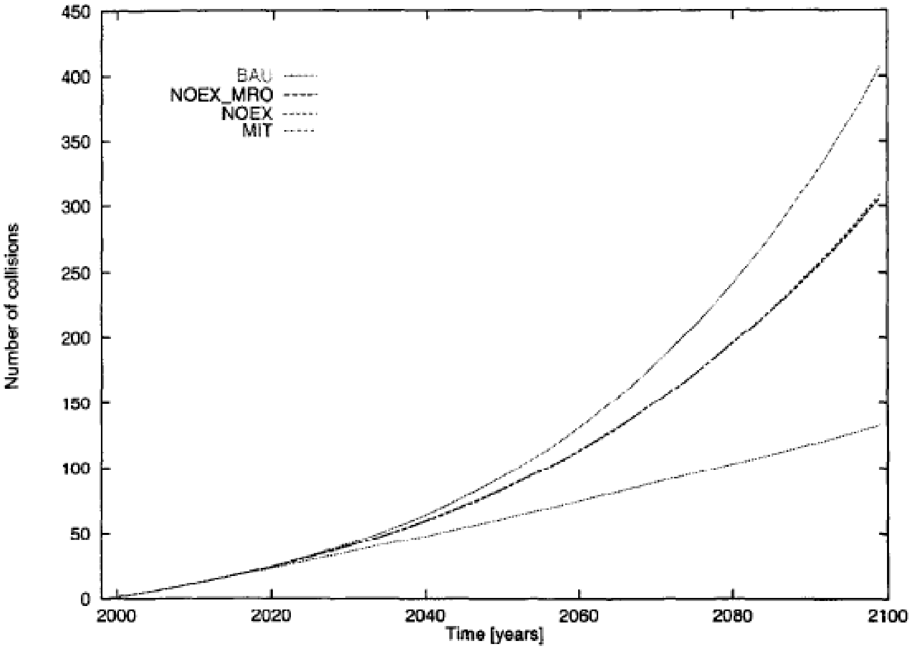


Figure 20 Cumulative number of collisions between objects larger than 1 cm (Anselmo, 2001)

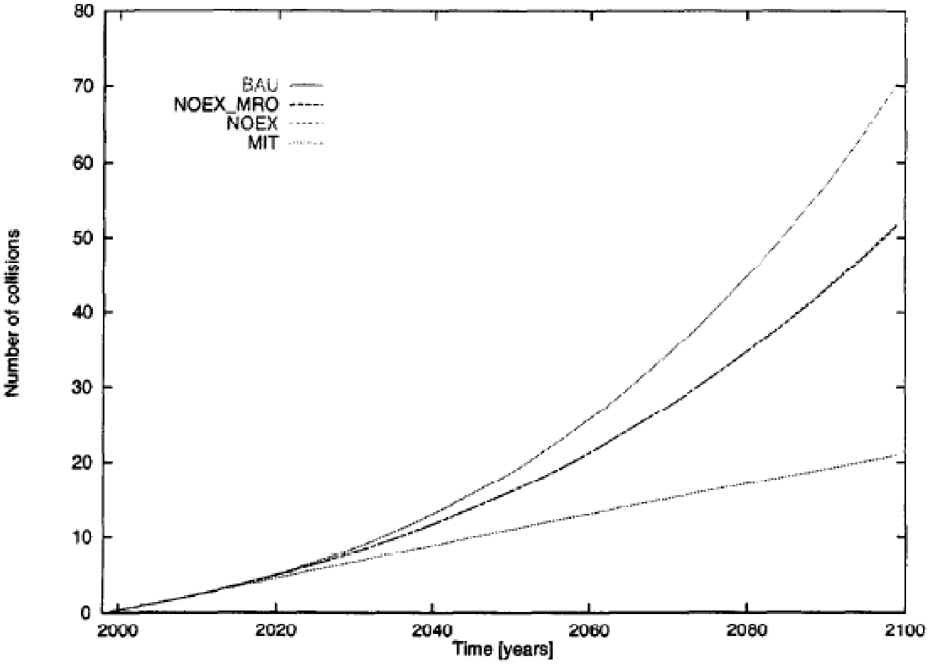


Figure 21 Cumulative number of collisions between objects larger than 10 cm (Anselmo, 2001)

As can been deduced from these charts, prevention of mission related objects as a space debris mitigation practice is more effective than the business as usual scenario. A divergent outlook is that "[t]he suppression of the mission related objects…has negligible long-term effects as a mitigation measure (Figures 17 to 21) (Anselmo, 2001). A common theme throughout this research is the revelation that some categories of mitigation measures influence insignificant impact on the debris population, while others show considerable alteration of the orbital debris environment.

The figures above also display a decreasing number of collisions with increasing debris size or cross section as evidenced in figures 20 and 21. This is due to the fact that the smaller sized space debris population is more numerous than larger sized population bins. For instance, the population for space debris greater than 1 centimeter and greater than 1 millimeter is two orders of magnitude larger than the population for space debris larger than 10 centimeters; this is shown when comparing figures 17 and 18 to figure 19. A hasty conclusion would be to attribute potential for debris production from on-orbit collisions to the smaller sized population subsets of the overall space debris population. A more intuitive exploration of the space debris environment points to the evidence that smaller debris rarely cause catastrophic collisions possible of causing breakups and consequently adding to the space debris population. On the contrary, collisions between larger sized debris objects carry with them more debris producing potential due to mass available for fragmentation. This exploration will be expounded upon later in the research.

Protective Design

In the early stages of spacecraft development, protective schemes can be included in the design of spacecraft and launchers in order to diminish the probability of breakups due to hyper velocity impacts. One way to implement protective design is to add some form of shielding that will absorb pressures from transient debris colliding with the structure of a spacecraft or launcher. A protective shield is attached to the most probable surface to receive an impact. The idea is for the shield to absorb the initial pressure from a collision and as the impacting debris penetrates the wall, its energy is dissipated, the impacting material is fragmented and may even change phases resulting in melting or liquefaction. Figures 22 to 25 portray the physical manifestations of a hypervelocity impact through a space object's wall.

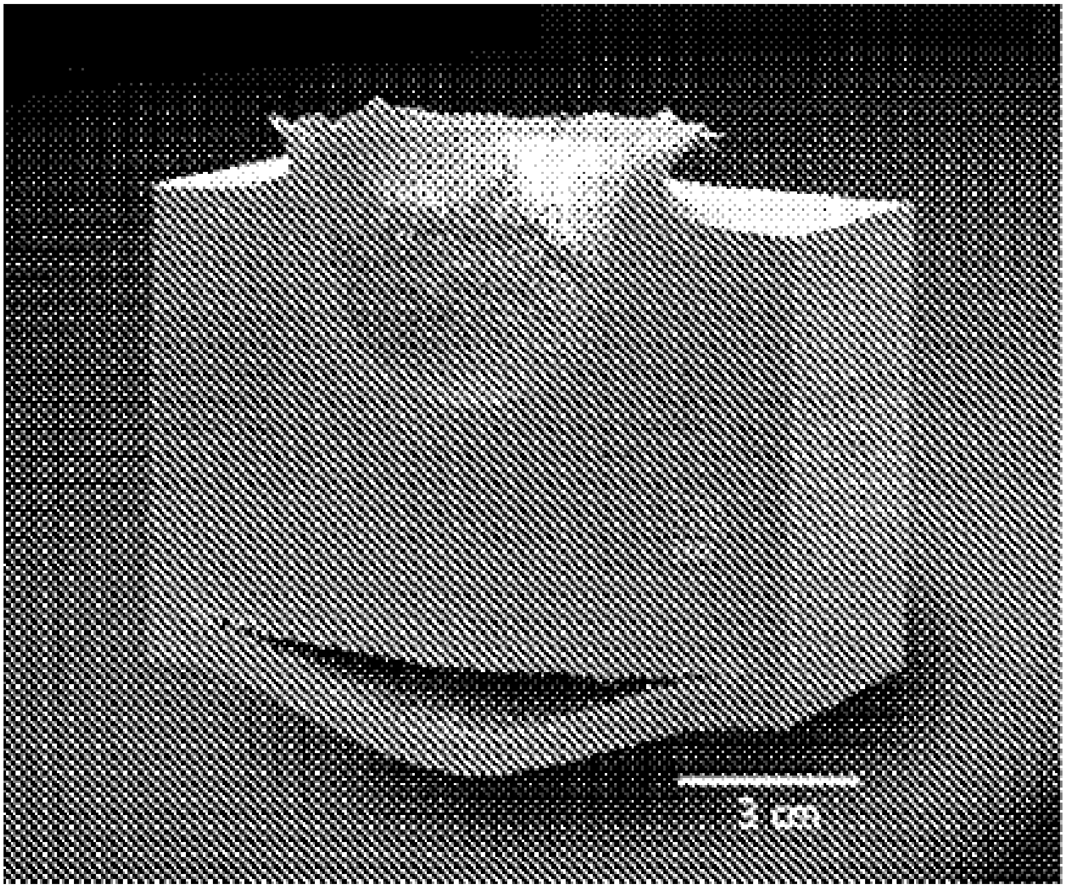


Figure 22 Crater profile of a hypervelocity impact on a thick Aluminum target (Thoma, 2000)

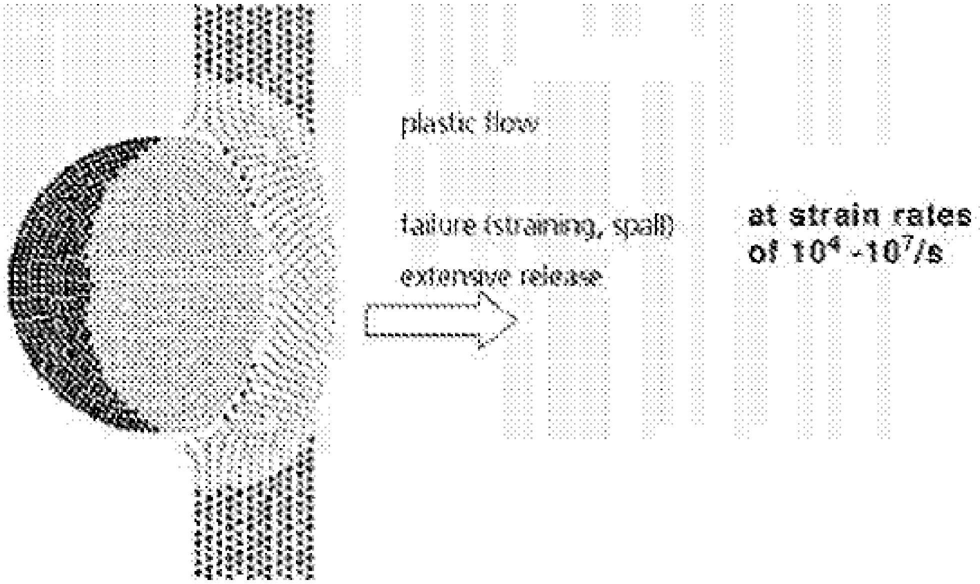


Figure 23 Simulation of a hypervelocity impact on a thin plate (Thoma, 2000)

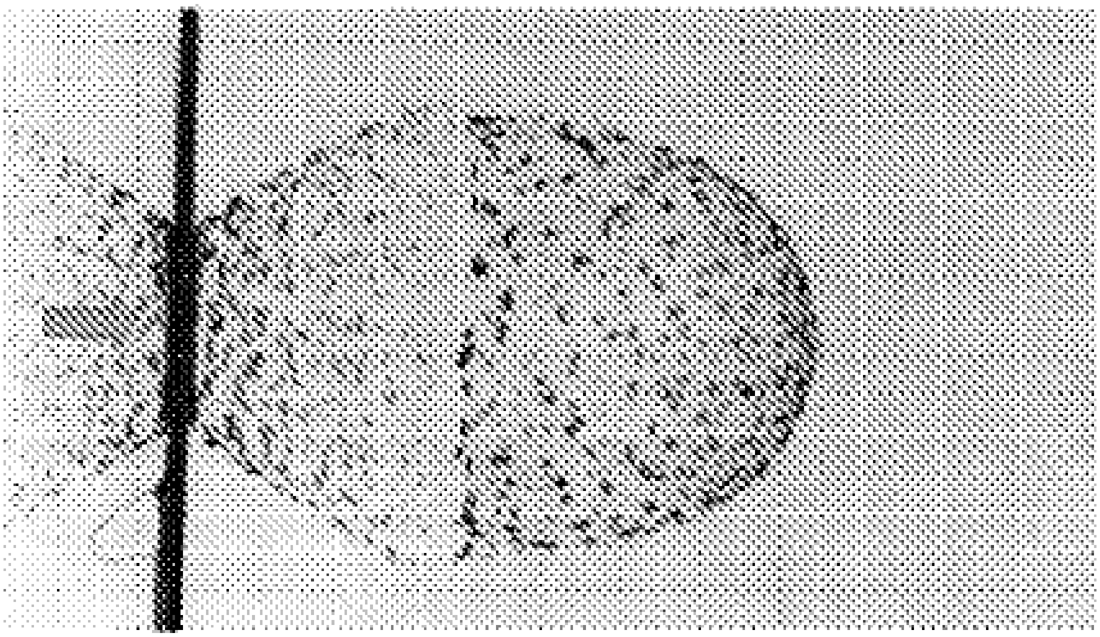


Figure 24 Example for shock-induced solid fragmentation (Thoma, 2000)

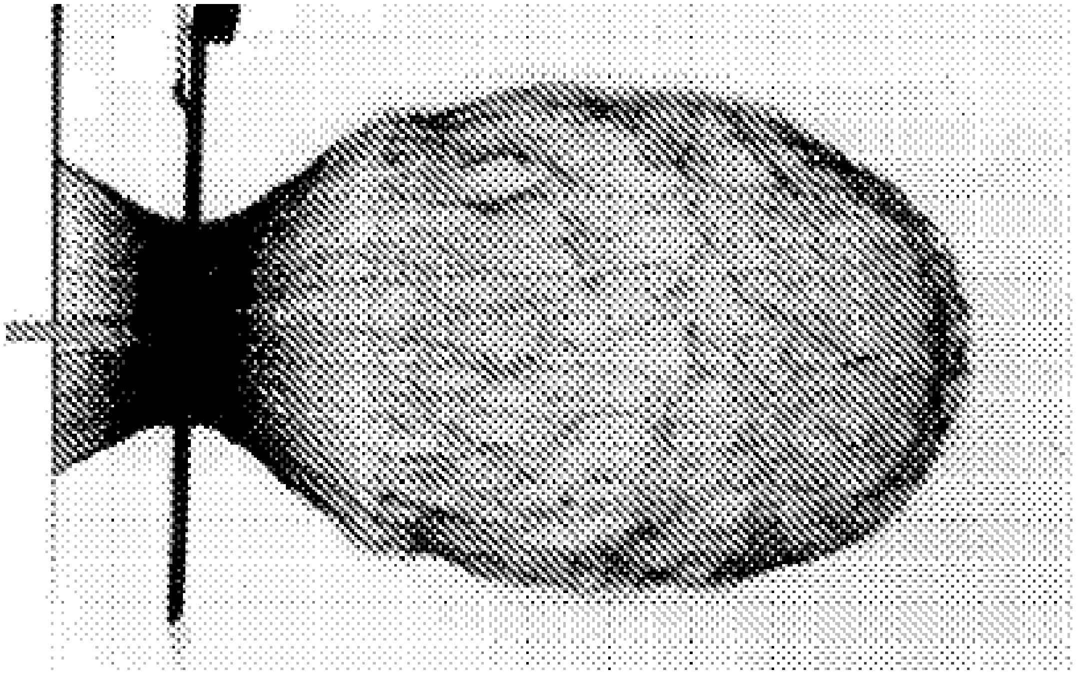
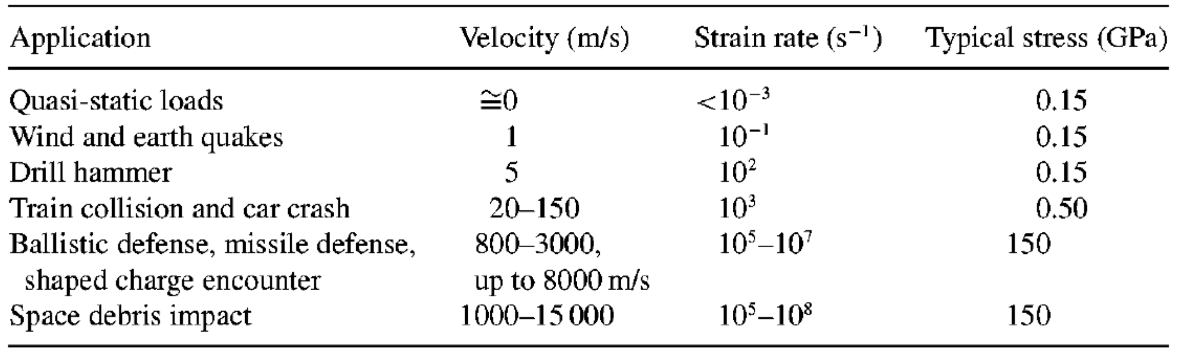


Figure 25 Example for shock-induced melting (Thoma, 2000)

Selection of shielding material and its placement on a structure is derived from an analysis of the material makeup, probability of impact of spacecraft surfaces, and relative velocities of the threat debris environment in addition to the failure modes assessed resulting from debris strikes. The last factor is especially important if a critical component is positioned on the main wall of impact. The most common material used in this technique is Kevlar. Available shielding options would have to withstand strain rates imposed by various orbital debris. Figure 26 illustrates relative stress inflicted by known and common events (Thoma, 2000).



Application	Velocity (m/s)	Strain rate (s^{-1})	Typical stress (GPa)
Quasi-static loads	≅0	$<10^{-3}$	0.15
Wind and earth quakes	1	10^{-1}	0.15
Drill hammer	5	10^{2}	0.15
Train collision and car crash	20–150	10^{3}	0.50
Ballistic defense, missile defense, shaped charge encounter	800–3000, up to 8000 m/s	10^{5}–10^{7}	150
Space debris impact	1000–15 000	10^{5}–10^{8}	150

Figure 26 Typical physical quantities for a range of impact velocities (Thoma, 2000)

Shielding demands a considerable tax on operational space objects. They increase required mass allowances and launch costs, are difficult to attach to structures and perturb thermal and center of gravity profiles of spacecraft. It's "valid only against smaller debris than a reference size, which is 1 cm" (Yasaka, 2003). "Therefore, they can reasonably be considered only for very valuable or critical satellites, such as manned or strategic spacecraft" (Bonnal, 2000).

Another way to implement protective design is to strategically arrange critical subcomponents throughout the structure to move them away from the surface at most risk of experiencing impacts. Perceptibly, this technique introduces negligible tax to mass allowances, doesn't introduce complexity of attaching added material to the structure, and doesn't complicate thermal and center of gravity characteristics of the space object. "Unfortunately, it has a limited efficiency, lower than the specific shields, and therefore can only slightly improve the risk" (Bonnal, 2000).

Protective design undertakes UNCOPUOS Space Debris Mitigation Guideline 2 which urges space operators to:

> Minimize the potential for break-ups during operational phases Spacecraft and launch vehicle orbital stages should be designed to avoid failure modes which may lead to accidental break-ups.

Also, it addresses IADC guideline 5.2.2., minimise the potential for break-ups during operational phases:

> During the design of spacecraft or orbital stages, each program or project should demonstrate, using failure mode and effects analyses or an equivalent analysis, that there is no probable failure mode leading to accidental break-ups. If such failures cannot be excluded, the design or operational procedures should minimise the probability of their occurrence.

However, protective design is effective only in “minimizing the effect, not the cause…therefore cannot be considered alone as a long term solution to the space debris problem” (Bonnal, 2000). It must then be included in a portfolio of debris mitigation measures.

Collision Avoidance

A current practice to prevent catastrophic fragmentation events is collision avoidance (COLA). Accordingly, this prevents the generation of debris in smaller sizes. The course of action is to execute a maneuver for an active spacecraft if it is within a certain miss distance of another orbiting space object and “when position uncertainties are greater than the calculated miss distance” (Johnson, 1999). Significant steps in the technique are:

1. Detect, catalog and track space objects in near earth orbit
2. Modeling the near Earth orbit space environment
    a. Propagate ephemeris for each individual space object
    b. Assess position uncertainties
    c. Calculate miss distances between space objects

3. Given the threshold of miss distance versus position uncertainty, perform a collision avoidance maneuver

The process lends itself to limitations while introducing additional performance, mass, risk and cost margins.

Cataloging and tracking are slaves to the detection limits of current sensors and the current effort of the international space faring community to make use of sensor data to perform assessment on collision risk. Currently, the only agency in the world performing conjunction analyses for space objects is the U.S. Strategic Command (USSTRATCOM). It has command and control of the Space Surveillance Network (SSN). Space objects observed by the SSN are enumerated in the US Space Catalog along with their respective ephemeris. USSTRATCOM has charged the Joint Space Operations Center's (JSpOC) Space Situational Awareness (SSA) cell with the task to perform conjunction analyses on space objects listed in the US Space Catalog. At present, the count of space objects in the catalog observed by the SSN sensors is more than 22,000. The SSN is comprised of a global arrangement of 29 space surveillance sensors of both optical and radar sensor types; currently, detection sensitivity of the sensors and, consequently, the US Space Catalog are limited to objects larger than 10 centimeters (Anonymous 2012).

The boundaries of the next step of modeling the near Earth orbit space environment is best articulated by an excerpt from an article from Centre National d'Etudes Spatiales (CNES):

> [T]he proper consideration of uncertainties is much more complex: the knowledge of where a satellite is at one given time is very [imprecise], leading either to [very] sophisticated computation methods, or to large margins.

The logical step that follows is the maneuvering of an active spacecraft in the effort to avoid a collision with another space object (Bonnal, 2000).

The final desired result of the collision avoidance method is to successfully separate space objects which are anticipated to crash into each other. The last step in achieving this desired result is the movement of an able spacecraft from its current position to avert the perilous condition of being in the way of space object traffic. Resultant in this requirement is the ensuing toll on additional budgets allotted for spacecraft performance, mass, cost and risk to which superfluous launch cost is also added. Performing COLA maneuvers will require a spacecraft to include in its development increased reliability and decreased failure risk in its propulsion, attitude and tracking, telemetry, and control subsystems. Propellant margins will then be supplemented to make room for COLA maneuvers. These drive up mass allowances and accordingly, cost. Another byproduct of this extra performance is the shortening of the operational lifetime of the spacecraft as a whole.

However, COLAs are only reactive in nature and do not remove the source by promoting the sink. After a COLA maneuver, the potential for fragment generation will remain in orbit. It can be observed that the rest of the process hinges on the first step of detection. Additionally, the limitations and uncertainties of the first step are inherited in the last two steps. As a result of the limitation in the detection domain, active spacecraft cannot perform COLA maneuvers against undetected and untracked space objects. Furthermore, it cannot be executed on derelict spacecraft that are still in operational orbits since they have no capability to execute these maneuvers. This is shown in the example of the Iridium and Cosmos collision mentioned above. Lastly, "[t]he total mass of the 'active' [spacecrafts] only accounts for about 9% of the mass in the environment" (Liou, 2011). For this reason and in all practicality, the technique "is strictly limited to highly valuable satellites, manned or strategic" (Bonnal, 2000).

With respect to the IADC, collision avoidance maneuvers address debris guideline 5.4, Prevention of On-Orbit Collisions, which states:

> In developing the design and mission profile of a spacecraft or orbital stage, a program or project should *estimate and limit the probability of accidental collision with known objects* during the spacecraft or orbital stage's orbital lifetime. If reliable orbital data is available, avoidance manoeuvres for spacecraft and co-ordination of launch windows may be considered if the collision risk is not considered negligible. Spacecraft design should limit the consequences of collision with small debris which could cause a loss of control, thus preventing post-mission disposal.

The spirit is echoed in guideline 3, Limit the probability of accidental collision in orbit, of the UNCOPUOS Space Debris Mitigation Guidelines:

> In developing the design and mission profile of spacecraft and launch vehicle stages, the *probability of accidental collision with known objects during the system's launch phase and orbital lifetime should be estimated and limited*. If available orbital data indicate a potential collision, adjustment of the launch time or an on-orbit avoidance manoeuvre should be considered. Some accidental collisions have already been identified. Numerous studies indicate that, as the number and mass of space debris increase, the primary source of new space debris is likely to be from collisions. Collision avoidance procedures have already been adopted by some member States and international organizations.

In response, NASA's technical standard for the above guidelines is encapsulated in requirement 4.5-1, limiting debris generated by collisions with large objects when operating in Earth orbit:

> For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001.

Industry standard in this vein is to conduct collision avoidance maneuvers for manned and strategic space vehicles with high import.

Launch Operations

The last technique discussed with respect to passive mitigation techniques is the control of launch characteristics for a given spacecraft. The technique endeavors to limit the orbital lifetime of upper stages in the Geosynchronous Transfer Orbits (GTO). Logic for the method lies in the relationship between the initial Sun angle of a launch and the lifetime of the upper stage in GTO. Gravitational perturbations by the Sun and Moon affect changes in the perigee altitudes of a given upper stage. The perigee of a body in GTO influences its lifetime; the intent here is for the GTO upper stage to cross LEO and expose it to atmospheric drag forces which introduce decay of the orbit in the least amount of time necessary. The initial sun angle orientation of a launch vehicle determines the most appropriate perigee altitude for expedient de-orbiting of an upper stage. The choice of the launch time for a vehicle can result in a GTO upper stage to stay in orbit from a range of a few months to several decades. Figure 27 shows the relationship between initial sun angle and time in orbit (Adimurthy, 2006; Loftus, 1992).

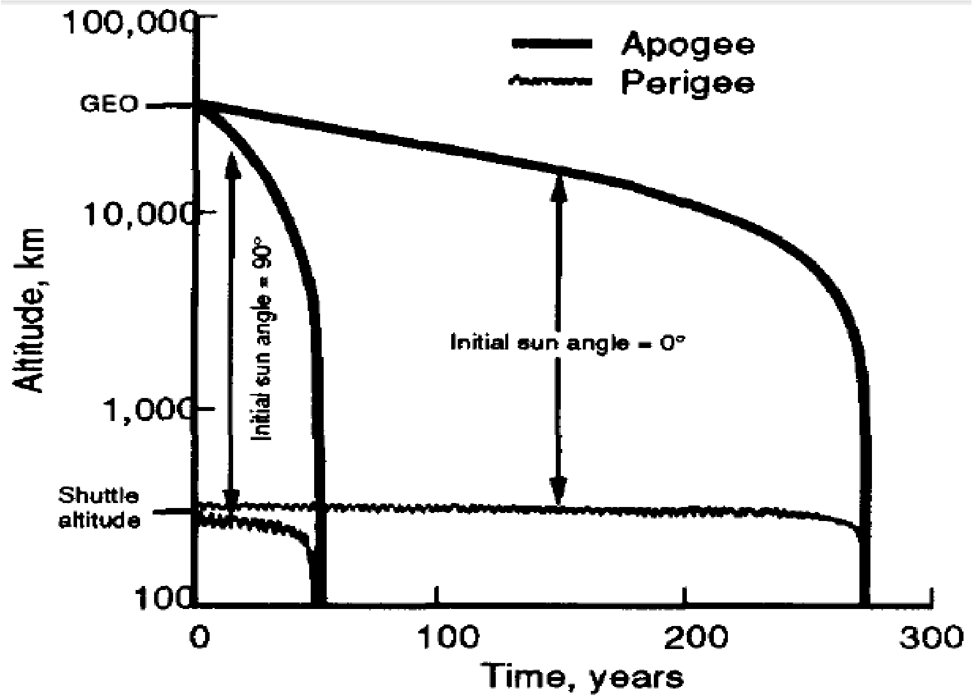


Figure 27 Shuttle launched LEO to GEO transfer stage lifetimes (Loftus, 1992).

It is important to note that this option is not always a viable one because, as the article "Space debris mitigation measures in India" puts it, "the launch time of a geostationary satellite is dictated by many other factors like thermal aspects and eclipse time related to the spacecraft design." A proven application of this technique was of the example of India's GSLV-D1 launched on 18 Apr 2001. The projections for the perigee and apogee evolutions are shown in figure 28. Reentry was predicted to take place approximately December 2002/January 2003. The actual date of the event was 18 January 2003 (Adimurthy, 2006).

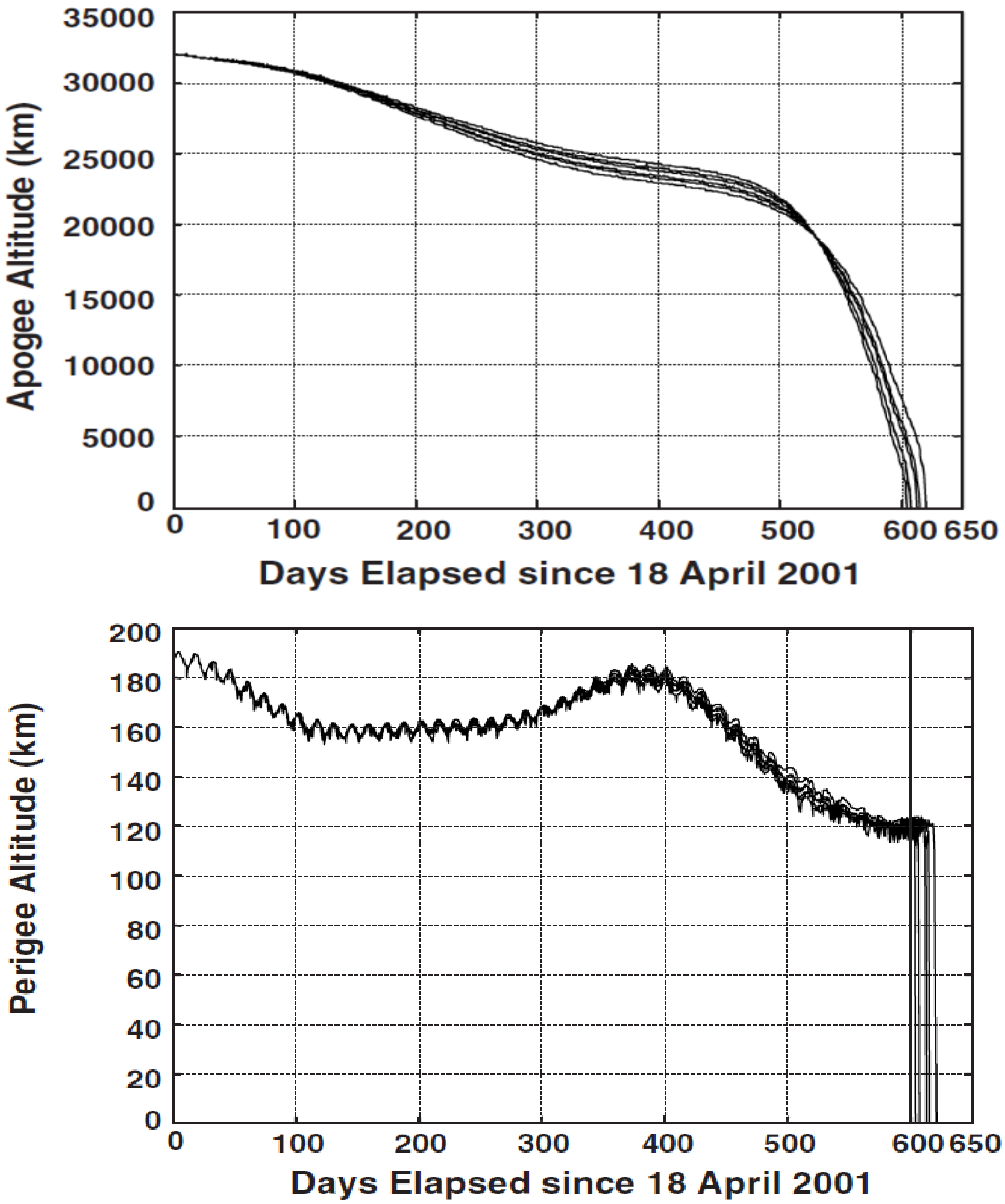


Figure 28 Orbital evolution of GSLV-D1 rocket body (Adimurthy, 2006)

Effectiveness of Passive Debris Mitigation

Passive Debris Mitigation techniques individually implemented are not effective against space debris accumulation. Moreover, Passive Debris Mitigation techniques implemented complementarily will still not favor sink against source of debris. As depicted previously in figures 4, 10 and 11, the future debris environment is predicted to have an increase in space debris objects and collisions even in the scenario where no changes to previous launch trends are achieved. The environment will then change with the entry of developing nations into the space foray and as entities sustain existing programs and development of new programs are forthcoming. Re-orbiting and de-orbiting methods aim to introduce decay of space objects within a certain amount of time. The goal time for space objects to linger on orbit is 25 years as recommended by IADC space debris mitigation guidelines, although, studies have been performed for other time regimes. Shown in figures 29 through 33 are re-orbiting and de-orbiting measures designed to remove space objects from orbit immediately, in 25 years and in 50 years.

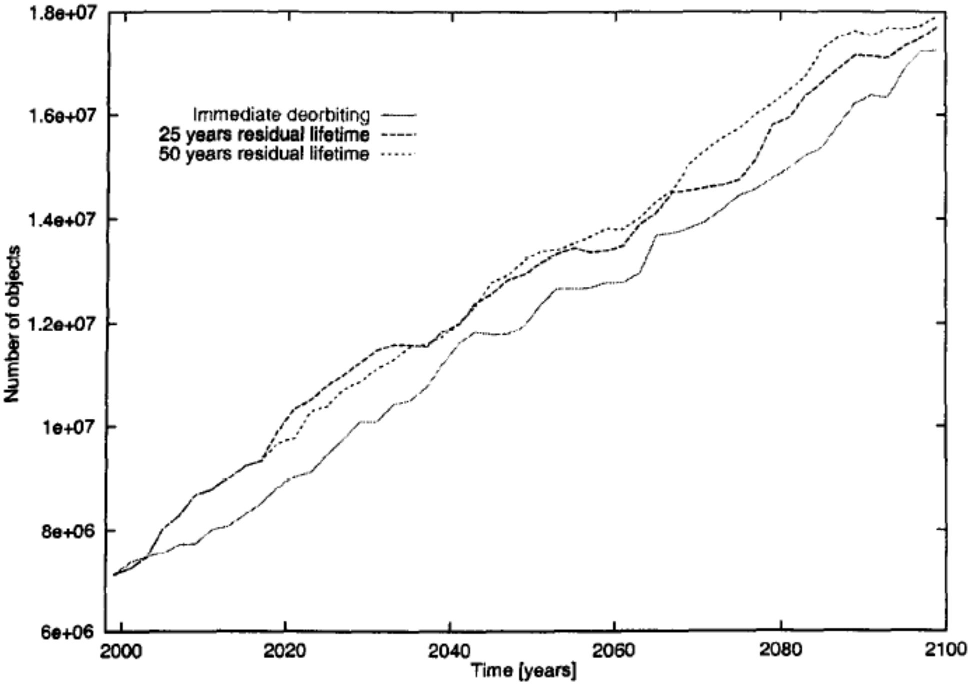


Figure 29 Number of objects larger than 1 millimeter (Anselmo, 2001)

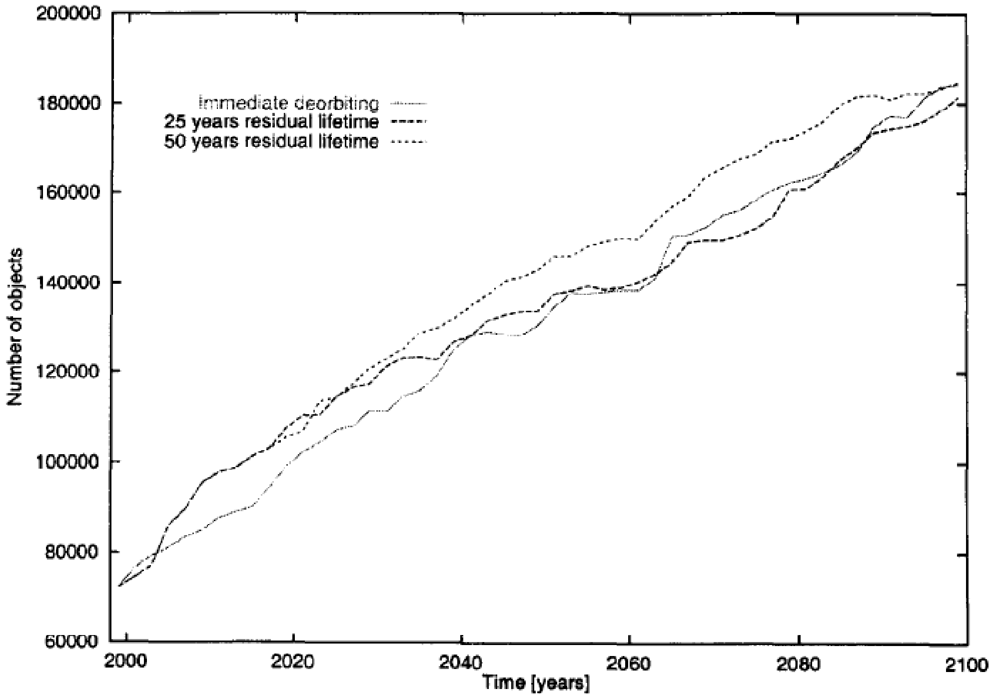


Figure 30 Number of objects larger than 1 centimeter (Anselmo, 2001)

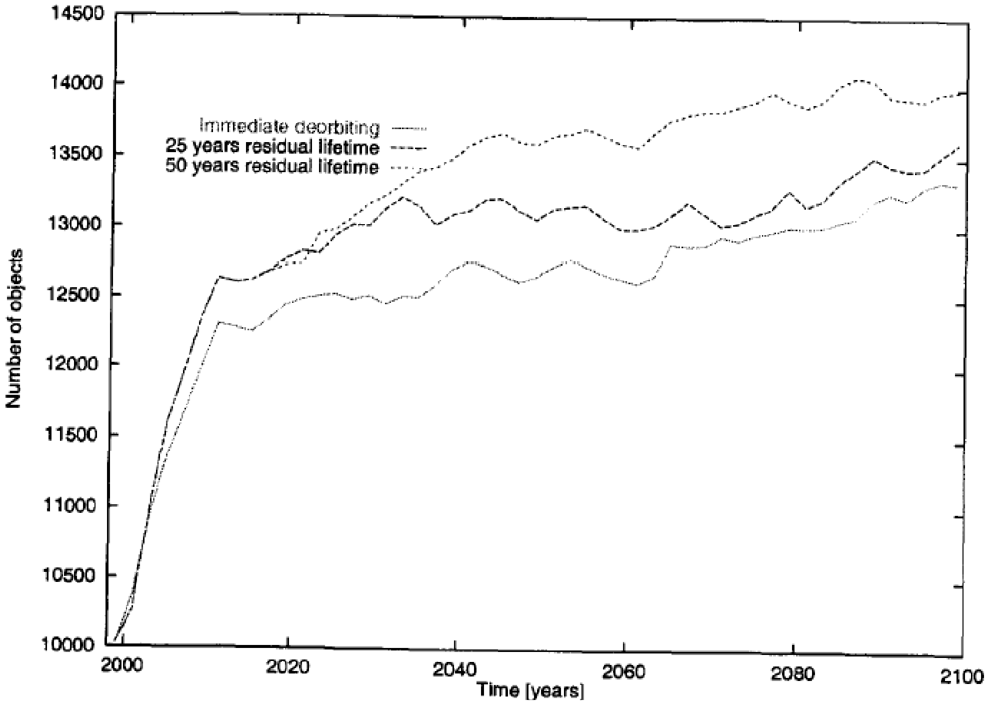


Figure 31 Number of objects larger than 10 centimeters (Anselmo, 2001)

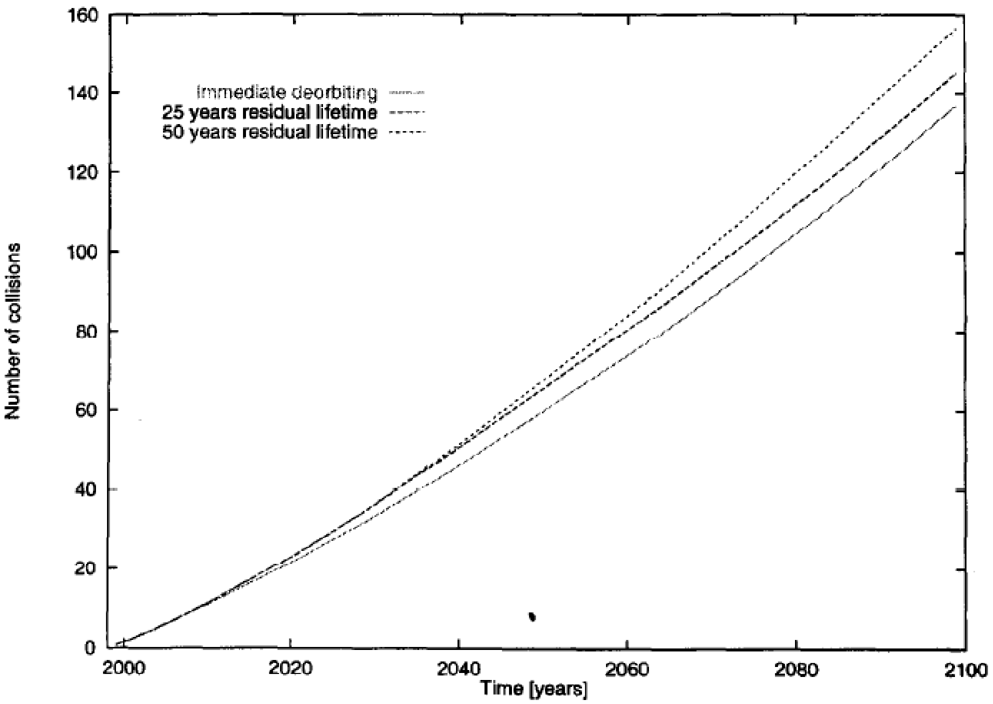


Figure 32 Cumulative number of collisions between objects larger than 1 centimeter (Anselmo, 2001)

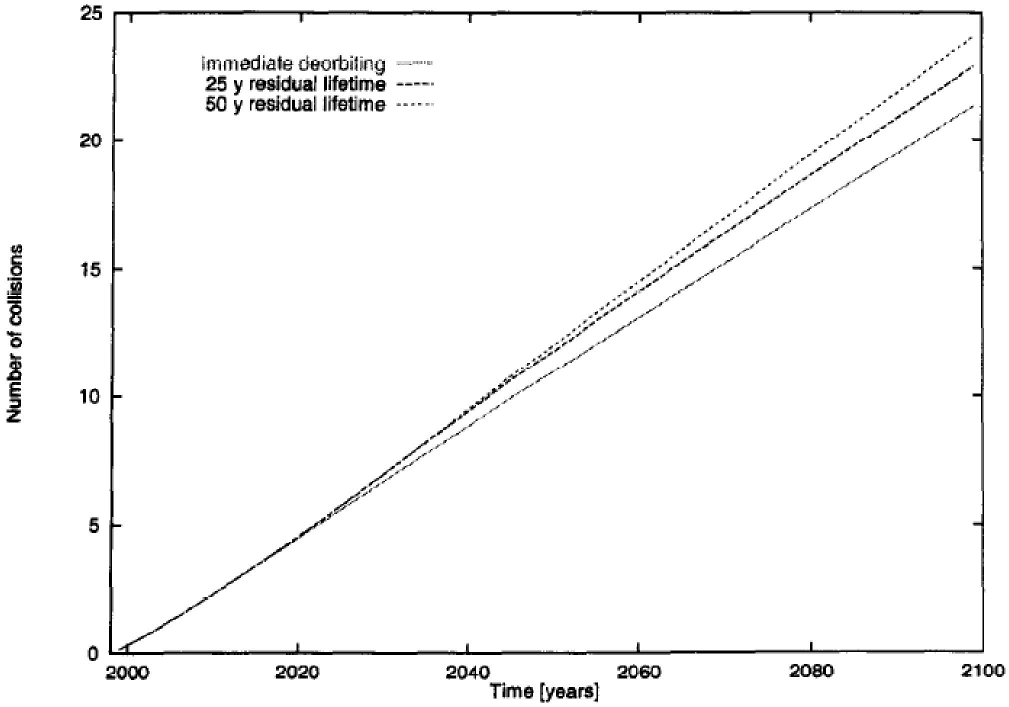


Figure 33 Cumulative number of collisions between objects larger than 10 centimeters (Anselmo, 2001)

While the space debris environment continues to increase, passive space debris mitigation measures do not remove space objects in sufficient time to relieve the collision probability. In the article "An active debris removal parametric study for LEO environment remediation", long time NASA space debris researcher, J.-C. Liou, fluently states that current passive "[p]ostmission disposal, such as the 25-year rule, will help, but will be insufficient to prevent the debris self-generating phenomenon from happening. To preserve the near-Earth space for future generations, [Active Space Debris Mitigation] must be considered."

Active Space Debris Mitigation

Robotic Arm

The idea of a robotic arm for active space debris removal is a conventional capture technique. A spacecraft is equipped with a robotic arm which is used to grasp unwanted space objects in orbit. First, the spacecraft would be launched into any of the orbital regimes. Next, after achieving its initial orbit, it would rendezvous with a target space object for removal. Then, using some type of sensor (most typically optical), assess the orientation of the target. Subsequently, the robotic arm attempts to seize the target object. This step is followed by the robotic arm spacecraft maneuvering with the target into a lower orbit for eventual release. Lastly, the target would then decay into the Earth to finalize disposal. The system bolsters the capability to perform the capture and de-orbiting task on more than one space debris object.

While the fundamental concept of a robotic arm is simple enough to understand, the actual operational requirements of such a system would be intensive. Such a system would require a dedicated operational mission area in order to be put into effect. This means having associated operations centers for command and control, remote ground stations for communications, and operations personnel. It would also require the launching of the robotic arm asset which incurs additional costs.

Additionally, there are several challenges at the component level of the spacecraft bus and robotic arm payload. As the robotic arm conducts its mission, maneuvers would be needed to rendezvous with a target object. This calls forth liens on propulsion, attitude and navigation subsystems. Propellant mass and overall spacecraft mass would increase, increasing development, production and launch costs. Attitude determination and navigation components would go up at a premium to respond to the additional reliability demanded by the mission especially since the system would optimally perform repeated capture and de-orbiting jobs.

Likewise, on the robotic arm payload side, other challenges dwell. Once rendezvous with the target is achieved, the interaction between the target and the robotic arm must occur. This involves optical instruments for the operator on the ground to see the target for an assessment on the robotic arm's approach of the target and the orienteering of the robotic arm for capture. Not only will optics add to the overall system cost but it adds a hidden cost of having a robust communications subsystem capable of wideband and high speed data transfers to cut down on latency for the best possible interaction between robotic arm and target.

As for grasping functions by the robotic arm, momentum of the target would have to be addressed as it would be transferred to the robotic arm servicer. At the time of this research, the only measure explored is that of "Joint Compliance". From the tip of the robot arm to the spacecraft attachment, it is proposed to have a joint or multiple joints that would act as part of a package that progressively dampens the momentum absorbed from the target. Suggestions have seen as much as seven degrees of freedom for such a system. Figure 34 shows a depiction of this concept (Nishida, 2009; Nishida, 2003; Xu, 2010).

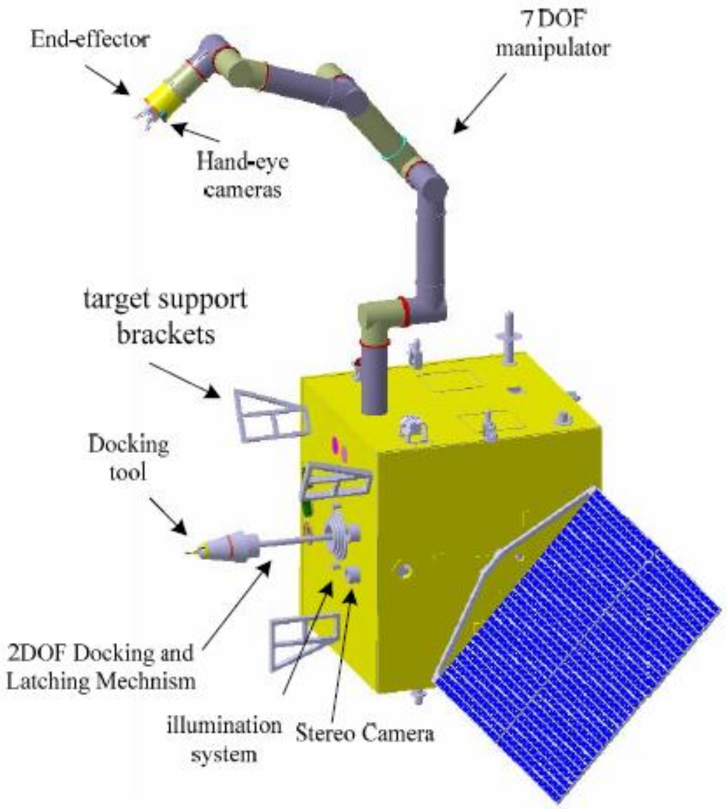


Figure 34 Robotic Arm Space Debris Removal Servicer with Joint Compliance Control (Xu, 2010)

There are foreseen cases when a target space object is “uncooperative”, meaning that it’s in a tumbling state. The robotic arm would have to compensate for the rotation of the target prior to grasping by the robotic arm. For this, a brush contactor is offered which purports to dampen the rotational motion of the target. A prototype of a brush contactor is shown in figure 35 and an illustration of the concept of utilization is shown in figure 36 (Nishida, 2011).

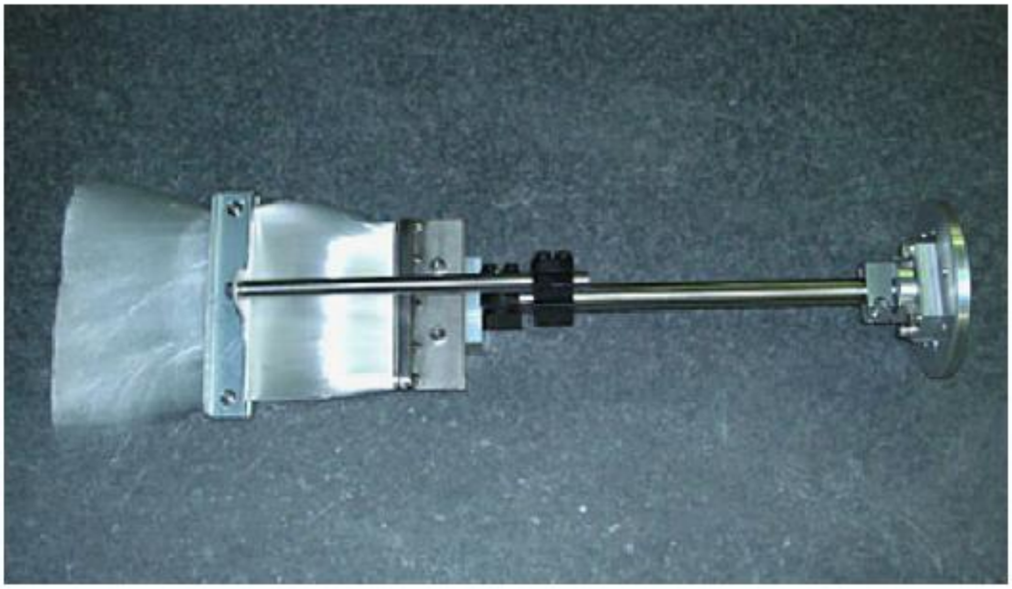


Figure 35 Prototype of brush contactor (Nishida, 2011)

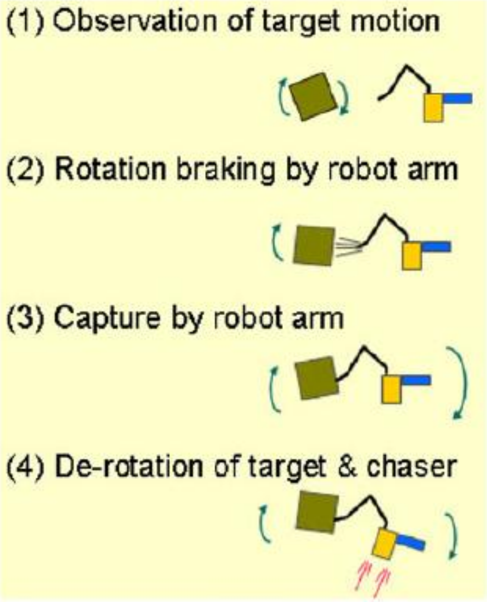


Figure 36 Brush contactor utilization concept (Nishida, 2011)

Variations of the robotic arm concept include additional features such as attaching tether systems which effectively relieves the robotic arm servicer from maneuvering with the target object and the use of lasers after capture to destroy the target.

Tethers

Tethers are considered in this study owing to the mechanism's implementation option to be attached to space debris targets that are unable to perform any disposal maneuvers. They are also viable choices for disposal methods in newer spacecraft. The component is essentially a drag augmentation device which takes advantage of naturally occurring forces in the space environment. Of this mechanism, there are two types: momentum transfer and electro-dynamic.

Momentum transfer tethers involve the interaction between two space objects. One is the target object and the other is a spacecraft in higher altitude which lowers the tether to the target. Once the connection is made the objects and the tether are now an integrated system. "The difference in velocity and perturbing accelerations will cause both vehicles to swing along an arc defined by the joining tether" (Barbee, 2011). This coupled with the Earth's gravity gradient in effect de-orbits the target object. After the servicer, tether and target traverse near Earth orbit, the tether is cut in order to release the target into a perigee closer to Earth where drag forces are more abundant and the servicer is released to that orbit's apogee seeking to dock with another target. A "swinging tether of a length L can reduce the perigee of a satellite by a factor close to 14xL" (Bonnal, 2000). This equates to requiring a 10 kilometer tether to lower an object by 100 kilometers. This is a rather long protrusion for a spacecraft and introduces increased collision probability to include micro debris. Demonstrations of the momentum transfer method have been shown in LEO with the SEDS-1, SEDS-2 and TSSI-R missions. It's notable that this method is viable in LEO, Sun Synchronous Orbit (SSO), and GEO Transfer Orbit (GTO) but not so in GEO due to the negligible gravity gradient in GEO (van der Heide, 2001).

Electro-dynamic tethers, on the other hand, uses a "bare tether with a cathode at the lower end" and as it moves "through the magnetic field of the Earth [it] will collect electrons" from ambient plasma and a current is induced. Due to the Earth's magnetic field, a Lorentz drag force is initiated. This type of tether differs from a momentum transfer tether in that the tether doesn't require a servicer attaching itself and the tether to a target object. However, execution of the method for targets that are not presently equipped with the tether necessitates that a servicer would still need to attach a tether to a target. As with momentum transfer tethers, the tether de-orbits a target with an induced drag force, although, in this case it is of a dissimilar kind. This force will "reduce the…mean altitude of the tethered system orbit at rates of two to 50 kilometers per day, decreasing with increasing debris mass, inclination or altitude." Along these lines, the method is most effective in LEO and not applied in SSO, GTO and GEO orbits due to the insignificant electromagnetic force which allows for de-orbiting. Typical tether lengths are five to 10 kilometers. The concept has been demonstrated successfully in the "Charge, Oedipus, PMG and TSS experiments." Figure 37 illustrates the electro-dynamic tether principle (van der Heide, 2001).

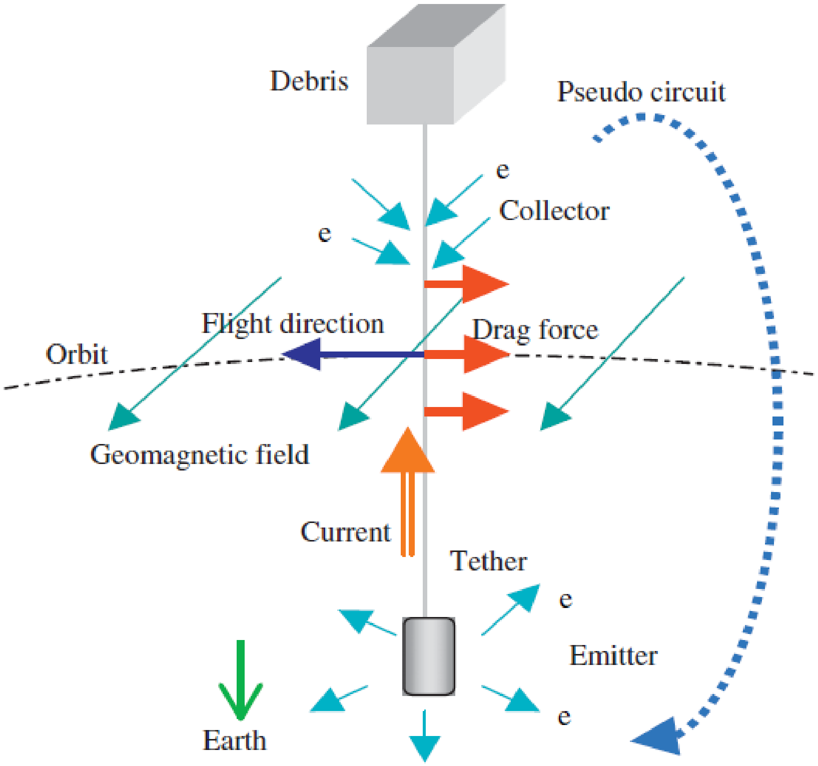


Figure 37 Principle of electro-dynamic tether (Nishida, 2009)

A modification of the design addresses a shortcoming. It is particular to the collision risk of such a long extension from a satellite. Not that it addresses reducing the risk of collision but it increases the availability of the tether in cases of collision with a space object. Namely, the modification introduces a double strand of tether with knots which effectively add redundancy to the tether system. An illustration follows in figure 38 (Kim, 2010).

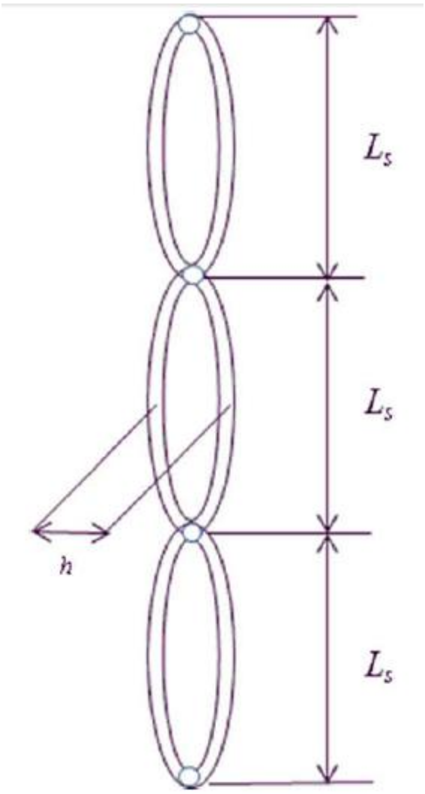


Figure 38 Detailed design of double strand tether with knots (Kim, 2010)

Net

A simple idea for active space debris removal is a net type capturing device. Although simple, during the literature search and review a lone article was found with any discussion of it. As with any net, the concept is to catch space debris objects in the net and de-orbit the net and its contents down to Earth. However, unlike any net, the device would have to be launch into orbit and deployed. It would travel along the track of the orbit and collect debris along its path. The lone article found contends that the idea "does not work". Bonnal and Alby, the authors of the article "Measures to reduce the growth or decrease the space debris population", asserts that it does not work for the following reasons: "it requires a huge surface in order to have a significant rate of ‘catches’, the ‘catch’ has to be performed without any debris generation, the orientation of the sweeper makes it efficient only for privileged directions, the system has to be complex, and requiring frequent changes of orbit and a final [de-orbiting], i.e. controlled from [the] ground.” Also, the system is expensive as it would require intensive development, associated command and control facilities and capabilities, and launch of the asset. All of the aforementioned toil would be cost prohibitive if the result was a paltry “withdrawal of several hundreds of small debris in the best case.” Additionally, execution of the method infers that it would pick up objects indiscriminately to include operational space assets. Lastly, the statement made by Bonnal and Alby that “the ‘catch’ has to be performed without any debris generation” is of import. This requirement is necessary because producing more debris in the process of removing them would be counterproductive. Moreover, the requirement can be met by judicious selection and/or development of materials composition for the net device or by the real-time assessment of the device’s approach of a target. The latter alternative would require some type of optical sensors and analysis of the target’s and the net’s ephemeris for an operator to correctly evaluate a safe approach (Bonnal, 2000).

Lasers

The central idea of using lasers for space debris removal is to use lasers to expel photons onto a space debris object to transfer momentum via radiation pressure. The momentum would be transferred in the incident angle of the beam against the target. As the photons hit the target, gases are ejected and, if properly oriented, would provide the target object with a small ΔV to drive it into a de-orbit maneuver. It will desirably reenter Earth's atmosphere through atmospheric drag. The alternative objective of this method is the total vaporization of the target object.

As with other active debris removal measures, it is quite a developmentally and operationally intensive method. Again, as with any target acquisition, the system requires that the target is seen before any interaction. Regular optics and radar from any source provide initial target tracking and ephemeris determination. However, another type of sensing called adaptive optics is required to focus and direct the laser onto the target as it passes overhead for engagement. Effectiveness of the system is reduced by turbulence through the atmosphere. To counter this turbulence, an adaptive optics system with an artificial guide star is needed to apply corrections in real time, "as local turbulence changes rapidly and the guide star moves across the sky as the telescope tracks the target" (Mason, 2011). Figure 39 illustrates this targeting and laser radiation process.

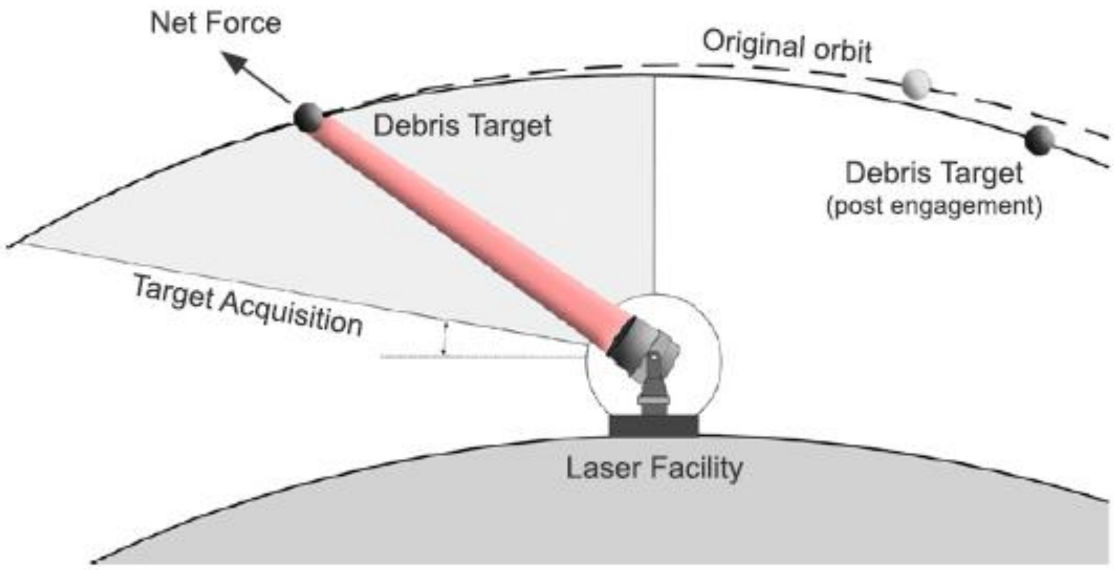


Figure 39 Schematic of laser system and operations (Mason, 2011)

As shown on the diagram, target acquisition precedes photon irradiation of the target by way of adaptive optics and a guide star. The performance of adaptive optics varies on the severity of turbulence in the path of the beam and the technical capabilities of the adaptive optics system (Mason, 2011).

Following the process of target acquisition is laser photon irradiation. There are three general categories in implementation and effect of irradiation: low intensity, high intensity with continuous wave (CW) lasers and high intensity with pulsed lasers. Low intensity irradiation applies to a target debris object lower energy insufficient to reach the threshold at which ablation would occur. A lower intensity system is suggested to influence sufficient force to targets to divert or maneuver them. However, such a system is deemed inefficient as the beam is vulnerable to transmission losses that are large in proportion to the beam strength and, therefore, is assessed to have “momentum transfer efficiency four to five orders of magnitude less than pulsed laser ablation” and “does not effectively address the debris growth problem” (Phipps, 2012).

On the other hand, high intensity irradiation with CW lasers applies enough pressure on a space debris object target to cause ablation. As the application of photons is continuous, it effectively slowly heats a debris object and releases an “ablation jet whose momentum contribution cancels itself out, on the average.” This implementation causes melt ejection that is messy rather than clean jet formation. This has the potential to add to the debris problem as melted ejecta agglomerate and change phase back to solid. Lastly, for targets at higher altitudes, CW lasers are unable to “reach the required intensity on target…without a very small illumination spot size, requiring an unacceptably large mirror” (Phipps, 2012).

Pulsed laser irradiation applies high intensity photon energy repetitively to a space debris target object, making a plasma jet. Because the application of energy is not constant, “very little target material is removed and the debris is not melted or fragmented.” This method is more efficient as comparatively more of the laser energy goes into generating the jet versus being influenced on the target object continuously resulting in melting. Design of the engagement is meant to point the jet “in the right direction to slow the target, on average, by the small amount (100–150 m/s) needed to drop its perigee to 200 km, which is adequate for rapid reentry.” Hundreds of these pulses are needed to be applied during a target object’s pass overhead of the laser facility at 10 nanosecond intervals. The current system proposal is purported to force re-entry of small objects in one single overhead pass. For larger debris objects, application of laser energy will have to be done throughout multiple overhead passes (Phipps, 2012).

A number of considerations need to be made in the laser irradiation regime. As mentioned earlier, turbulence perturbs the beam as it traverses the Earth’s atmosphere on its way to the target object. And, that these perturbations are compensated for with the use of adaptive optics and a guide star. This study will now explore the considerations of irradiating tumbling objects, and the diversity of material compositions of space debris objects.

Tumbling space debris targets require special thought as “spin state of a debris object introduces a degree of randomness into calculating the response to directed photon pressure.” The tumble makes it difficult to fire the laser on the right angle of incident against the object to effectively transfer the momentum along the track. This could result in increased tumbling, the maneuvering the object in undesired positions, the complete absorption of the photon energy into the object causing hazardous melting or fragmentation creating further debris or the inefficient application of laser energy (Mason, 2011).

An additional consideration must be made for the variation in materials compositions that can be found amongst the space debris population. Utilization of laser irradiation on different materials results in divergent effects. To illustrate this point, the article “Orbital Debris Removal by Laser Radiation” examines the effects of laser irradiation on a variety of materials. Samples of Al_2O_3 Ceramics, Acrylic Glass, Mild Steel and Aluminum were tested for reactions to laser irradiation.

Al_2O_3 Ceramics cracked with less than 100 milliseconds of exposure to the laser under thermal stress. No displacement of the sample was observed. On the other hand, the Acrylic Glass was irradiated for 10 milliseconds only but was in motion up to 40 milliseconds later. The position of displacement was not described in the study. Mild Steel was irradiated for one second and displaced by approximately three centimeters horizontally and .05 centimeters vertically. Mild Steel lost 11% of mass material at a rate of ablation of 100 milligrams per second. Lastly, the Aluminum probe was displaced by only one centimeter and, within less than two seconds, it melted and dropped to the floor (Schall, 1991).

It is clear that the variety of materials reacted in varying ways to the irradiation of lasers. The implication here is that laser irradiation campaigns must account for the materials composition of the target. This aspect of the laser irradiation method is still in need of much study and experimentation. Target characterization, as well, would involve intensive analysis in order to correctly gauge the laser system's approach of the target debris.

Safety Considerations

A general consideration for practitioners of space debris mitigation is safety. This is true for both passive and active space debris mitigation methods and it is especially a factor when it comes to any method which involves maneuvering. Two categories of the safety aspect are terrestrial and space safety.

Terrestrial safety is of significant concern for de-orbiting operations. De-orbiting objects are desired to eventually reenter the Earth's atmosphere. But the question must be asked: How is the safety of air operations, naval operations, land and people ensured when an uncontrolled space object reenters the Earth's Atmosphere? The first response to this question is to characterize object reentry. On one hand, there are objects that are in small sizes of homogenous material composition which will uniformly break up or burn up in the atmosphere and have more predictable survivability. These objects are significantly less threatening than larger reentry objects that are of inhomogeneous composition. This second category, of course, is made up of intact spacecraft or upper stages, will have more survivability potential and less predictable break up scenarios for fragmentation. Modeling is available and can be further developed for these objects. An example of modeling software available is SCARAB which "can be employed to model the entry process, the break-up, and the dispersion of impactor fragments on ground" (Alwes, 2004)

Other aspects of a concept of operations for object reentry emergency actions haven't been spelled out, however. One of which is a method of handing off active tracking from those that watch the space environment to those that watch the terrestrial environment for an object upon reentry into the atmosphere. The next logical step would be to characterize the object's trajectory in real-time; here, roles and responsibilities have not been defined. After characterization, some type of emergency notification would sensibly follow. Then, emergency actions in the event of falling space debris need to be coordinated. Lastly, after actions would have to be enacted after a re-entry event; examples of these are a safety investigation and some process for compensation if damages are incurred.

In addition to terrestrial safety concerns, the international space faring community must be mindful of space safety. Space safety is of particular concern when executing debris removal techniques involving the maneuvering of space debris objects as these add to the current traffic conditions already in play on orbit.

In the case of passivation prior to any de-orbiting or re-orbiting, space operators must take care to coordinate disposal actions that enable the elimination of any potential energy while ensuring that any re-orbiting to disposal regions in an orbital regime takes place before hand. This implies that budgets for propellants, batteries, and subsystem availability and reliability are defined throughout the design of the spacecraft. Of course, this is only possible with relatively newer spacecraft that were developed after the genesis of space debris mitigation methods. The inference here is that older spacecraft or spent upper stages are incapable of any collision avoidance maneuvering and thus present collision risks when implementing re-orbiting to disposal regions. In addition, during the disposal of a spacecraft at the end of its mission life, Radio Frequency Interference may be introduced while it travels in proximity to other active spacecraft in its Hohmann transfer orbit. During this time it's possible to lose communications with the disposed spacecraft for a few minutes presenting uncertainty due to loss of command and control.

De-orbiting with tethers presents other space safety risks. In cases when newer space systems include tethers in their design and mission profiles, the tethers themselves pose a hazard in the forms of collision and the resulting fragmentation. "Typical tether lengths of five to ten kilometers" protrude enough for probable collision scenarios as the tether maneuvers the space object. These scenarios are less significant when a tether is impacted by micro debris of less than ten centimeter sizes but are a major concern if the impacted object is an intact spacecraft or upper stage. The protuberance increases risk to conventional passive de-orbiting events as additional mass and area are now available. To make matters worse, active control is absent in the tether de-orbit technique due to the design of using naturally occurring forces for passive propulsion. In the dissimilar case of attaching tethers to nonoperational space objects, risk is introduced early during the target acquisition and affixing stages because of the need to properly phase the servicer with the target and to accurately fasten the tether (van der Heide, 2001)

Laser irradiation schemes inherently present dangers due to targeting and beam shooting. First, target selection and tracking is of importance. Discrimination must be exercised to target only approved objects to ensure the safety of operational spacecraft; this means that a vetting process has to be established with multinational participation. Once a target is selected, tracking and ephemeris propagation need to be precise to ascertain that the right target is being irradiated. Weather and atmospheric conditions have to be assessed as well, as the beam path may be altered sufficiently to hit objects not intended for irradiation. Lastly, care must be taken to analyze materials compositions of the current space debris population. Rules of engagement would call for differing laser irradiation campaigns for the variation of materials of which targets may be composed as the beam can reflect off a target and hit other objects unintentionally or cause the complete fragmentation of the target creating other debris.

Robotic arms, tethers, nets and other space-borne active space debris removal schemes offer up an inherent space safety risk of collision and debris production. As space assets, they add to the population of objects with debris generating potential which comes with mass, moving through space traffic with other objects, and the ubiquitous mission related objects emitted during the course of mission life. Included in these mission profiles are launch and orbit acquisition operations involving rocket bodies and upper stages. In addition, these systems are designed to engage multiple targets, making a rendezvous between objects. This increased traffic pattern amplifies collision probabilities because their mission profiles act counter intuitively to collision avoidance principles. Instead of making an effort to stay away from a space object, space-borne active debris removal spacecraft purposefully close in on a target.

Active Space Debris Removal as a Space Weapon

For active debris removal methods, there’s a negative connotation and trepidation that they can be used as weapons against other operational spacecraft by State actors. There’s an obvious potential for active methods for destructive and harmful purposes. Foreboding of this possibility is found in the Chinese Fengyun-1C ASAT test and the emerging threat of North Korean and Iranian launch capabilities. Robot arms, nets, tethers, and lasers may very well be used on operational space objects with malicious intent to destroy the capability for space operators. These active debris removal measures may simply render a space asset ineffective by moving it away from its operational slot or completely destroy it by intentionally colliding it with another space object. More significant than the destructive capability is the debris it stands to generate, fueling the Kessler Syndrome.

Both UNCOPUOS and IADC guidelines attempt to mitigate intentional dangerous activities as both bodies drafted associated guidance. IADC guideline 5.2.3. is below:

> 5.2.3 Avoidance of intentional destruction and other harmful activities
>
> *Intentional destruction* of a spacecraft or orbital stage, (self-destruction, intentional collision, etc.), and *other harmful activities* that may significantly increase collision risks to other spacecraft and orbital stages should be *avoided*. For instance, intentional break-ups should be conducted at sufficiently low altitudes so that orbital fragments are short lived.

While UNCOPUOS guideline 4 is as follows:

> Guideline 4: Avoid intentional destruction and other harmful activities
>
> Recognizing that an increased risk of collision could pose a threat to space operations, the *intentional destruction* of any on-orbit spacecraft and launch vehicle orbital stages or *other harmful activities* that generate long-lived debris should be *avoided*. When intentional break-ups are necessary, they should be conducted at sufficiently low altitudes to limit the orbital lifetime of resulting fragments.

These statements also allow provisions for necessary intentional breakups as in the case of the US' purposeful intercept of a decaying defunct National Reconnaissance Office (NRO) satellite with a modified Standard Missile 3 (SM-3) in 2008. USA-193 was de-orbiting after it malfunctioned soon after its deployment in LEO. An estimated 1,000 pounds of hydrazine fuel remained which was deemed hazardous to humans upon its eventual reentry into Earth's atmosphere. The intentional destruction carried with it the objective “to rupture the fuel tank to dissipate…hydrazine” and upheld the spirit and intent of the IADC and UNCOPUOS space debris mitigation guidelines mentioned above. The intercept was designed to occur in low altitude to diminish the generation of debris orbiting in space. Nearly all debris from this shoot down reentered and burned up in the Earth’s atmosphere and did “not affect any orbiting space systems.” In contrast, the January 2007 Chinese ASAT test involving the shooting of the Fengyun-1C “[destroyed] a 2,200-pound satellite that was orbiting 528 miles above the Earth [which] left more than 100,000 pieces of debris orbiting the planet, [as] NASA estimated -- 2,600 of them more than [four] inches across. [NASA] called the breakup of the Fengyun-1C satellite the worst in history” (Anonymous 2008; Anonymous 2008)

Summary

This chapter explored a multidisciplinary approach to space debris mitigation. The factors considered were technical and legal. Technical measures were listed from both the passive and native standpoints to widen options for possible solution sets. Legal measures, which also encompass international relations, strengthen the execution of an effective space debris mitigation program.

III. Methodology

Chapter Overview

The methodology employed for this study takes the form of meta-analyses. Over 120 documents from a multidisciplinary collection of professionals were reviewed; these were opinions that cut across the space technical and policy making communities. Such an approach to the development of space debris concept of operations is required because space cuts across technical and legal disciplines internationally (Bond, 2006). The study organizes 120 documents in bins namely Space Debris Mitigation, Space Debris Characterization, and Space Law. Of the 120 documents, 49 belonged to the Space Debris Mitigation bin, 15 belonged to the Space Debris Characterization bin, and 39 belonged to the Space Law bin. An additional 17 documents were found citing commentary and news articles by various leaders in the space faring community.

The results of these documents are synthesized to determine whether a trend emerges in the following data points:

1. Prioritization of Space Debris Mitigation Targeting
    a. Prioritization of debris removal by size
    b. Prioritization of debris removal by orbit
2. Promotion of active debris removal
3. Recognition of Central International Agency in Regulating the Space Debris Environment
4. Nomination of an agency charged with enforcing space debris environment regulation

Knowing this, we can begin defining a concept of operations. In cases when a conclusive understanding of these data points is absent, a recommendation will follow.

Our first two technical data points of prioritization hopes to steer the focus of the space debris removal solution. With respect to prioritization by size, the study seeks to expose the space debris population subset that poses the most risk of promulgating space debris and catastrophic impact events. Prioritization by orbit aims to make a distinction between LEO, MEO, HEO and GEO in terms of the relative collision hazard to operational satellites. The third technical data point intends to reveal whether a plea exists for initiating ventures for active debris removal from the international spacer faring community.

In addition, relevant studies of space law and policy-making need to be examined in order to open the discourse between States regarding binding roles, responsibilities and directives for an international regime for space debris regulation with flexibility and adaptability at the national level. Hopefully, a pattern will emerge revealing an agency in the forefront of space stewardship. A proposed chain of command with the formation of sub organizations that fill functional gaps in the space debris solution set by and large will follow in Chapter 5.

International space ambition can be divided into two branches: developed and developing nations. Each group is distinct in space operational capability beginning with budgets, resources, and active space asset inventories and each will have different roles and responsibilities commensurate with their ability to contribute. Despite differences in space operational capability, our meta-analyses will allow us to disclose if there is enough consensus that nation States can be legally bound to internationally agree upon regulation.

For each data point, a document is polled and tallied for a true or false score. The total score is then calculated against the entire population of documents in the relevant bin. The resultant final score will be a simple percentage (Bond, 2006).

Meta Analysis and Parameters

The methodology used in this research is a meta-analysis. Using this method, results from different studies and documents were compared and contrasted in hopes of identifying patterns among their conclusions, divergences in results and relationships that may have been uncovered during the review. The overall effect of this method is to compile a sizeable volume of studies to augment the validity of the study (Bond, 2006).

Literature sought after for this study consisted of the subject matters of space legal, space policy, international relations, space debris mitigation guidelines, active space debris mitigation methods, passive space debris mitigation methods, space debris models, space debris events of interest and space debris monitoring and tracking. Documentation found using the keywords above were organized into bins: Space Legal, Space Debris Mitigation, and Space Debris Characterization. The Space Legal bin consisted of articles discussing space legal, policy, international relations, and debris mitigation guidelines. The Space Debris Mitigation bin contains those methods and technologies utilized for passive space debris mitigation and proposed for active space debris mitigation. Lastly, the Space Debris Characterization bin comprises of articles in which space debris events of interest, space debris monitoring and tracking. The bins were the most logical organization of the documents while keeping a coherent collection of resources to answer the questions pursued by this study.

The literature selection for the study favored articles published within the last 30 years. The "age" of documentation ideally had to be in the recent past to illustrate the current space debris environment which encompasses the current international legal and policy climate, technologies and methods in space debris mitigation and space environment modeling and the most up to date space events of significance such as recent catastrophic collisions.

After bounding the documents in the aforementioned bins, each document was polled against relevant questions for that bin. As each document was reviewed, a binary question or data point was asked to extract a pattern in the writing for the collection of documents in that bin (Bond, 2006). The following paragraphs discuss the data points for each bin in more detail.

With regard to the Space Debris Mitigation bin, five main data points with sub points were used to poll against the documents in the bin. Namely those were:

- Prioritization of Space Debris Mitigation Targeting
- Active Mitigation Techniques
- Passive Mitigation Techniques
- Technology
- Effectiveness

Sub points were also used to poll against the documents for the last four data points mentioned above. For example, under the Technology data point, considerations for maturity, cost, complexity and the potential for the technique to become a debris hazard during implementation were taken. 49 documents of the main population were organized into the Space Debris Mitigation bin.

Next, questions asked of the Space Debris Characterization bin, again, encompassed sub points under the three main data points used to poll against the documents in the bin:

- Orbit of Interest
- Type of Sensor
- Capability

For orbit of interest, the documents belonging to this bin were inspected for an orbit centered focus. The documents in this bin were also evaluated for sensor types and capability to detect with respect to debris size. Of the initial collection of documents from the literature search, 15 were sorted into the Space Debris Characterization bin.

Lastly, data points consistent from the aspect of the Space Law bin included five data points, without sub points, used to poll against the documents in the bin:

- Recognition of Central International Agency in Regulating the Space Debris Environment
- Nomination of an agency charged with enforcing space debris environment regulation
- Prescribes partnership of nations
- Suggests fines for noncompliance
- Recognizes national interpretation of international law

These data points addressed the organization of the space debris mitigation effort internationally. They also reveal opinions on punitive or compensative actions for damages occurring from on orbit collisions and the license to which a single nation can deviate from legal language applicable to space operations. The sample containing these documents resulted in 39 documents for the Space Law bin.

Summary

Chapter 3 explains the methodology used in this study. Carrying out the meta-analysis resulted in the review of 120 documents. Bins or buckets were formulated to organize the documents into logical groupings. While in these groupings, the documents were reviewed against data points related to the pertinent questions of this study.

IV. Analysis and Results

Overview

This chapter discloses analyses taken against the documents found and organized in the research via the methodology of meta-analysis. Results gathered after the analysis are also divulged. Polls are taken according to the most significant data points as listed below and in chapter 3:

1. Prioritization of Space Debris Mitigation Targeting
    a. Prioritization of debris removal by size
    b. Prioritization of debris removal by orbit
2. Promotion of active debris removal
3. Recognition of Central International Agency in Regulating the Space Debris Environment
4. Nomination of an agency charged with enforcing space debris environment regulation

As the documents were grouped into their relevant bins and evaluated against significant data points, patterns emerged implying consensus amongst the experts which authored the documents. Table 2, 3 and 4 display results polling each document in the Space Debris Mitigation, Space Debris Characterization and Space Law bins against data points selected for each bin. Matches were recorded when a data point was discussed in the document. The total matches were tallied and a percentage was taken against the total documents contained in each bin. For example, out of the 49 documents organized into the Space Debris Mitigation bin, 23 matched the "Prioritization of Space Debris

Mitigation Targeting” data point which was calculated at 47% of the document subpopulation.

Table 2 Space Debris Mitigation Bin Data Points (49 documents found)

Data Point	**Documents Matched**	**Percentage**
Prioritization of Space Debris Mitigation Targeting	23	47%
Proponent of Active Mitigation	21	43%
Active Mitigation Techniques		
Tethers	11	22%
Robot Arm	12	24%
Models exist for targeting?	38	78%
Proponent of passive mitigation?	34	69%
De/Re-orbiting of upper stages	28	57%
Shielding	11	22%
De/Re-orbiting of S/C at EOL	28	57%
Collision avoidance	13	27%
Considers collision avoidance and RF interference during de/re-orbiting operations	5	10%
Passive Mitigation		
Passivation	25	51%
Slag prevention	7	14%
MRO prevention	20	41%
Other	5	10%
Proponent of in situ ADR techniques	16	33%
Net	3	6%
Laser	1	2%
Other	7	14%
Proponent of ground based ADR techniques	6	12%
Ground Based Laser	6	12%
Considers Air, naval and ground safety during de-orbiting operations	7	14%
Technology		
Maturity	7	14%
Cost	10	20%
Complexity	15	31%
Potential Debris Hazard	17	35%
Effectiveness		
Time to remove debris	7	14%
Target acquisition	13	27%
Multiple targets	18	37%

Table 3 Space Debris Characterization Bin Data Points (15 documents found)

Data Point	Documents Matched	Percentage
Orbit of Interest		
LEO	12	80%
GTO	5	33%
GEO	6	40%
HEO	4	27%
MEO	2	13%
Type of sensor		
Radar	7	47%
Optical	7	47%
Impact	2	13%
Capability		
Millimeter	5	33%
Centimeter	9	60%
Meter	3	20%
Submicron	1	7%

Table 4 Space Law Bin Data Points (39 documents found)

Data Point	Documents Matched	Percentage
Recognition of Central International Agency in Regulating the Space Debris Environment	20	51%
Nomination of an agency charged with enforcing space debris environment regulation	19	49%
Prescribes partnership of nations	28	72%
Suggests fines for noncompliance	7	18%
Recognizes national interpretation of international law	16	41%

Prioritization of Space Debris Mitigation Targeting

Taking a poll of the space removal documents for some form of prioritization produced mixed results. Of the 120 documents, 49 belonged to the Space Debris Mitigation bin, and 15 belonged to the Space Debris Characterization bin. Out of 49 documents discussing space debris mitigation, 23 mentioned some type of prioritization of debris removal in various ways which equaled 47%. Of the 23 articles, 26% recognized a need to rank mass as the prime characteristic for targeting. An even 50/50 split was shown when decomposed further into distinguishing between small versus large mass debris. The divergence denotes lack of clear objectives regarding space debris targeting prioritization.

On the other hand, the search for prioritization by orbit showed a greater number of documents. A vast majority equaling 78% showed conviction that operational orbit takes a higher precedence when it came to mitigating debris. When broken down, the proposed orbit treated with space debris mitigation which would benefit mankind the most was split between four specific orbits, however, the LEO orbit was suggested most. 61% of the articles prioritizing by orbit chose the LEO orbit as most important while the Sun Synchronous (SSO), Geosynchronous (GEO), and GEO Transfer (GTO) Orbits were rated 11%, 16% and 16% respectively.

Outliers did turn up in the form of recommending attacking the space debris problem by other targeting criteria. Namely they were prioritizing space debris mitigation of launchers and satellites that have reached end of life and have been passivated. Of the 23 articles, two emerged with these suggestions coming to an 8% total. Because the results above favor prioritization of the LEO orbit, one can reasonably conclude that space debris mitigation should start in LEO first. This study proposes another perspective which is discussed below.

A. Space Debris Target Prioritization By Mass

Classifying the space debris problem by population subsets based on size is a prudent approach. Debris in small sizes is typically defined as less than 10 centimeters in width and consequently will have less mass. Large sized debris is larger than 10 centimeters and will have more mass. Small sized debris is more numerous with higher particle fluxes than large sized debris on orbit. By virtue of these aspects, there's a higher likelihood of collision. On the contrary, large sized debris has a lesser probability of impact. However, impacts of large debris are catastrophic in nature especially in the collisions between two pieces of large debris as illustrated by the aforementioned Cosmos and Iridium collision event. Current sensor capabilities best serve the larger sized debris as fidelity of data decreases with size. Due to this, cataloguing and tracking are more accessible with larger debris sizes.

The ideal large sized debris to be removed from orbit is intact spacecraft and rocket bodies. These objects can be better controlled by operators when sufficient propulsion budgets for de-orbiting are added in the design and mission profile. "In general, R/Bs should be considered first because they have simple shapes/structures and belong to only a few classes (see the two sample R/B and S/C images at the upper-right corner of Fig. 13). In addition, R/Bs do not carry any sensitive instruments, so it will be easier to achieve an international agreement on selecting them as removal targets" (Liou, 2011).

B. Space Debris Target Prioritization By Orbit

Debris fluxes and populations differ in orbits. LEO experiences the most traffic due to its value to communications and optical assets not to mention the presence of manned space missions. In addition, orbital velocities in LEO relative to other orbits are faster. The above contribute to LEO's higher debris fluxes and population sizes. As a result, spacecraft in LEO are subject to increased debris hazard risk to operations. GEO on the other hand has slower relative velocities and is allocated less spacecraft relative to LEO although rising in operational need. This signifies that debris fluxes and population are less when compared to LEO hence reduced debris hazard risk. MEO and GTO orbits, when evaluated with the same criteria, are attributed with lower debris hazard risk than LEO and GEO. "Only a few accidental collisions between [less than] 10 cm objects are predicted in MEO and GEO in the next 200 years" (Liou, 2011). However, objects in GTO have the unique characteristic of passing in and out of the GEO and LEO orbits adding to the debris hazard. Impact events in any orbit can be classified as catastrophic in nature due to already great velocities involved. LEO then, as shown in the meta-analysis above, is a clear frontrunner in priority concerning the clearing of debris from its orbit.

While the meta-analysis points toward prioritizing by orbital regime, especially in the case of LEO, this study must diverge and put forth prioritization by mass. This is due to the relatively higher potential of debris with a large mass to break up and add to the debris population as a result of a catastrophic collision. We can reasonably make the priority large pieces of debris. Sensor suites can best support this population subset and any eventual active debris removal engagements on derelict space objects lacking maneuverability can be performed sparingly to reduce cost and effort. We can go a step further to put precedence on large debris in LEO to decrease congestion in a heavily used orbit.

Promotion of Active Debris Removal

Of the 120 documents yielded by the literature search, 49 belonged to the Space Debris Mitigation bin. Review of the documents showed that 43% advocated active debris removal as a necessary step in controlling the debris environment. Anecdotal evidence revealed that the intentions behind this support were mixed. In seeking solutions for the removal of space debris in near-Earth orbit, the results above offer a rather tepid welcome to the consideration of adding active space debris mitigation techniques to existing passive space debris mitigation techniques. Delving deeper into the documentation, it is offered that passive space debris mitigation techniques will not sustain a safe orbital environment.

Some professionals and scholars are convinced that the space environment has breached the threshold for the Kessler Syndrome. The sentiment exclaimed is that debris hazards “pose a serious hazard to near-Earth space activities, and so, effective measures to mitigate it are becoming urgent” (Nishida, 2011).

Others, while not convinced of the above, are eager to push forward the development of active debris removal missions. For example, “advances [in low-cost, light-weight modular design for large mirrors, calculations of laser-induced orbit changes and in design of repetitive, multi-kilojoule lasers, that build on inertial fusion research] now suggest that laser orbital debris removal (LODR) is the most cost-effective way to mitigate the debris problem" (Phipps, 2012).

The remainder desires the cleanup of the orbits, the reversal of present conditions and eventually maintaining prevention of space debris. They believe that "[t]he risk to active satellites and the need for avoidance maneuvering have increased dramatically in the past few years." With "[r]ecent analyses on the instability of the orbital debris population in the low Earth orbit (LEO) region and the collision between Iridium 33 and Cosmos 2251 [having] reignited interest in using active debris removal (ADR) to remediate the environment" (Liou, 2011). While practice of passive debris mitigation tactics is a good start, "active debris removal (ADR) have been presented as necessary steps to curb the runaway growth of debris in the most congested orbital regimes such as low-Earth sun synchronous orbit" (Mason, 2011). In order to buck the trend of debris congestion in orbit "experts from both NASA and ESA have stated that 10 to 20 pieces of orbital debris need to be removed per year to stabilize the orbital debris environment." Figure 40 offers an illustration (Barbee, 2011).

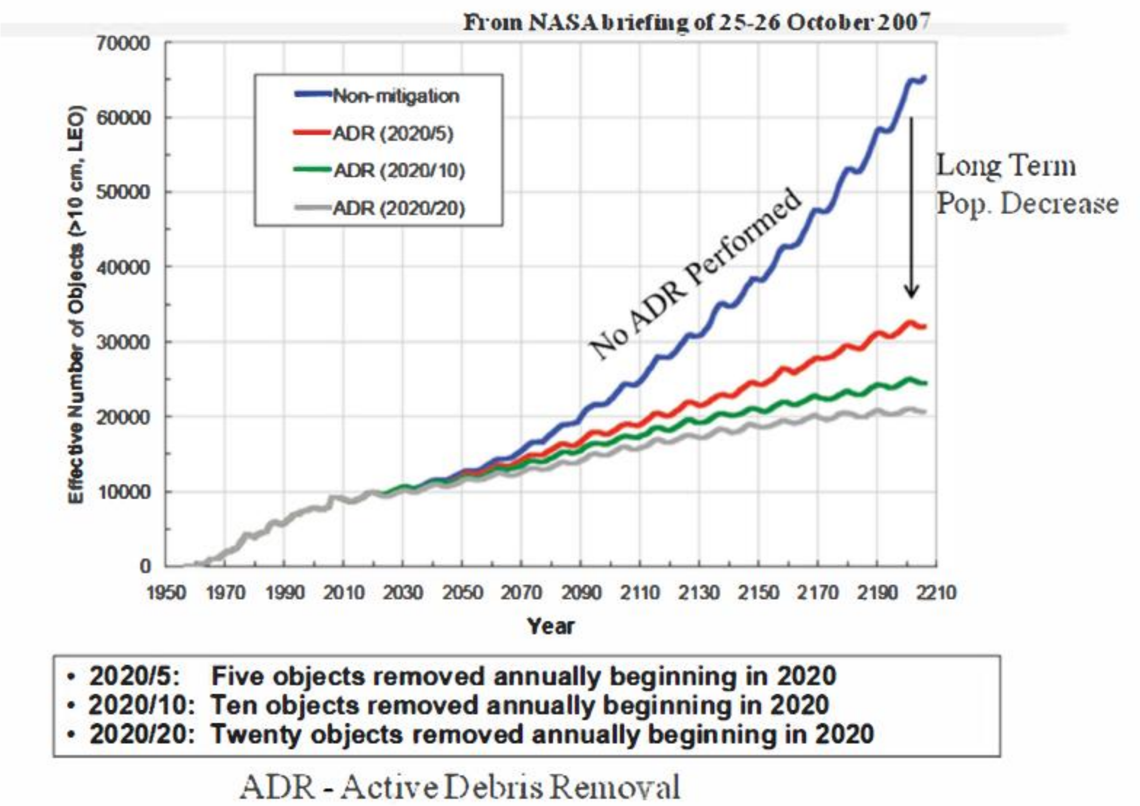


Figure 40 Potential long term benefits of large debris mitigation (Barbee, Brent William 2011)

Recognition of a Central International Agency in Regulating the Space Debris Environment

The documentation found during the literature review in the aspect of "Space Law" showed that 51% of the authors recognized a champion for space debris regulation on the global stage. The result shows a majority opinion that the space debris problem needs a leading agent, one that would rally all nations together and set the attitude toward solving the problem. One article in particular, "The 2010 US space policy: A view from Europe", attributed this leadership role to the USA due to its prominence in space activities and its substantial capabilities to develop and launch space programs (Brachet, 2011). The view, however, is unilateral and space is a multilateral foray.

The dominant commentary of many space professionals is to continue observing the currently standing institutions such as the UNCOPUOS as the primary legislative body to have the final say in regulation. This is due to the long standing relationship of these central forums with the international community, the establishment of precedence in generating space policy and the forums' composition of multinational representation (Billings, 2006; Danilenko, 1989; Christol, 1987; Goh, 2004; Swaminathan, 2005; Perek, 1994; Dos Santos, 2008; Sterns, 1990; Christol, 1990; Williamson, 2004; Yoshida, 1994; Perek, 1991; Flury, 1994; Prasad, 2005; Brachet, 2011; Viikari, 2005; Jakhu, 2009; Christol, 1994).

Nomination of an Agency Charged With Enforcing Space Debris Environment Regulation

Logically, the UNCOPUOS is the frontrunner in the minds of space professionals. Representative of this position is 48%, 19 out of the 39, of the text acknowledging UNCOPUOS to set the standards for the space debris issue. While slightly under 50%, the result exhibits a significant subset of the population of documents in the Space Law bin. It reveals that, along with the charge of leading the execution of space debris mitigation efforts, the UNCOPUOS is looked upon to set standards and policy as well. One of the 19 documents submits the USA as the notional leader in space activities and that other nations should follow suit with its standards. However, this would denote unilateral effort in tackling a global commons as previously established by the OST.

The UNCOPOUS has set precedence in setting space policy. It is the principal forum for issues concerning the space environment. Other organizations such as the International Astronautics Association and the IADC have merely advisory roles to the UNCOPUOS in both technical and policy viewpoints. The international community has proven time and time again that the UN and the UNCOPUOS remain the conduit for discourse and setting binding policy that nations observe.

Summary

This chapter conveyed the analysis and results of the study. The data points sought after in the Chapter 3 were used to evaluate the documents reviewed while performing the methodology of a meta-analysis. Table 5 and figure 42 below depict the trended values of articles matching the data points found during the review against the total number of documents found during the literature search which is displayed in table 6.

Table 5 Trended Values Of Articles Matching Data Points

Data Point	**Number of Articles**	**Percentage**
Prioritization of Space Debris Mitigation Targeting	23	46
Promotion of active debris removal	21	42
Recognition of Central International Agency in Regulating the Space Debris Environment	20	51
Nomination of an agency charged with enforcing space debris environment regulation	19	48

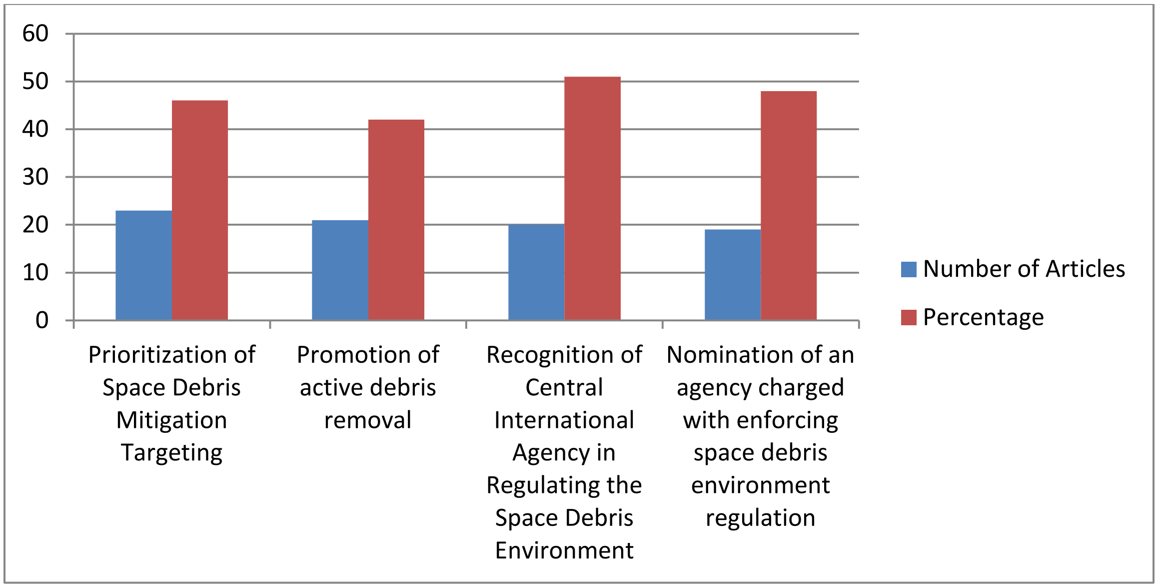


Figure 41 Graph of Trended Values Of Articles Matching Data Points

Table 6 Number of Documents by Bin

Bin	**Number of Articles**
Space Debris Mitigation	49
Space Debris Characterization	15
Space Law	39

V. Conclusions and Recommendations

Limitations of the Study

Several limitations are submitted by this study. Personal interviews and surveys weren’t conducted with space debris mitigation technical and legal experts. A meta-analysis regards the literature review to stand in place of a testimony. With that said, opinions expressed by those authors in the documentation collected were current as of their publishing. In addition, truth data from the testing of mitigation technologies, passive and active, were not gathered for the research. Technical experts and operators were not contacted to request any testing data from any phase of the development of mitigation methods. Another limitation of this study was that I was the sole coder for the meta-analysis. Lastly, a potential exists that a different coder would’ve coded the same documents using a different rubric. However, a coder working in collaboration would’ve been open to discussion of the data points considered and a consensus would’ve been reached prior to performing the meta-analysis.

Impacts of the Study

This study aspires to broaden the space debris mitigation efforts with respect to international cooperation and legal realms. Progress in global collaboration to tackle the space debris problem with sensible changes in international space policy is necessary to take the next step in the right direction. It also advocates the appointment of a leading organization with authority to make decisions and execute plans with respect to space debris on behalf of the international community. Furthermore, this study expands space debris research to enumerate numerous technical materiel and non materiel options to create an inclusive collection from which flexible solution sets may be drawn. Additionally, the study urges furtherance of the pursuit of an active debris mitigation regime. Lastly, the study promotes an effects based approach to space debris mitigation by prioritizing target sets according to their respective collision threat.

Technical Recommendations

The space debris mitigation guidelines put forth by the IADC and adopted by UNCOPUOS are a good start. We must move forward in our efforts to ensure spaceflight safety. The objectives this study sheds light on are to prioritize the minimization of the orbital lifetimes of large pieces of debris larger than ten centimeters and to prioritize decreasing those large pieces of debris in the LEO orbit due to its high traffic. Target debris for the former are launchers and spacecraft. The current regimen of re-orbiting or de-orbiting launchers and spacecraft at the end of mission life needs to be continued to meet this intent.

As far as ADR is concerned, the prospect of a land-based laser irradiation method for the de-orbiting of space debris should be pursued. This technology has the most promise for development testing and keeping down cost to design and develop. It also does not introduce collision risk due to space flight since it is not a space-borne asset and does not need to be launched.

Policy/Legal Recommendations

The legal or policy making aspect of the space debris discourse describes the boundaries of the technical aspect. Therefore, its definitions demand attention and effort. In the forefront, the space faring community should continue to utilize the UNCOPUOS forum for solving the space debris problem and space related issues. The international community also recognizes that the UNCOPUOS is the leading intergovernmental organization which sets policy and legislation for space related matters. This study suggests that conditions in space safety and non-binding nature of current space debris mitigation policy compel the development and endorsement of a binding UN resolution or treaty to impose the adherence of passive debris mitigation measures.

Supplementary agencies, driven by drafted UNCOPUOS policy, also should be added to enable certain functions that support the mitigation of space debris. As mentioned previously, those critical functions are enforcement of attribution and reparations for space debris related matters, monitoring of the observance of space debris mitigating techniques and mission profiles, setting of standards and evaluation of compliance, and assessment of a launching party's operational effectiveness in space debris mitigation. Namely they are proposed as an International Tribunal for Outer Space (ITOS), International Space Surveillance Agency (ISSA), and International Space Inspection Agency (ISIA), respectively. To reiterate, they would fall under the UNCOPUOS and UN OOSA for command and control. Membership in the above mentioned agencies would be an equitable representation of advanced and developing space faring nations. Assets required to carry out the mission of the ISSA, namely optical and radar sensors, would need to be shared by those who own them; that is, data for the mission set will be collected but ownership of the assets themselves remain with the original owner.

Championing of ADR necessitates sustainment. The international community should drive towards the goal of developing an effective ADR architecture. Multilateral agreements for the development of ADR need to be entered; this is to include rules of engagement upon the employment of ADR. It is a global problem that requires the attention and efforts of all mankind pursuant to the peaceful use of space. This study also solicits the concerted efforts of technical and legal groups to solve the space debris problem. The intellectual capital of professionals with deep knowledge bases of the space debris problem needs to be summoned.

Recommendations for Future Research

The mitigation and aspiration of elimination of space debris is inherently a global problem. It requires no less than the collective attention and action of the international space faring community. A lot of ground work remains before a viable solution set is reached. Further research in this problem area is still needed. In the vein of advancing laser irradiation techniques for de-orbiting large space debris, investigations in cost, placement, and mission profile should be performed. Also, world-wide sharing of modeling and sensor data should be explored to involve the combined intellectual capital of as many experts as possible. Next, we should draft a protocol for air, naval, and land safety procedures in the event a space object is de-orbited back to Earth.

From a legal standpoint, an analysis and proposal should be made for a comprehensive set of rules regarding the enforcement for the employment of passive space debris methods in space programs as part of a global effort to ensure space safety. It would ideally address certification that a space asset, to include its launch vehicle, by and large has a design for space debris mitigation mechanisms. Also, it would audit the space program for a plan in the mission profile for space debris mitigation techniques while in flight. This would be achieved via a multiphase pre-launch inspection.

Space debris poses a risk to the use of space for many functions beneficial to all mankind. Since everyone shares its benefits and it's been declared that space is the province of mankind, everyone shares the burden in solving problems or issues that arise with its use. As we strive to be good stewards of the Earth's environment, we should also strive to be good stewards of the near-Earth space environment. It's necessary to accelerate the momentum of efforts to mitigate and eventually eliminate space debris. The world is being called to action and needs to respond effectively and expediently.

Summary

This chapter concludes the study by outlining limitations and impacts. Also, recommendations from the technical, policy and legal perspectives are shared. Lastly, suggestions on further research close out the chapter. Solving the space debris problem requires a system wide approach. The system includes not only space technical issues that encompass launch operations, debris mitigation technologies, and routine spacecraft state of health maintenance, but also space policy and international relations issues as well.

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14. ABSTRACT
Space debris remains an unsolved hazard for space operators and astronomers alike. Passive debris mitigation techniques have been enumerated and codified by the UNCOPUOS and IADC and several proposals for actively mitigating space debris have been presented. However, the space debris problem requires reframing. On the way to developing a viable CONOPS, a multi-disciplinary construct for building solution sets to tackle the space debris problem must be created. It must be shaped by building blocks of active and passive debris mitigation techniques, debris characterization and law. Central considerations must be taken. First, targeting of space debris for removal must be prioritized to unite effort and to make significant reductions in the space debris threat. Next, a leading agent must be identified and empowered to act as an executor for a space debris mitigation program, passive or active. Also needed is enactment of enforcement measures to ensure space faring nations comply with binding regulations. Lastly, active space debris mitigation programs must be urged along by the international community with contributions from all nations. Aside from monetary contributions, aid can be rendered via intellectual space and manpower. We must seek the right questions to effectively solve the space debris problem.

15. SUBJECT TERMS
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