HOLISTIC SPACE OPERATIONS FRAMEWORK

Darren McKnight[(1)], Victoria Samson [(2)], Audrey Schaffer[(3)], and Marco Aliberti[(4)]

[(1)] LeoLabs, 4795 Meadow Wood Lane, Chantilly, VA, USA, darren@leolabs.space
[(2)] Secure World Foundation, 1779 Mass. Ave., NW, Washington, DC USA, vsamson@swfound.org
[(3)] Slingshot Aerospace, 5475 Tech Center Dr, Colorado Springs, CO, USA, audrey@slingshot.space
[(4)] European Space Policy Institute (ESPI), Schwarzenbergplatz 16, 1010 Vienna, Austria, Marco.ALIBERTI@espi.or.at

ABSTRACT

Space security, space safety, and space sustainability are often treated as independent domains of space operations. There is, however, a tight coupling between these areas that requires a thorough examination of use cases. Space safety focuses on short-term collision risk, often to operational satellites, as they attempt to conduct their missions. Many responsible behaviors for space traffic coordination are like those needed to reduce tensions related to space security. Further, space sustainability focuses on long-term collision risk to all space objects and means to promote actions that reduce the possibility of deleterious growth of lethal debris. Reducing the growth of debris contributes not only to short-term space safety but, particularly when focusing on stopping deliberately-created debris, is a factor in mitigating the possibility of space conflict.

Lastly, space security is a realm that is currently masked with lack of transparency for missions and behaviors of those space systems. More openness and discussions about capabilities that could be interpreted differently depending on the perception of the owner (e.g., the ability to grapple a space object can be seen as both a weapon and an enabler for cleaning up the debris environment) could reduce sparking events for space security. This, in turn, can enhance transparency of space activities that will in turn aid both space safety and space sustainability.

This paper examines several use cases that illustrate the connectivity between space safety, space sustainability, and space security to promote potential means to enhance all three cooperatively for the global space community.

1. INTRODUCTION

There are currently over 90 countries operating satellites in Earth orbit. These spacefaring entities span the spectrum from university-led research cubesats to massive commercial constellations providing global connectivity and almost everything in between. This diversity of missions and diversity of space operations sophistication create natural tensions from disparate objectives and expertise for space operations. As a result, misperceptions of intent are a likely outcome since consequences are so high as everyone's actions do have some measurable effect on each other as the space commons is largely a persistent environment where remnants of previous missions can linger for years to decades and possibly even for centuries.

Fig. 1 depicts the on-orbit population in low Earth orbit (LEO, i.e., average altitude below 2,000 km) which is the fastest growing region of Earth orbit due largely to deployment of constellations. However, the back story, often hidden by the ramp up of constellations, is the changing nature of these payloads and the massive derelicts left in their wake. Operational payload masses have more than halved in the last 25 years on average while the average derelict abandoned in LEO has increased about 35% in mass. So, smaller operational objects and larger orbital debris are not intuitive trends to be happening simultaneously. This illustrates the complexity of understanding the emerging dynamics in LEO considering only simple bookkeeping of objects and object mass; the situation is further complicated when adding in the complex supply chains behind deployed assets, continuing explosions of hardware on orbit, and ever more complicated regulatory realities.

As more and more countries see being "spacefaring" as a requirement for global status and an enabler for economic prosperity, the evolving regulatory, policy, and operational developments will have potentially massive effects on nation states. These rules and regulations will be complicated as the estimated global space economy is expected to approach $2T by 2035 [1].

Reliable, regular, and cost-effective access to space may be an enabler to address many terrestrial ills such as over-population, climate change, etc. A holistic framework of space operations is required to minimize accidental deleterious actions by international co-inhabitants of space and to inform all spacefaring entities about the utility of transparency and responsible behavior in space.

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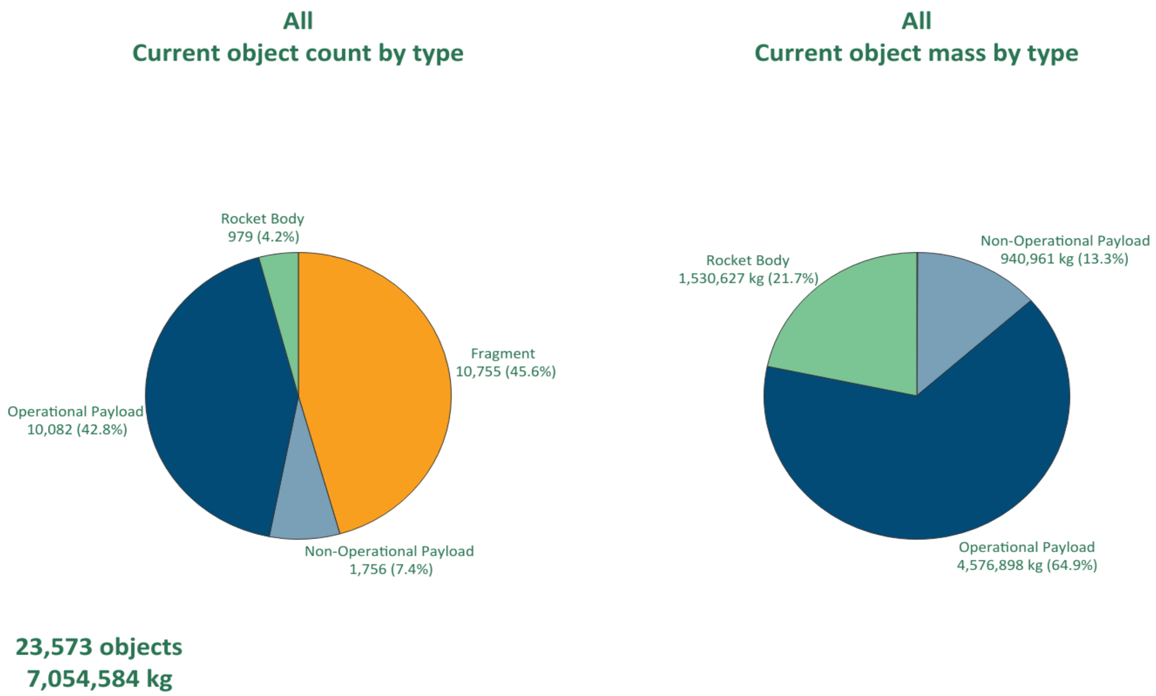

	Before 2000	After 2000
Derelict Number	2,034	701
Derelict Mass	~1.7 Mkg	~0.8 Mkg
Average Derelict	~810 kg	~1,100 kg
Average Operational Payload Mass	~1,100 kg	~450 kg

Figure 1. The LEO space object population is now driven largely by operational payloads filling out large constellations, however, the overall demographics have changed drastically over the last 25 years. The pie charts represent the LEO space object population as of 1 March 2025 from LeoLabs.

2. MOTIVATION

Fig. 2 is provided as a strawman for a comprehensive, coherent, and compelling aperture into addressing potentially accidental detrimental actions between space operators that occur because of a lack of appreciation for this interconnected "space triad" of operations. Space security primarily depends on space domain awareness to detect, identify, and track deliberate threats from other objects or operators in orbit. These threats range from reversible disruptions of satellite operations to irreversible destruction of space assets. The concerns span activities from simple identification of space assets that might pose a threat to other adversarial systems to actual aggressive close approach and attack. Space security, therefore, leverages space domain awareness (SDA).

Public research by China details how they could "disrupt" the Starlink constellation using "lasers, microwaves, and other operations," [2] it is clear that space security issues are starting to affect commercial space safety.

Space safety, which relies in part on space traffic management, is focused on assuring the reliable and safe operations of satellites. In the past, this was largely a concern of providing Conjunction Data Messages (CDM) to warn operational spacecraft of potential close approaches with orbital debris. While this is still a large part of space safety, the rapid increase in operational satellites in LEO has made the cooperation and exchange of operator ephemeris and maneuver plans between operators (i.e., space traffic coordination) a growing component of space safety to avoid collisions between operational objects.

Currently, there seems to be good coordination between a subset of constellations and single satellite operators but not between all. Part of this disparity is due to varying regulatory constructs worldwide but some of it is more

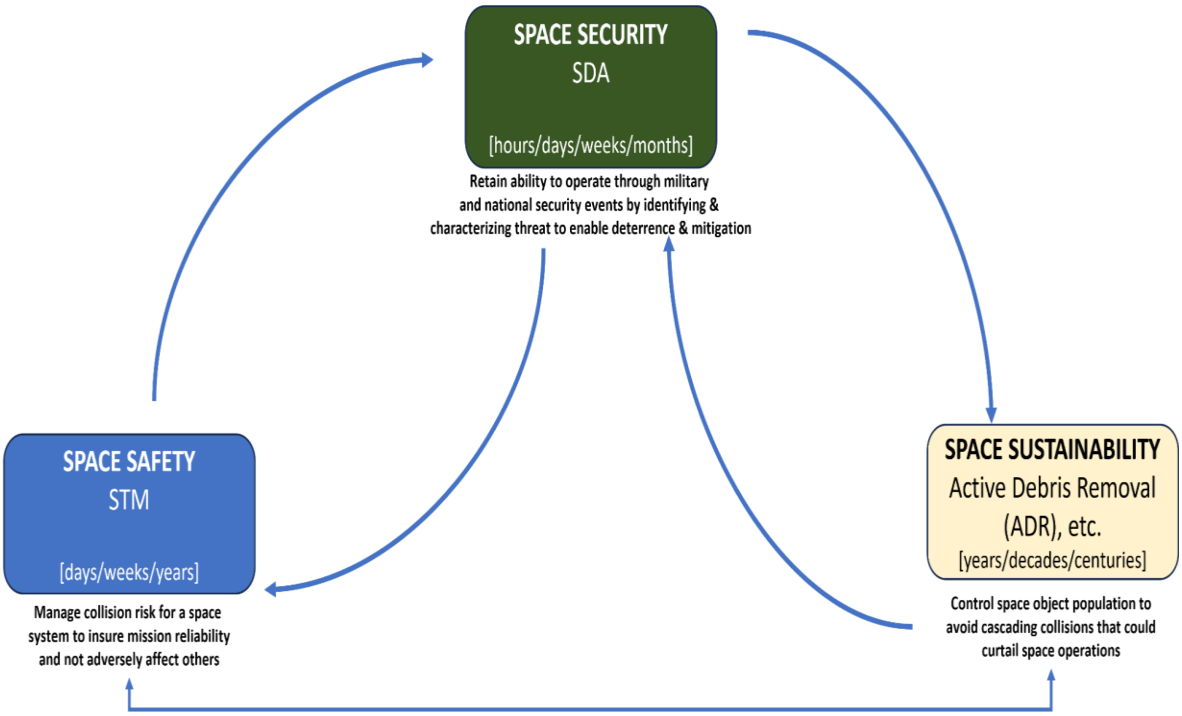

Figure 2. Space security, space safety, and space sustainability are intimately connected; if a spacefaring entity is unaware of potential linkages between these domains it may lead to increased political tension, degraded space operations reliability, and reduced economic growth globally.

fundamental to lack of trust between operators stemming from current poor diplomatic relations terrestrially.

Space sustainability principles strive to encourage behavior that will ensure long-term reliable access to space and space operations. These activities generally fall in two major categories - do not create more debris (mitigation) and remove debris that is currently residing in Earth orbit (remediation). The timeline for space sustainability outcomes is often measured in years to decades and even centuries. Unfortunately, looking too far out into the future (e.g., centuries) may be counterproductive and may obscure true interdependencies with space safety. For example, current traditional guidelines of post mission disposal (PMD) guidelines remaining at 25 years puts many of the newly deployed constellations' safety at risk. This result is clear when it is explained that an intact object will have an orbital lifetime of 25 years if abandoned at ~615 km. However, many new constellations currently operate below this altitude leaving the natural decay of derelict hardware to filter through these large constellations.

These three domains are not only different from an operational perspective but are also different from governance and economic perspectives. The diversity of timelines, regulations, and culture for the international spacefaring community adds to the potential for difficulty in identifying and resolving cross-cutting issues represented in this space operations assurance triad.

3. SPACE OPERATIONS TRIAD

The interactions between the three areas of space safety, space sustainability, and space security will now be detailed separately. These two-dimensional insights and discussion will contribute to an appreciation for a full three-dimensional (i.e., integrates all three domains together) appreciation for space operations.

3.1 Space Security - Space Sustainability

Actions taken to advance space security can impact space sustainability and vice versa. These interactions can be amplified or diminished by how a particular operation is conducted.

The most obvious example of a space security operation impacting space sustainability is the deliberate fragmentation of a space object. Three examples are the 2007 Chinese and 2021 Russian anti-satellite missile tests and the 2008 U.S. engagement of a hazardous reentering satellite. Each of these events was undertaken for security reasons; in the case of the Russian and Chinese activities, to test a direct-ascent anti-satellite missile, and in the case of the U.S. activity to protect people on Earth from hazardous chemicals onboard a satellite experiencing an uncontrolled reentry. In each case, the engagement produced many fragments – debris which could have significant impacts on the sustainability of the outer space environment.

The way these target satellites were engaged in each of these cases significantly affected each operation's impact on space sustainability. The Chinese test had the greatest impact on space sustainability. Because the test was conducted at a high altitude, over 70% of the over 3,500 fragments generated (i.e., more than 2,500 fragments) are still in orbit.

Most of these will continue to pose a collision hazard across LEO for decades or even centuries. The Russian test had a moderate impact on space sustainability. Although it too generated over 1,800 fragments, the test was conducted at a lower altitude and, as a result, only 11 remain in orbit over three years later. This event had substantial short-term space safety effects but minimal space sustainability concerns. Finally, the U.S. engagement was conducted at the lowest altitude and with an engagement geometry designed specifically to reduce long-term orbital debris, resulting in virtually no impact on space sustainability or space safety [3].

The second oft-cited example of the intersection between space security and space sustainability is the development, testing, and operation of on-orbit servicing and active debris removal spacecraft. Servicing a satellite or removing it from orbit requires technologies and techniques such as capturing another satellite, deliberately modifying it, and potentially even changing its orientation and/or orbit. These kinds of space sustainability activities are essential because they can reduce the number of defunct objects on orbit, minimizing the possibility of a catastrophic collision and reducing crowding in the most useful orbits.

The same capabilities used for space sustainability missions, however, can also be used uncooperatively to harm a satellite by deliberately damaging an on-board component or modifying the satellite's operational profile so that it can no longer perform its intended mission. Satellite operators and nation states, therefore, have become concerned that a satellite whose stated mission is active debris removal or on-orbit servicing could be used as a space weapon, thus creating a space security concern and raising tensions.

Indeed, the way these technologies are used in operations has a significant impact on the extent to which a purported space sustainability activity could impact space security. This is true for any dual-use technology. In the case of on-orbit servicing or active debris removal, transparency – or lack thereof – can lessen or raise space security concerns. Following industry best practices [4] such as sharing telemetry or video footage in real-time about the spacecraft's location and behavior can reduce the perception that a given on-orbit servicing mission is cover for something more nefarious. Furthermore, using on-orbit servicing technologies cooperatively is paramount to minimizing concerns.

For example, commercial company Astroscale conducted the ADRAS-J inspection mission [5] under contract with the Japanese government. The company undertook measures for safety and transparency based on Japanese government guidelines for spacecraft performing on-orbit servicing, shared video of its mission, and conducted proximity operations on an approved target. This approach provided interested observers with confidence that the mission was being conducted cooperatively and not intended to hide a security purpose.

Finally, when space security and space sustainability are broadly defined (i.e., having confidence that space operations can continue in perpetuity without interference) then in fact there is very little difference between space security and space sustainability. The long-term viability of space activities generally depends on individual operators believing that their satellites will be safe from harm whether that harm is accidental or purposeful. Very few operators will continue their space activities if space becomes so littered with debris or fraught with conflict that they lack confidence in their own mission. Therefore, space security and space sustainability are inextricably linked.

3.2 Space Safety - Space Security

Space safety and space security can mutually reinforce each other or work against each other, depending on the actions taken. That is why it is so crucial to fully understand how dependent they are upon each other.

A complicated space security environment can negatively affect space safety. As discussed, we have seen this in the creation of debris from anti-satellite (ASAT) tests: of the sixteen ASAT tests that resulted in debris from the beginning of the Space Age to present time, 6851 pieces of trackable debris were created [6]. Of that, 2920 trackable pieces are still in orbit creating persistent space safety challenges. It is also important to note that this is just the debris that we have been able to detect and track; there are undoubtedly fragments that are too small to detect but could have significant and deleterious impacts on spacecraft if they were to impact them.

Additionally, the debris from these ASAT tests are often kicked up to much higher orbits from the force of the impact. For example, the 2007 Chinese FY-1C ASAT test, which was held at an altitude of roughly 880 km, resulted in debris well over 3300 km [7]. The higher altitude the debris, the longer it takes to de-orbit, which means that it poses a spaceflight safety hazard for that much longer (i.e., is a space sustainability issue). Due to the physics of the space environment, any space actor – whether ally or adversary of the nation creating the debris – can be at risk from it.

More recently, for months after Russia's November 2021 ASAT test, which created over 1800 pieces of trackable debris, remote sensing satellites in Sun-synchronous orbit went through "squalls" where they had thousands of close approaches with debris from that test [8]. In August 2022, SpaceX' Starlink constellation had an event where those satellites had over 6000 close approaches to debris from Russia's test [9].

Rendezvous and proximity operations (RPO) can also have long-term effects on both space safety and security. The United States, China, and Russia have all conducted uncoordinated RPO activities near other countries' satellites; some of this may be being done to develop and enhance co-orbital counterspace capabilities, while some of it may be traced to intelligence gathering and general SSA capabilities. These uncoordinated RPOs being undertaken for space security reasons can in turn affect space safety, particularly if the satellites being approached are not aware of their proximity neighbor and inadvertently manuever in a way that increases the risk of collision.

Similarly, propulsive capability is a key enabler for space safety by enabling risk reduction maneuvers, however, maneuverability is also an enabler for most counterspace threats. The capabiloity to manage one's own collision risk may be foundation for executing counterspace threats.

As well, space security considerations can shape how spaceflight safety actions are interpreted. For example, several times in 2021, a Starlink satellite maneuvered near the Chinese space station. In a December 2021 note verbale to the United Nations, the Chinese described this maneuver as "buzzing" the Chinese space station, asserting that, in one case, if the Chinese space station had not subsequently maneuvered, the Starlink satellite in question would have come within one km of it [10].

The United States responded in its January 2022 note verbale to the United Nations that "Because the activities did not meet the threshold of established emergency collision criteria, emergency notifications were not warranted in either case," and "If there had been a significant probability of collision involving the China Space Station, the United States would have provided a close approach notification directly to the designated Chinese point of contact."

The complicated US-Chinese relationship on the ground and geopolitical rivalry in space no doubt affected how the actions were interpreted, and a case where greater transparency and communication to ensure spaceflight safety could have had positive consequences on space security overall.

There has been a traditional propensity towards secrecy for national security reasons that has been used as an excuse for poor safety practice. Within the UN COPUOS LTS this has included implementation of Guideline A.5 (registration of space objects), B1 (provision of contact information), and B.2 (dissemination of orbital info on space objects). Further, in the US, debris mitigation guidelines can be waived for mission [25]. While the exact number of these waivers is unknown, it is clear that the national security mission has at times trumped the space safety mission.

Another way in which security considerations have had effects on space safety is an artifact of the historical trend to classifying militarily sensitive objects or programs on orbit. Countries unwilling to acknowledge that national security payloads are in orbit also do not often register those objects with the UN; furthermore, orbital information about those spacecraft is not made public either. This propensity to secrecy can lead to a dereliction of space safety practices as spelled out in the UN Guidelines for the Long-Term Sustainability of Outer Space Activities.

Even innocuous steps taken to improve space safety have the potential for unintended consequences for space security. For example, SSA data collection and sharing used to be solely the provenance of state actors, and as such, states were able to keep the existence of extraordinarily sensitive national security assets more or less classified.

Now that SSA capabilities are proliferating globally, both in terms of the number of countries that can collect their own SSA observations and in the type of actors that can do so – that is to say, commercial SSA companies – this ability to keep certain kinds of satellites in the shadows is ebbing away. As well, actions and behaviors on orbit can be called out by commercial actors and used to verify if agreed-upon responsible behaviors at multilateral fora are being implemented. It should be clear: this expansion of SSA data is in the end, a very good thing for spaceflight safety; it simply may also have effects on overall space security if state actors no longer feel they can hide sensitive space operations.

Case Study: Safety Standards as Key Element to Attain Space Sustainability.

The LTS Guideline B.8 (Design and operation of space objects regardless of their physical and operational characteristics) recommends manufacturers and operators to design space objects "to implement applicable international and national space debris mitigation standards and/or guidelines to limit the long-term presence of space objects in protected regions of outer space after the end of their mission. This is also endorsed by the Space Safety Coalition (SSC). In its Best Practice 5, the SSC recommends designers to "consider means to further improve the reliability of passivation functions, including the ability to complete passivation even after loss of command or loss of contact. As shown in Fig. 3, there is a strong consensus on the potential effectiveness and long-term benefits of these measures, if fully implemented.

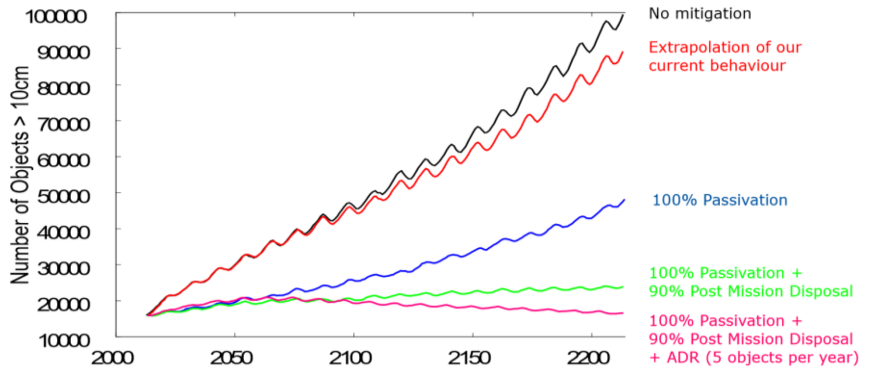

Figure 3: Effectiveness of spacecraft passivation and post-mission disposal (credit: Ref 15)

3.3 Space Safety - Space Sustainability

The connection between safety and sustainability is the most apparent one in the triad comprising the "space operations assurance enterprise." [11]. It is also the most acknowledged within the scientific literature for both general [12] and space-specific discussions. This connection is evident for operational, national, and international policymaking [11, 13-16].

Maintaining safety is in fact the first requirement to ensure the long-term sustainability of the space environment. It is no coincidence that the largest portion of the UN Long-Term Sustainability (LTS) Guidelines (Guideline B.1-B.10) deals with the promotion of national and international practices and frameworks for mitigating the safety risks associated with the conduct of space activities so that their benefits can be sustained in the long run [17].

Space safety was largely "invented" when it became clear that a space object needed to have and retain an ability to avoid collisions during operations and leave orbit at the end of its operational life. However, this is still not a requirement; though it is one of the major ways that poor space safety adversely affects space sustainability.

What differentiates the two pillars is mainly the time horizon and the configuration of interests of the actors involved. Specifically, safety is mostly concerned with short-term measures aimed at *preventing* specific outcomes through coordination, while sustainability is concerned with long-term measures aimed at *ensuring* outcomes that would not be accessible by individual actors without cooperation mechanisms [18].

The two pillars, however, remain so closely interwoven that it is barely impossible to address one without impacting the other. A few examples suffice to illustrate how safety-oriented behavior (or lack thereof) can greatly support (or impair) long-term sustainability, and vice-versa.

Performing a risk reduction maneuver in case of conjunction assessment is paramount not only to prevent possible damage, including the loss of critical functions or even the termination of a mission, but also to prevent the generation of new debris and minimize the risk of successive (and potentially cross-contaminating) break-ups events, which today represent a key source of debris.

Over the years, several collisions between catalogued objects have been observed. In the case of the Cosmos 2251 and Iridium 33 collision in 2009, over 2300 fragments have been catalogued but less than 1,000 remain in orbit today. However, as reported by ESA in its annual space environment report, collisions represent less than 1% of all past fragmentation events [19]. Fragmentations stemming from non-collisional events remain today the dominant source of space debris.

Similarly, adhering to safety standards and best practices such as the ones put forward by the Inter-Agency Space Debris Coordination Committee (IADC) today continues to "remain the most effective method to reduce the long-term environmental impacts of global space activity by slowing the rate of growth of the space debris population observed” [13].

Failure to adhere to safety standards and agreed-upon international guidelines is inevitably doomed to create an unsustainable operational environment. For instance, lack of adherence to post mission disposal thresholds can likely fuel long-term collision dynamics leading to a cascade of collision events over the next decades.

Whereas the adoption of space debris mitigation practices at a global level has been gradually improving over the past five years, both ESA and the IADC have highlighted that compliance to the IADC space debris mitigation guidelines, “is still at a too low level to ensure a sustainable environment in the long run” [13].

According to the data presented in the 2025 IADC report to COPUOS, the combined compliance rate for non-naturally compliant satellites that reached end-of-life from 2017 onwards is estimated to be 60% [13].

The report also notes that with this current level of adoption of, and compliance to, IADC guidelines, the extrapolation of current space launch activity could lead to a doubling of the space debris population in less than 50 years [13] and a substantial increase in the number of catastrophic collisions. Yet, even with a widespread adoption of the guidelines and recommendations, “environmental impacts cannot be removed completely, and additional steps should be taken, such as enabling the technology for active debris removal” [13].

If the long-term outlook of the space environment cannot be dissociated from the measures implemented in the short term, overlooking the requirements associated to sustainability-oriented behavior such as undertaking de-orbit or re-orbit through ADR can potentially harm short term space safety.

As noted in the introduction, massive derelicts abandoned at high altitudes in clusters pose a unique long-term hazard (i.e., pose a challenge to space sustainability). Short-term operational safety shortcuts of leaving rocket bodies where they had deployed their satellites has now been shown to be a poor practice [24]. The abandonment of massive derelicts in orbit can, for instance, pose direct collision hazards to operational satellites, as shown in Fig. 1.

4. OBSERVATIONS

From discussions of the individual linkages of the space triad there are several observations:

There is an inherent connection among each of the constituent elements of the space operations triad. Any action pertaining to one element will likely have ripple effects on the other two.

Space safety miscues become more relevant as hurdles to space sustainability the more mass that is involved and the higher altitude where they occur.

How one operates in space has a significant impact on the extent to which it impacts more than one of the three domains of the space triad.

There are certain activities within the three domains of our space triad that seem to be the glue that hold this holistic space operations framework together. Fig. 4 casts a new design of the space triad where the key activities in the middle cross all domains.

Placing any object in orbit that cannot take actions to avoid collisions with resident space objects is not safe. Further, leaving massive derelicts at altitudes where they may linger for decades to centuries also adversely affects hopes for a sustainable space environment.

Since the turn of the century, despite the adoption of the 25-yr rule, the rate of abandoned rocket body mass in LEO over 615 km (i.e., orbital lifetime greater than 25 yrs) has increased relative to before then. This inability to learn from our previous mistakes may haunt the LEO environment for decades to centuries.

Some good news is that destructive anti-satellite tests, while still occurring, are being executed at much lower altitudes, minimizing the safety and sustainability risks from such space security activities.

Recognizing the important nexus between the three S”, in 2020 the Journal of Space Safety Engineering introduced a new section, "Space Security, Safety, and Sustainability” with the aim to provide a platform for promoting scholarship analyzing issues at the interface of the safety, security and sustainability of space activities [14].

Similarly, in 2019 the European External Action Service (EEAS) launched a public diplomacy initiative called “3SOS”, which stands for Safety, Security and Sustainability of Space Activities, aimed at promoting discussions with industry, space agencies and think tanks to build a common understanding of the need of a ethical conduct in space [20]. Irrespective of its ill-fated outcome, the initiative demonstrates awareness of the intimate relations between safety, security and sustainability and importance of addressing them holistically.

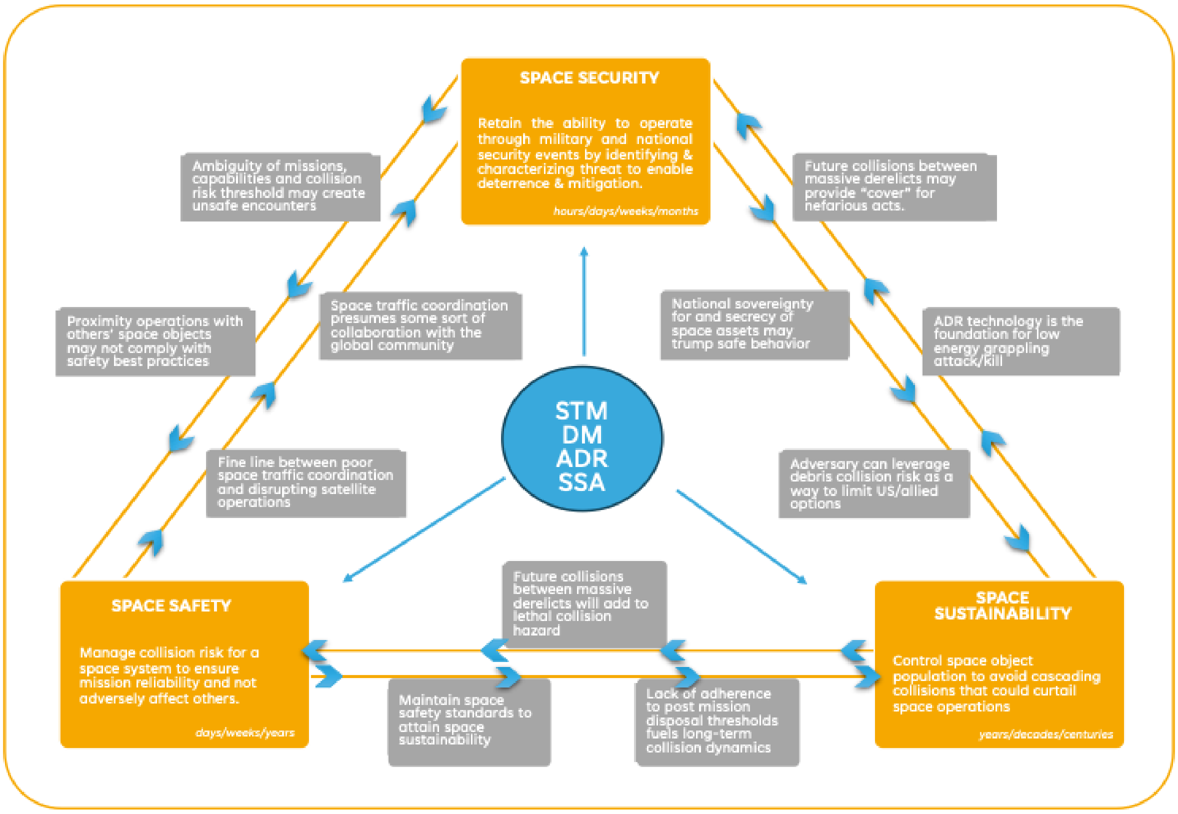

Figure 4. Four key activities (Space Traffic Management [STM], Debris Mitigation [DM], Active Debris Removal [ADR], and Space Situational Awareness [SSA]) serve as the nexus for the space safety, space sustainability, and space security domains.

In Ref. 13, the concept of "space operations assurance enterprise" is discussed to show the relationships between these elements. "Space operations assurance addresses the three critical space operations aspects of security, safety, and sustainability.

These issues are dependent on an underlying foundation of SSA capabilities, data, and information; in particular, SST. To better understand the relationships between these three aspects, consider the following. Note that these aspects—safety, sustainability, and security—may overlap in each of STM, STC, SDA, and SEP" [13].

Overall concluding message: it will not be possible to craft internationally shared, effective solutions for STM/STC, DM, ADR by ignoring the entanglements and that impact that any action or omission can have across the "three S".

Future research should address how to effectively implement a holistic space operation framework in the decision-making processes of operators, national policymakers and the diplomatic community engaged in multilateral discussions.

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23.The simulated collision configurations include two different impacting bodies (small-class 100 kg satellite, defunct rocket stage), two impact positions (glancing impact on ENVISAT radiator, collision on the central body), and two impact velocities (1 and 10 km/s). For each impact configuration, fragments area to mass, characteristic lengths, and velocity distributions are reported and the severity of different collision scenarios is discussed.

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