Space Environment Management:
A Common Sense Framework for Controlling Orbital Debris Risk

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Abstract

The primary risk to assured operations in space is the lethal nontrackable (LNT) debris population. This is the component of the orbital debris environment that is too small to see and avoid, but large enough for a collision to compromise a satellite's mission. Current space safety discussions, however, are largely dominated by concern over the trackable population, a component that represents only a very small fraction of a satellite's mission-terminating collisional risk profile.

While necessary for assured space operations, the disproportionate focus on space traffic management (STM, dealing with data sharing and collision avoidance, CA), space situational awareness (SSA, providing information on orbiting objects), and debris mitigation leads to in debris remediation being largely ignored.

The lack of emphasis on debris remediation is largely due to an unclear value proposition for it in the past and the fact that there is no organization that has the charter to deal with this issue going forward.

The authors propose establishing a new initiative called space environment management (SEM). SEM includes debris mitigation and debris remediation.

It is hoped that this paper will help to motivate countries and companies to actively pursue efforts in SEM parallel with current STM activities in both level of effort and assignment of responsibilities for execution.

1. INTRODUCTION

Space traffic management (STM) is a popular moniker today for responsible behavior in space. [1-4]

STM is largely satellite command and control (C^2) to manage the interactions between space operators and the catalog population. STM has real-time, operational needs to include, but are not limited to, reliability of spacecraft (deployment, mission operations, and retirement), defining an operating envelope (temporally, spatially, etc.), collision avoidance (involving at least one operational satellite), and automated decision support (covering all of the previous activities).

The Space Data Association (SDA) is one practitioner in this domain; their experience and insights should be considered carefully. [5]

Pursuing collision avoidance by active satellites from each other and the trackable cataloged[1] environment, however, is a necessary, but not sufficient, activity to provide space operations assurance (SOA). SOA is the condition which enables space systems to continue to function with reliability consistent with current operations and has three major enabling components: STM, space situational awareness (SSA), and space environment management (SEM).

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[1] The "satellite catalog" is a compilation by the US Air Force Combined Space Operations Center (CSpOC) of all objects in orbit about the Earth that they maintain reliable element sets of which exceed 10 cm in size in low Earth orbit (LEO) or 1 m in size in higher orbits. The catalog includes debris fragments, abandoned rocket bodies, defunct payloads, mission-related hardware, and operational satellites.

Fig. 1 depicts the overall relationship between SOA, SSA, STM, and SEM.

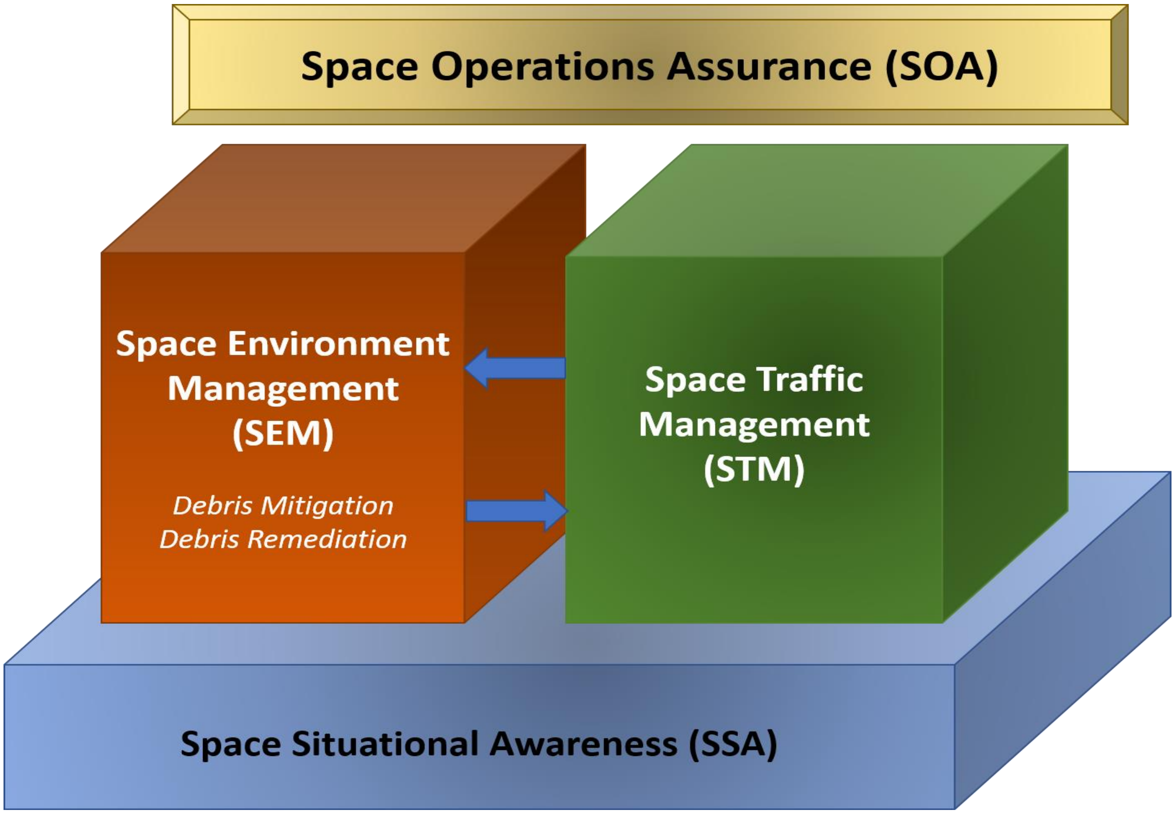

Fig. 1. Space operations assurance is the collective objective enabled by STM, SSA, and SEM.

STM is supported significantly by SSA that discovers, monitors, characterizes, and distributes information about the space environment and space objects (with an emphasis on non-operational objects since operators of active satellites normally know their own locations and characteristics better than anyone else). SSA also includes spacecraft anomaly/failure attribution analysis that is often neglected but could provide an additional means of quantifying the critical LNT population. Further, SSA seeks to characterize continuous sources of very small debris from surface erosion called "debris wakes" (i.e., localized, transient clouds of very small debris) and the migration of high area-to-mass ratio objects.

The observations gathered by SSA resources are leveraged to support uncorrelated target processing, discovery of newly created space objects, space catalog maintenance, and collision risk for individual conjunctions (for dead-on-dead and dead-on-operational while providing screening for operational-on-operational). SSA also contains, but is not limited to, space weather/predictions, debris growth modeling, statistical collision risk, and the identification of hazards that are posed "with intent" (i.e., attack) or "without" (i.e., natural hazards).

SEM activities strive to reduce debris growth, largely by preventing the addition of new debris from operations and by eliminating collisions between non-operational objects, especially clustered massive derelicts. [6] Debris mitigation prevents debris via operator actions while debris remediation focuses on preventing debris creation, especially LNT, from collisions between on-orbit derelicts.

Mitigation guidelines specifically address debris production during deployment and operations; prevention of explosions and collisions; minimizing the time after mission completion before removing an object from orbit; and reducing the risk of ground casualty due to re-entry of an object.

Remediation may occur by either removing the massive intact derelict objects or preventing them from colliding. Ways to execute this will include, but is not limited to, several debris possible remediation options: active debris removal [ADR], just-in-time collision avoidance [JCA], and Just-in-time ADR [JADR]. [7-10] Further, operational and regulatory aspects of evolving debris mitigation guidelines and nascent debris remediation work are also part of SEM activities.

It is important to understand the relationship between activities supporting SOA: failure of SEM (both mitigation and remediation) drives the population monitored by SSA assets and also directly affects space operators executing STM functions.

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SSA, STM, and SEM are normally each run by different people with different skills yet the final positive outcome of SOA depends on contributions from all of them. SOA is proposed as the overarching collective objective that is enabled by SSA, SEM, and STM as shown in Fig. 1.

Fig. 2 summarizes the contributions by each of the three pillars SSA, STM, and SEM.

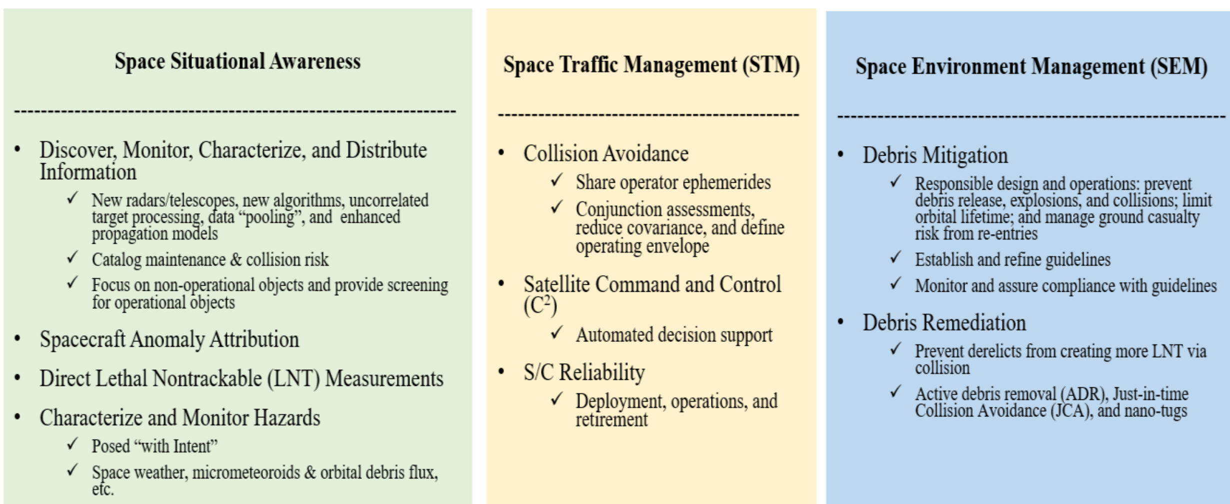

Fig. 2. STM, SSA, and SEM activities provide a complementary set of functions that support SOA.

2. NECESSARY BUT NOT SUFFICIENT

So, why is it said collision avoidance is necessary but not sufficient for SOA? That is because in low Earth orbit (LEO) the trackable population of debris represents only 3-4% of the mission-terminating collision risk from orbital debris. Due to the estimated 500,000 to 900,000 lethal nontrackable (LNT) debris particles as small as 5 mm to 10 cm in low Earth orbit (LEO), collision avoidance efforts prevent only a small fraction of the potential mission-terminating collisions from debris. Indeed, what you cannot see, can kill you.

Where has this LNT come from? It is primarily the result of hundreds of collisions and explosions in space. Most of this debris has been created by explosions of abandoned rocket stages but this will change in the future as collisions become more frequent.

How might we manage the risk from LNT? Since LNT are non-trackable and dispersed it is problematic to try to clean them up after their generation and the only natural cleansing mechanism for them is atmospheric drag which is ineffective above 800-1000 km. As a result, the only reliable or efficient means to manage LNT is to prevent them from being generated in the first place.

Debris mitigation guidelines have been in force to varying degrees for more than twenty years, yet explosions still occur and massive objects, such as used rocket stages and non-operational payloads, are still being left in long-lived orbits. Debris mitigation compliance must be improved; the compliance rate for the 25 yr re-entry threshold globally is only 15-75%, depending on how it is measured. [11] So, again, compliance to debris mitigation guidelines are also necessary, but not sufficient, for SOA.

If collision avoidance and debris mitigation are both necessary but not sufficient for SOA, what else is needed? Over half of the 10,500 rocket bodies and payloads ever deployed in space remain orbiting the Earth. Unfortunately, the story gets worse; over a third of this massive derelict population resides in the small sliver of space in the persistent portion of LEO between 600 and 2,000 km in altitude (called LEO HIGH). Objects with orbits totally below 600 km are considered to be in LEO LOW.

Fig. 3 depicts the accumulated mass of abandoned rocket bodies and defunct payloads over time for four specific orbital regions accentuating the residual debris-generating potential accumulated in LEO HIGH. Please note that the leveling off for mass is partially due to the fact that payloads deployed recently have not yet reached the end of their operational lifetime. In addition, LEO HIGH is not being used as much with new missions as LEO LOW so the leveling is partially a reflection of less use of that region relative to LEO LOW. For LEO LOW, atmospheric drag provides a cleansing mechanism for many of the objects but the objects in the lower portion of LEO HIGH will descend into LEO LOW over time due to atmospheric drag. The SEMI and GEO orbits have many fewer objects and longer mission lifetimes so there has been little increase derelict hardware in those two other critical regions in Earth orbit in the last few years.

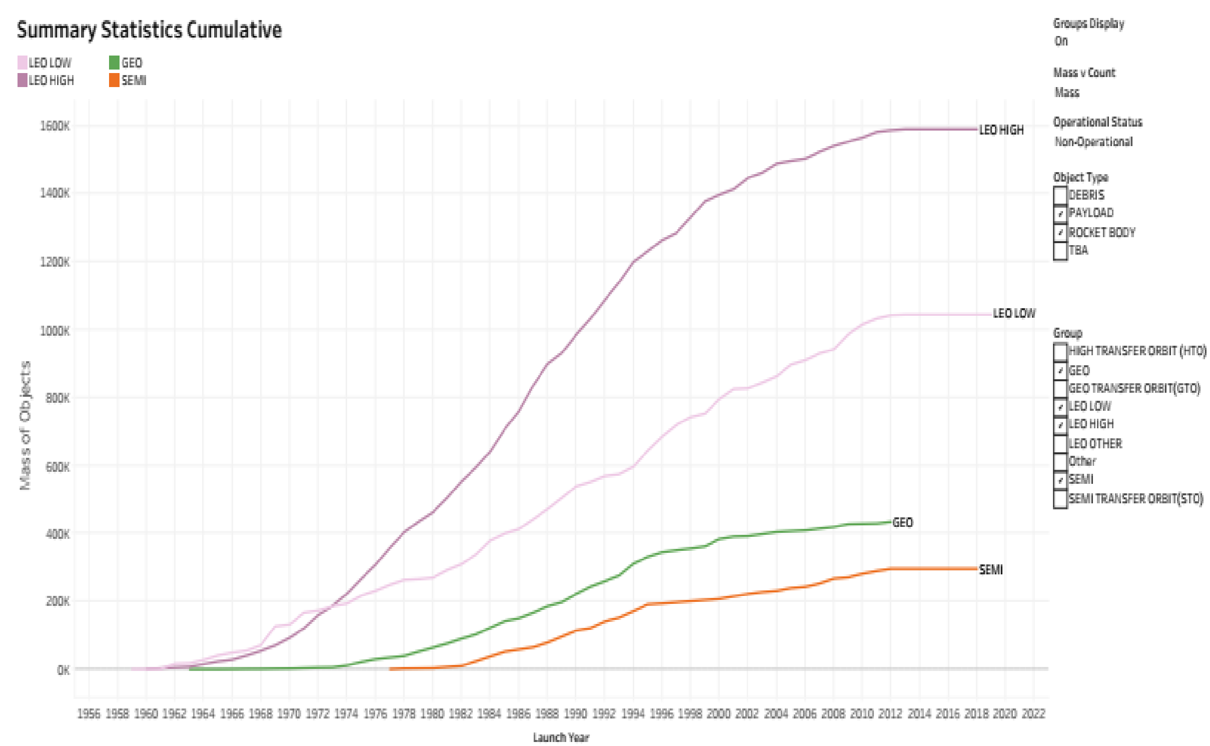

Fig. 3. The accumulated mass of intact derelicts in the upper region of LEO (i.e., LEO HIGH) is significant and is not being reduced via atmospheric drag.

(LEO HIGH is the higher part of LEO with perigee above 600 km and apogee below 2,000 km. LEO LOW are orbits under 600 km. SEMI is the semi-synchronous region from 18,000-24,000 km. GEO is geosynchronous orbit region from 35,586-35,986 km.)

Worse yet, of the nearly 2,000 derelict massive rocket bodies and payloads abandoned in LEO, a quarter of these are contained within three, even more concentrated, clusters of very large objects centered at 775, 850, and 975 km that were largely populated between 1980 and 2000. Close approaches less than 1,000 m occur on average 1,000 times a year between objects within these three clusters.

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 LNT. 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 produce about 4,500 trackable fragments and upwards of 60,000 LNT.

Tab. 1 summarizes the general characteristics, annual probability of collision (PC) 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 the proposed 588-satellite OneWeb constellation. Furthermore, OneWeb has a sophisticated constellation design and collision avoidance capability while the C975 cluster members have neither!

Tab. 1. Cluster characteristics highlight the debris-generating risk these collections of massive derelicts pose.

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**

3. SPACE ENVIRONMENT MANAGEMENT (SEM)

The risk from the concentration of massive derelicts in tight clusters in LEO potentially adding to the LNT mission-terminating collision risk is largely ignored in debris management efforts. The associated challenge is to introduce and execute a parallel thrust to STM called SEM. SEM comprises (1) continuing the critical efforts to refine and apply stringent debris mitigation guidelines and (2) proactively preventing massive collisions (i.e., debris remediation) which would potentially create large amounts of LNT.

The debris remediation part of SEM includes not only traditional active debris removal (ADR) where a derelict object is grappled, stabilized, and de-orbited but also a few new concepts. Possibly a more efficient means to prevent collisions in space is by simply nudging one of the two objects enough to avoid an imminent collision. This is called just-in-time collision avoidance (JCA). Ballistically-launched clouds of talcum powder, rocket body plumes, and space-based lasers have all been proposed for this mission. [7-10]

Another potential approach is to make the dead derelicts "alive" again by attaching a smallsat with a GPS receiver to determine its location precisely, orthogonal accelerometers to sense the derelict's stability, a beacon to warn others, and a series of electric thrusters to provide detumble & maneuver capability. This proposed system is called a nano-tug. [12]

None of these debris remediation activities is easy and none is operational, however, a number of companies are now exploring the viability of commercial on-orbit services, including active debris removal (ADR).

This set of debris remediation options is portrayed in Fig. 4.

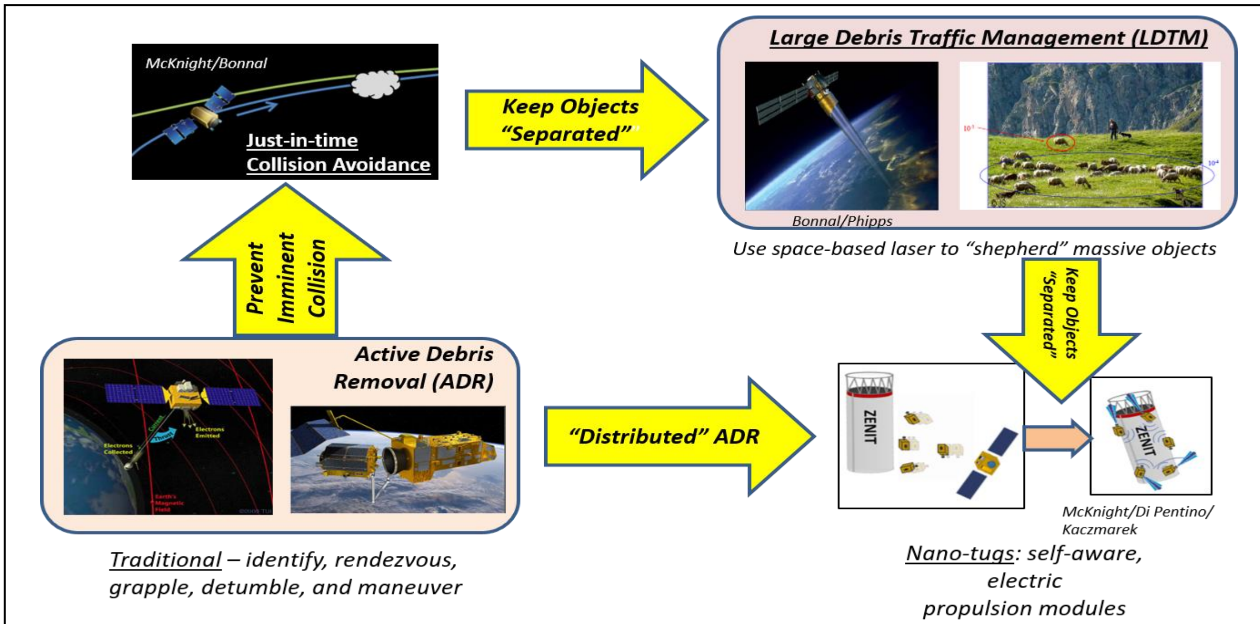

Fig. 4. There is a wide range of options under consideration for debris remediation in addition to traditional active debris removal (ADR).

4. SUMMARY

The call for establishing the new activity called space environment management (SEM) is not intended to diminish the importance of space traffic management (STM) and space situational awareness (SSA) activities. Rather, it is posing the hypothesis that for space safety, as with any domain, there needs to be three dimensions of risk management:

1. safe operations (STM),
2. do not make the environment worse (debris mitigation), and
3. make the environment better (debris remediation).

We propose SEM comprises both debris mitigation and debris remediation. Further, SSA (with improvements in tracking, anomaly attribution, and LNT measurement) constitutes a foundation for both SEM and STM components needed for space operations assurance.

While debris mitigation discussions, policy evolution, and systems solutions development have progressed, debris remediation activities have been left to a few industrial visionaries – more needs to be done! Indeed, debris mitigation and remediation are closely related since poor compliance to mitigate debris creation begets more urgency in debris remediation.

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Improvements in SSA and STM are good and necessary pieces of the puzzle, but these alone are not sufficient to assure safe space operations. A truly comprehensive approach must address the risk of large-scale LNT generation. This requires urgent leadership in funding debris remediation technology development (such as ADR, JCA, and nano-tugs) and more comprehensive execution of responsible design and operational practices across the industry, to include a strengthening of existing debris mitigation guidelines (e.g., changing the 25-yr rule to a maximum of 5 yr).

The establishment of SEM as an equally important pillar as STM to enable SOA must be coupled with assignment of responsibility for this activity to an appropriate department or agency to establish regulations and best practices; monitor performance/compliance; and execute remediation activities. Unfortunately, there have been decades of massive derelict deposition before mitigation guidelines were developed, much less implemented reliably, whereby there is already significant mass in concentrated clusters that require attention.

Space operations assurance cannot be achieved by studying, waiting, and hoping; it requires organization, governance (i.e., responsibility), and action.

As we continue to scrutinize collision avoidance, possibly at the expense of debris remediation, it reminds us of a quote from Taleb Nassim: "while we fret over the minor and the predictable, we miss the primary cataclysmic drivers since we cannot model them." [13]

5. REFERENCES

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