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Space Environment Management: Framing the Objective and Setting Priorities for Controlling Orbital Debris Risk

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Abstract

Interest in orbital debris risk has been on the rise in recent years, as small satellites are launched in accelerating numbers, proposals for large low-Earth orbit (LEO) constellations mature, and the orbital debris population continues to grow. Environmental models are being exercised to predict collisional risk, private equity is now supporting the development of commercial Space Situational Awareness (SSA) and Active Debris Removal (ADR) services, and debris mitigation best practices and licensing guidelines are being updated by industry groups and national administrations. These are all positive responses to an increasingly challenging space operational environment, but as is often the case, we tend to rush to solutions before adequately defining the problem we are trying to solve. The authors propose Space Operations Assurance (SOA) as a deceptively simple objective for an industry operating in a debris-laden space environment, and establish the lethal nontrackable (LNT) debris population as the primary risk to assured operations in space. The authors then make the case that SAA and Space Traffic Management (STM) alone are insufficient responses to collision risk and propose Space Environment Management (SEM), consisting of both debris mitigation and debris remediation, as a critical component of a comprehensive framework the space community can use to assess the efficacy of its efforts and to prioritize the appropriation of its resources. The paper concludes with recommendations for setting priorities and directing the community's efforts and resources.

Keywords: Space Environment Management, Space Operations Assurance, Space Situational Awareness, Space Traffic Management, Debris Mitigation, Debris Remediation

Acronyms/Abbreviations
Active Debris Removal (ADR)
European Space Agency (ESA)
Inter-Agency Space Debris Coord Committee (IADC)
International Organization for Standardization (ISO)
Lethal Nontrackable (LNT)
Low-Earth Orbit (LEO)
Space Environment Management (SEM)
Space Operations Assurance (SOA)
Space Situational Awareness (SSA)
Space Traffic Management (STM)

1. Introduction

Recent years have seen the introduction of a new era of commercial space activity, driven by technology advancements, reductions in satellite manufacturing and launch costs, and increased private equity interest. Small satellites are being launched in accelerating numbers, and proposals for large, low-Earth-orbit (LEO) constellations are becoming a reality. Meanwhile, the orbital debris population has also continued to grow, prompting heightened calls for better Space Situational Awareness (SAA), Space Traffic Management (STM), and operator coordination in conducting collision avoidance assessments and maneuvers. While preventing collisions between active satellites and the rest of the cataloged population is important, the authors believe a more comprehensive approach to managing collision risk is needed if our ultimate goal is Space Operations Assurance (SOA) in an increasingly congested environment.

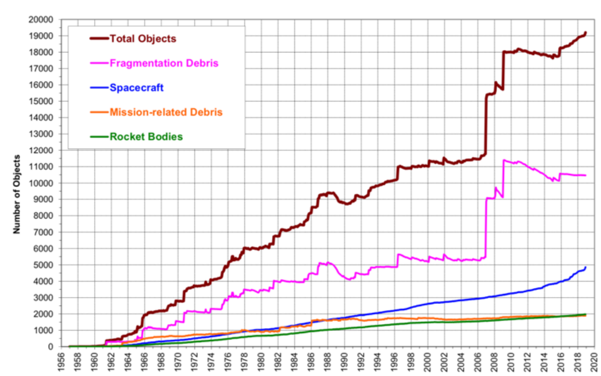

Fig. 1. Growth of the catalog of objects in Earth orbit [1]

Figure 1 illustrates the historical growth in the cataloged debris population [1] and the impact that over 60 years of space activity has had on our space environment. After nearly 5,500 launches of almost

9,000 payloads, only about 2,000 are still active today while another 3,000+ remain as orbiting refuse. In total, there is more than 8,400 metric tons of human-deposited mass in orbit [2].

Unseen are the far more numerous, so-called "lethal non-trackable" objects, or LNTs, which are too small to be cataloged but that still possess enough kinetic energy to disable a satellite upon impact. The principal sources of LNTs in LEO are the several hundred explosions of satellites and spent launch vehicle upper stages that have occurred over decades of activity, but a few collision events have contributed to the LNT population as well. LNTs represent the vast majority of mission-ending collision risk to satellites operating in LEO today, and will likely dominate the risk profile well into the future. Therefore, while STM is necessary to assure mission safety, STM alone is far from being a sufficient response to the growing challenges of operating in an increasingly congested environment.

2. Defining the Problem

Defining risk requires the consideration of both probability and consequence. The orbital population (and, therefore, collision probability) increases roughly logarithmically with decreasing object size. The damage caused by a collision in space, however (both to one's mission and to the environment) is largely driven by impact energy, making the consequences proportional to impactor size. These inverse relationships are depicted in Fig. 2, along with an indication of tracking limitations.

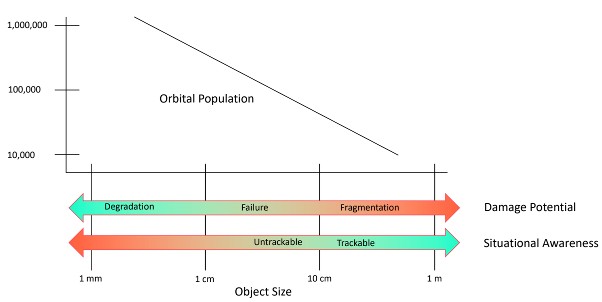

Fig. 2. Orbital debris population, impact damage potential, and tracking capabilities as a function of object size

These factors combine to paint a risk profile that looks like Fig. 3 for a typical LEO satellite. At the low-mass end of the spectrum, impact probability is very high, but satellites are inherently resilient (to varying degrees) to the sandblasting effects of very small particulates. At the right end of the spectrum, collisional consequences are high, but the probability is very low because the population is far lower, and operators generally have the capability to avoid collisions with well-tracked objects. The LNTs, however, ranging from below 1 cm to about 10 cm, remain unmitigated, and represent the vast majority of collisional risk to a LEO mission. In fact, even if no SSA or STM were employed at all, LNTs would still make up ~95-97% of the mission-terminating collisional risk to a typical LEO satellite.

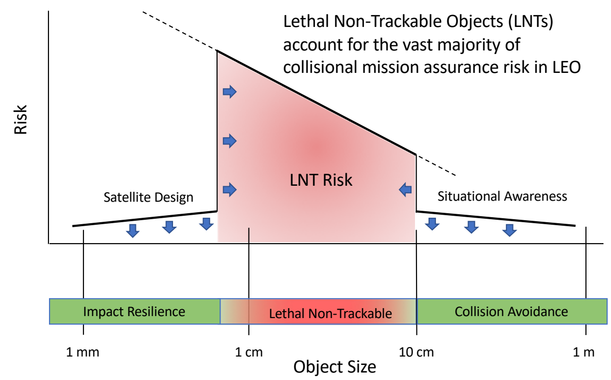

Fig. 3. Risk profile for a typical LEO satellite, illustrating limitations that improvements in satellite design and SSA have on remaining LNT risk

This risk profile can be improved, but only to marginal benefit. For example, impact resilience can be improved through enhanced satellite design techniques. Satellite components can be configured to protect critical or impact-sensitive components from direct impact, and shielding can be added to harden the spacecraft against particle penetrations. For larger objects, collision avoidance can be improved through enhanced SSA capabilities. Better tracking sensitivities and better orbit determination and propagation accuracies would enable operators to maneuver around smaller (more) objects with greater confidence.

Ultimately, however, the gap between resilience and collision avoidance limits will remain, and we are left with the challenge of managing LNT risk.

3. Space Environment Management

Since we cannot protect ourselves effectively from it, and we cannot actively avoid it, our only remaining option is to reduce the LNT population itself. It is difficult to envision ways to actively clean up LNT debris, and the only natural remediation process is orbital decay from atmospheric drag. We can, however, make significant progress in limiting the generation of more untrackable debris by adopting design and operational practices that limit the potential for new missions to become sources of debris, and by actively removing the more massive, derelict objects in LEO that represent pre-existing potential sources.

If we can agree that SOA in the presence of collisional hazards is the objective, and that SSA is the foundation upon which we build our understanding of the environment we operate in, then we can break the problem into two principal blocks. One is to operate within the existing environment, and the other is to change, or manage, the environment in which we operate. This latter block, which the authors are calling Space Environment Management (SEM), consists of mitigating the potential for new missions to create more debris (Debris Mitigation) and cleaning up pre-existing potential sources of debris (Debris Remediation).

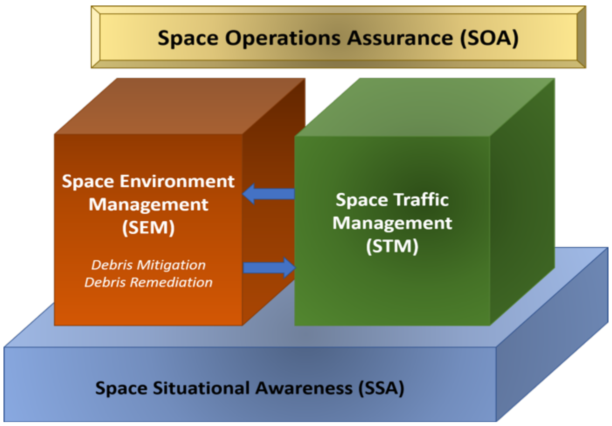

Fig. 4. A comprehensive framework for SOA in a congested environment, with SEM playing a critical role on par with STM

In this construct, depicted in Fig. 4, SSA discovers, monitors, characterizes, and distributes information about the space environment and space objects. It includes the identification of debris sources, from explosions and collisions, to surface erosion processes that create "debris wakes" associated with larger objects. SSA also characterizes physical processes that affect orbital motion, like space weather and atmospheric density variations. This used to be the exclusive domain of governments, but with the emergence of companies like LeoLabs and Exoanalytic Solutions, commercial SSA products are becoming available.

STM is the domain of operating safely within the known environment. The focus is on avoiding collisions between an operational satellite and other tracked objects. STM processes rely on SSA information for orbit predictions and conjunction notices, and when the conjunction involves another operator, STM calls for the coordination of any collision avoidance maneuvers to take place between operators. This is also the domain for data aggregators, such as the Space Data Association, which ingest operator information to facilitate operator-operator coordination.

4. Debris Mitigation

SEM consists of Debris Mitigation and Debris Remediation. Debris Mitigation outlines the responsible design and operational practices that should be implemented to minimize the impact of a mission on the environment. Debris mitigation practices were first formalized by NASA in 1995 [3], and other organizations (ESA [4], the IADC [5], ISO [6], etc.) have since adopted derivative standards. Compliance levels have been low, however, and none of these original standards committees had any way to predict the rapid acceleration of commercial space activity the industry has witnessed in recent years.

Hence debris mitigation has two challenges. One is to update recommended practices, and the other is to encourage widespread adoption. The first is being addressed in a number of fora, including inter-agency governmental working groups as well as industry associations and ad hoc groups of space sustainability stakeholders.

The second requires international coordination involving governments, regulatory agencies, and industry. Here, the authors propose a three-tiered approach, as illustrated in Table 1. At its foundational layer, a core set of minimum requirements must be established within internationally coordinated licensing regimes. These requirements represent the minimum behavioral threshold an operator must meet in order to be granted authorization to launch. It is important for these to be negotiated and normalized internationally to prevent operators from "shopping" for the most permissive licensing regime.

Table 1. Tiered approach to encouraging adoption of debris mitigation practices

Tier	Bar	Mechanism	Incentive
Aspirational	High	WEF SSR	Rating certification
Expected	Medium	Recommendations Norms Standards	Corporate image Peer pressure Contracts
Required	Low	Licensing	Permission to launch

A middle tier is where behavioral expectations are set. This is where standards, norms of behavior, and recommendations reside. IADC recommendations, ISO standards, industry association positions, and the like, all contribute to the establishment of what stakeholder expect of each other, which is often well above the minimum licensing requirements discussed above.

Finally, there needs to be an aspirational tier. This layer articulates the spirit a particular metric, and might even be evaluated on a sliding scale with an unattainable top end. The benefit of this element is to encourage industry's best behaviors by offering some sort of incentive for going above and beyond the behavioral norms. The World Economic Forum is creating the Space Sustainability Rating to do this, with a concept that missions would be evaluated against a number of metrics and awarded an environmental rating commensurate with their achievements towards pre-established, aspirational goals.

5. Debris Remediation

While all of these discussions on STM, SSA, and debris mitigation are necessary, there also needs to be an increased discussion of debris remediation, and specifically active debris removal (ADR). This need is largely motivated by the potential for existing massive derelict objects to collide and create step-increases in the LNT population. More specifically, of the nearly 2,000 derelict massive rocket bodies and payloads abandoned in LEO, a quarter of these are contained within three concentrated clusters of very large objects centered at 775, 850, and 975 km that were largely populated between 1980 and 2000. Close approaches of less than 1,000 m occur on average 1,000 times a year between objects within these three clusters.

Table 2 summarizes the general characteristics, annual probability of collision between members of each cluster (i.e., cluster collision rate), and consequences from collisions in the three most hazardous clusters. Note that C975 contains nearly four times the mass in the same altitude span as OneWeb's entire constellation of 600+ satellites. Furthermore, OneWeb has a sophisticated constellation design and collision avoidance capability while the C975 cluster members have neither!

Table 2. Characteristics of clusters of massive, derelict objects in LEO

Center of Cluster (Span)	# of Objects and Mass (kg)	PC/yr and Probability of First Collision by 2019	Mass Involved in Typical Collision	Debris Generated from Collision Trackable (LNT)	Comments
775 km (60)	101 ~100,000	~1/400 4%	~1,600 – 2,800 kg	~4,500 (~60,000)	**Most operational satellites affected**
850 km (45)	75 ~208,000	~1/800 1%	~6,000 – 18,000 kg	~16,000 (~200,000)	**Most consequential events**
975 km (115)	314 ~335,000	~1/90 11%	~1,600 – 2,800 kg	~4,500 (~60,000)	**Most likely events**

In Cluster 850 (C850), conjunctions within 5 km occur on average of about once a day, with the closest miss over the last four years being 87 m with a relative velocity of typically 12 km/s. If a collision were to occur between two objects in this cluster, the catalog population could double in an instant with the liberation of roughly 16,000 trackable fragments and 200,000 or more LNTs. These events are so consequential because 18 of the 25 most massive objects in LEO were abandoned in orbit within a 45 km altitude span. The cluster centered at 975 km (i.e., C975) has about 60 conjunctions daily within 5 km and typically has monthly conjunctions that meet or exceed the probability of collision when Iridium-33 and Cosmos 2251 collided in 2009. Each of these events would be likely to produce ~4,500 trackable fragments and upwards of 60,000 LNTs.

C775 has a moderate collision risk and a moderate consequence but is situated in LEO with one of the highest populations of operational satellites largely due to the number of satellites in sun-synchronous orbits in this altitude range and the close proximity of communications constellations (Iridium and Orbcomm). In summary, these three clusters of massive derelicts each present their own unique potential for LNT-generating events that are not being addressed by SSA, STM, or debris mitigation efforts.

A recent analysis on massive derelict objects collocated in similar orbits has been expanded to include additional clusters. Results of this ongoing analysis will be discussed in future publications ensure that future debris remediation activities are focused appropriately.

6. Conclusion

In this new era of rapidly accelerating commercial space activity holds tremendous potential for new and expanded services, technology advancements, and contributions to society (e.g., science, education, healthcare, etc.). It also elevates concern about space sustainability and the risks that increasing congestion in LEO pose to mission operations and the orbital environment.

In response, much of the public discussion has focused on increasing our collision avoidance capabilities, such as tracking accuracy, data sharing, conjunction identification and assessment, and operator-operator coordination. While these SSA and STM activities are essential for SOA, they are insufficient by themselves. For a typical mission in LEO, collision risk is dominated by the LNT population.

It is critical that we add SEM to our response to this growing threat to SOA. In addition to being able to operate safely in a given environment, we must also manage the environment itself. Broadly speaking, SEM adds, "not making the environment worse," and "actively making the environment better" to our list of priorities. The former is about updating and adopting responsible design and operational practices (Debris Mitigation), and the latter is about removing from orbit large potential sources of LNTs that already exist (Debris Remediation).

Furthermore, SEM and STM are intrinsically linked. If we do not properly manage the environment, STM gets harder and more expensive. Furthermore, if we fail to implement debris mitigation measures well, the need for active environmental remediation increases. As with any of our terrestrial environments, we must simultaneously operate in, and manage, our natural space resources if we are to preserve a sustainable orbital operating environment.

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