AEROSPACE | Space Safety Institute

2024 SPACE SAFETY COMPENDIUM

COLLABORATING FOR SUSTAINABLE SPACE FUTURES

THE AEROSPACE CORPORATION

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PURPOSE

The space enterprise is a complex environment with numerous stakeholders, areas of concern, and interlocking and overlapping interests that can impact operations and safety. Actions in any one area of this complex domain can and do directly impact other areas. This requires us to work together to build a holistic space safety approach compatible with the new space age.

The Aerospace Corporation's (Aerospace's) Space Safety Institute (SSI) leverages the corporation's expertise on space safety issues to provide more targeted and impactful thought leadership across the range of challenges described in this *2024 Space Safety Compendium*, which aims to illuminate this state of play for readers—particularly non-space professional policymakers and new space entrants. We believe that safety must be approached holistically and that we must always consider the broader implications of individual actions and policies.

This compendium consolidates and describes high-priority technical and policy considerations for the future sustainability of space operations. It discusses SSI's six focus areas in general terms, shares our extensive analysis of topics within those areas, and offers recommendations that we believe will improve overall space safety for the entire space community. Most recommendations are broad, discussing directions for further research and improvements that may yield more nuanced and mature technological and policy solutions to space safety problems in the future. In many cases, additional research is needed to better understand, and resolve, these challenges. We hope this compendium will spur that research.

A second, ongoing purpose of these periodic *Compendiums* is to solicit discussion, insights, and feedback from members of the space community and to gather their inputs and contributions on what the issues are and what the recommendations should be. Aerospace recognizes the importance of comprehensive community representation when guiding decision-making; a holistic approach to space safety requires a broad set of viewpoints and perspectives gleaned from many different stakeholders across the space enterprise. The intended audience for this *Compendium* is therefore broad—inclusive of the entire space community—though specific observations or recommendations contained within may pertain more closely to one or more subsets of the space sector.

Finally, we acknowledge that the discussion of policies and regulations in this document are largely U.S.-centric. While we do reference governance work underway in other countries and at the international level, a comprehensive assessment of international policies and regulations is beyond the scope of this document.

ACKNOWLEDGMENTS

The *2024 Space Safety Compendium* was made possible by numerous experts at the SSI who have considerable expertise in the subjects discussed herein. These experts include William Ailor, Kirsten Bauernschmidt, Danielle Bernstein, Ronald Birk, Uma Bruegman, Jordan Campbell, Grant Cates, Robin Dickey, Joseph Gangestad, Michael Gleason, Lori Gordon, Matthew Hejduk, Hunter Johnston, Robert Kalinowski, Kimberly King, Josef Koller, Catrina Melograna, Jamie Morin, Ted Muelhaupt, Anastasia Muszynski, Samira Patel, Paula Pool, Martin Ross, Marlon Sorge, David Spencer, Colleen Stover, Robert Unverzagt, Brian Weeden, Parker Wishik, and Victoria Woodburn.

We also received a significant amount of feedback from external government and industry stakeholders. We thank all those who took the time to provide feedback. Where feasible, we have incorporated many of their insights, though the conclusions represented in this document remain those of the authors and of Aerospace.

The *Compendium* has been developed in collaboration with Aerospace's Center for Space Policy and Strategy (CSPS) to produce the thought leadership pieces on space safety seen within. SSI would like to thank CSPS for kindly allowing SSI to use material from previously published policy papers, referenced throughout each chapter, as a foundation for this and other editions of the *Space Safety Compendium*.

INTRODUCTION

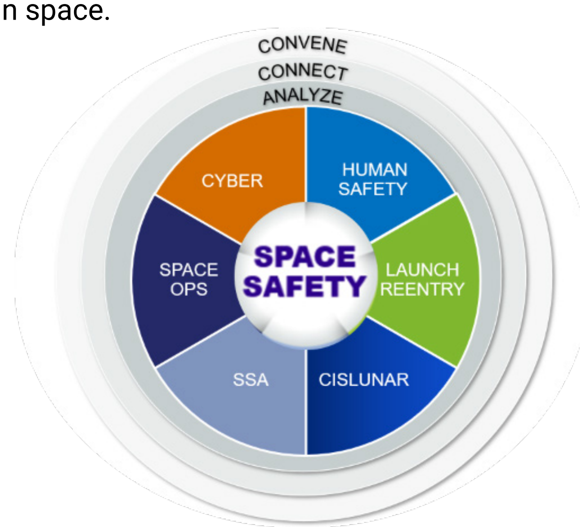
While innovation has always been a key part of humanity's spacefaring history—whether you look back a single year, three years, a decade, or back to the beginning of the Space Age—the current pace of innovation in space is unprecedented. In this decade, technological innovations and commercial exploits have emerged to change the entire fabric of the space domain. Not only is the shift from centralized, government-led space activities toward a private, industry-first model in full swing—but the vibrant commercial marketplace driving that change also continues to expand, diversify, and alter the definition of what is achievable in space.

In February 2024, we witnessed—one day apart—the first-ever commercial robotic landing on the surface of the moon (which was also the first American landing there in more than 50 years) and the first licensed commercial spacecraft to return to the United States payloads manufactured in the microgravity of space.[1, 2] More recently, SpaceX crew members conducted the first-ever commercial spacewalk as part of the Polaris Dawn mission.[3] Pursuits in space that were once the exclusive purview of governments are now accessible to private citizens and enterprises.

Unfortunately, these achievements are not the only headlines marking dynamic change in space daily. Risks are also growing, and threats are evolving, in part by virtue of the exponential growth and evolution of space activity by diverse space actors coming into increasing exposure with one another and the debris they each introduce into Earth orbit.

Space has been democratized, and there is no single profile for a space actor in 2024. They comprise established prime contractors supporting government programs, visionary investors, scrappy startups, researchers, and student groups, as well as government space agencies and military organizations from around the globe—some of whom do not share the same norms, values, risk definitions, or even terminologies for what constitutes safe space behavior. Safety, in the context of this compendium, means the ability to continue to conduct operations without undue negative consequences or broader impact on the space environment. In other words, safety is about sustaining freedom of operations in space.

Aerospace recognized the critical importance of promoting safe space activities and behaviors in a holistic, enterprise-focused way when it established the SSI in April 2021. The first edition of the *Space Safety Compendium*, published in 2022, catalyzed a debate that included public- and private-sector space stakeholders and indicated just how quickly space events were overcoming even recent research, demonstrating very clearly the urgency of addressing critical needs within the broad space safety challenge.



Today, SSI focuses on six mission areas: **space situational awareness** (observations of space activities), **space operations assurance** (activities done in space to reduce risk), **launch and reentry**, **cyber and spectrum**, **human spaceflight**, and **cislunar space**. Cislunar space is a new formal focus for SSI—our response to a clear demand signal from multiple players in the enterprise to establish a sustainable ecosystem there. It receives its own chapter within the 2024 edition of the *Compendium*, as do our other focus areas. Also new are launch and reentry safety recommendations for improving and validating reentry models, supporting research into the global impacts of spaceflight emissions, and including environmental impacts in design considerations.

Most issues and recommendations from the previous edition of the *Compendium* continue to be relevant and relatively unaddressed since initial publication, so they remain in place. For example, though the Federal Aviation Administration's (FAA's) Human Spaceflight Regulatory Moratorium, or learning period, has been continually considered by the U.S. Congress and has been extended several times, the future of the moratorium (now extended through 2024) remains a top consideration for the emerging industry as well as other members of the space community working on safety issues.

Our recommendations are time-bound and limited in scope. Space safety is both an evolving aspect of our collective space mission and a shared objective; no single individual or organization can solve the myriad questions within the broader space safety challenge alone. Several other organizations have generated similar recommendations on best practices for space operations, and we make no effort to duplicate or overwrite their dedicated work here. In many cases, Aerospace actively endorses and participates in those activities, some of which are referenced within this compendium.[4, 5, 6, 7]

Despite the vastness of space, it is a delicate, multilateral domain predicated on cooperation and partnerships enabled by safe space operations. Space is a non-zero-sum game, and the actions of any participant can affect outcomes for all. To manage this domain and address growing challenges, the space sector needs to look at a **holistic approach**, and we recommend evaluating the value a safety-dedicated consortium could bring to that goal.

As space activities continue to grow, we will also continue to look toward the future of space activities and responsible, safe behavior. The growth of the space economy and the value that space provides to society depends on safe and sustainable operations in space.

Uma Bruegman
Executive Director, Space Safety Institute
The Aerospace Corporation

SUMMARY OF RECOMMENDATIONS

SPACE SITUATIONAL AWARENESS

Recommendation 1.1: Utilize a holistic approach to space situational awareness (SSA).

Recommendation 1.2: Enhance SSA data analysis, services, and tools.

Recommendation 1.3: Reduce tracking uncertainties to make more informed space traffic coordination (STC) decisions.

Recommendation 1.4: Expand and improve the use of owner-operator data.

Recommendation 1.5: Actively explore the design and establishment of a space transponder system.

SPACE OPERATIONS

Recommendation 2.1: Continue to authorize and support the Office of Space Commerce (OSC) to perform space traffic coordination (STC) and support its rapid and effective implementation.

Recommendation 2.2: Establish mechanisms for international coordination and cooperation between stakeholders.

Recommendation 2.3: Match norm characteristics to development approaches.

Recommendation 2.4: Consider the whole lifecycle of norm development.

Recommendation 2.5: Implement a principles-based active debris removal (ADR) framework.

Recommendation 2.6: Enable commercial ventures and establish public-private partnerships to increase the technology readiness level (TRL) of ADR.

Recommendation 2.7: Encourage provisions for on-orbit servicing as a first step toward ADR.

Recommendation 2.8: Continue to promote U.S. leadership in rendezvous and proximity operations (RPO) norms development.

Recommendation 2.9: Explore the assessment of risk at the constellation level.

Recommendation 2.10: Establish performance-based regulatory approvals for constellations.

Recommendation 2.11: Promote effective post-mission satellite disposal methods to offset collision possibility.

LAUNCH AND REENTRY

Recommendation 3.1: Implement a comprehensive National Airspace System (NAS) integration strategy for launch and reentry.

Recommendation 3.2: Consider a larger risk posture to make more informed decisions regarding launch risks.

Recommendation 3.3: Design spacecraft and disposal plans to limit hazard risks.

Recommendation 3.4: Control reentry points.

Recommendation 3.5: Improve and validate reentry hazard models.

Recommendation 3.6: Implement model development strategies.

Recommendation 3.7: Develop strategies and processes to maximize data sharing.

Recommendation 3.8: Support scientific investigation of spaceflight emissions and their global impacts.

Recommendation 3.9*:* Include environmental impacts into design considerations.

CYBER AND SPECTRUM

Recommendation 4.1: Properly support and promote cybersecurity best practices.

Recommendation 4.2: Provide cybersecurity requirements and guidance on next-generation platforms.

Recommendation 4.3: Develop and deploy defense-in-depth (DiD) cybersecurity principles.

Recommendation 4.4: Integrate onboard cyber-intrusion detection and prevention techniques.

Recommendation 4.5: Apply robust supply chain risk management (SCRM) in cybersecurity and counterfeit-parts prevention planning.

Recommendation 4.6: Conduct cost-benefit analyses of spectrum sharing and reallocation.

Recommendation 4.7: Design space systems responsive to spectrum changes.

HUMAN SPACEFLIGHT SAFETY

Recommendation 5.1: Update human spaceflight mishap investigation requirements.

Recommendation 5.2: Implement a safety-case approach to human spaceflight.

Recommendation 5.3: Develop and implement a future-proof safety framework.

Recommendation 5.4: Address the in-space rescue capabilities gap.

Recommendation 5.5: Ensure that operators utilize common docking systems for spacecraft.

Recommendation 5.6: Integrate rescue plans into launch plans.

CISLUNAR SPACE SAFETY

Recommendation 6.1: Extend the nation's space situational awareness architecture to cover cislunar space.

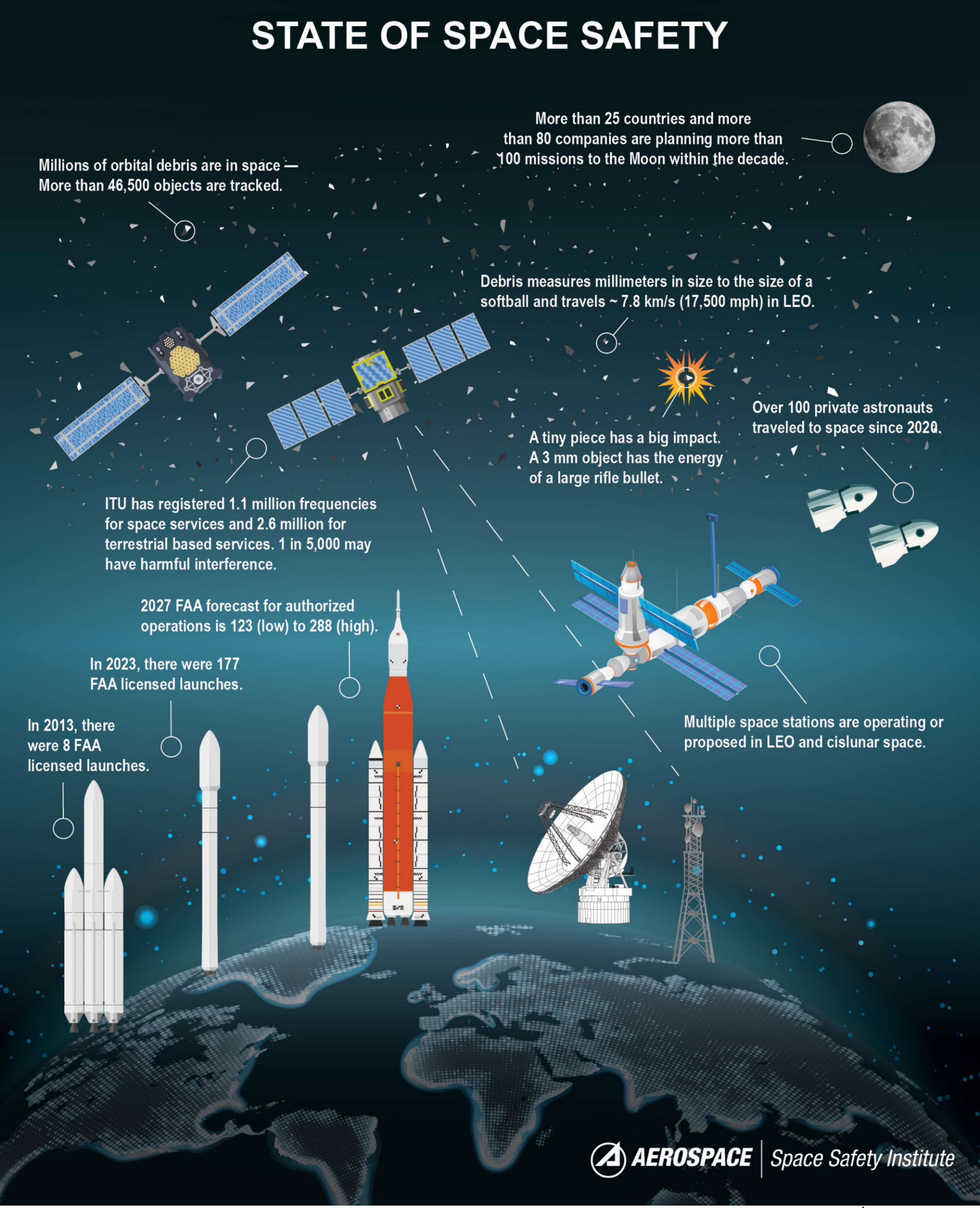
Recommendation 6.2: Develop and deploy upgraded collision-risk-assessment and risk mitigation maneuver capabilities that are valid in the cislunar regime.

Recommendation 6.3: Develop policy and requirements that address the validity and acceptability of lunar impact as a disposal option.

Recommendation 6.4: Update current disposal options to be consistent with cislunar operations.

Recommendation 6.5: Determine the viability of new disposal orbits in cislunar space and develop policy to guide their potential adoption.

Recommendation 6.6: Develop definitions of cislunar protected regions for post-mission disposal and flight safety.


STATE OF SPACE SAFETY
More than 25 countries and more than 80 companies are planning more than 100 missions to the Moon within the decade.
Millions of orbital debris are in space — More than 46,500 objects are tracked.
Debris measures millimeters in size to the size of a softball and travels ~ 7.8 km/s (17,500 mph) in LEO.
Over 100 private astronauts traveled to space since 2020.
A tiny piece has a big impact. A 3 mm object has the energy of a large rifle bullet.
ITU has registered 1.1 million frequencies for space services and 2.6 million for terrestrial based services. 1 in 5,000 may have harmful interference.
2027 FAA forecast for authorized operations is 123 (low) to 288 (high).
In 2023, there were 177 FAA licensed launches.
In 2013, there were 8 FAA licensed launches.
Multiple space stations are operating or proposed in LEO and cislunar space.
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CONTENTS

A NEW AGE OF OPPORTUNITIES AND CHALLENGES

The past decade has been marked by invigorating and exciting transformation within the space sector, with more innovation, progress, and activity than any period since the dawn of the space age in the mid-20th century. In our new space age, we are witnessing exponential growth in the number of active satellites and in the rate of launches.

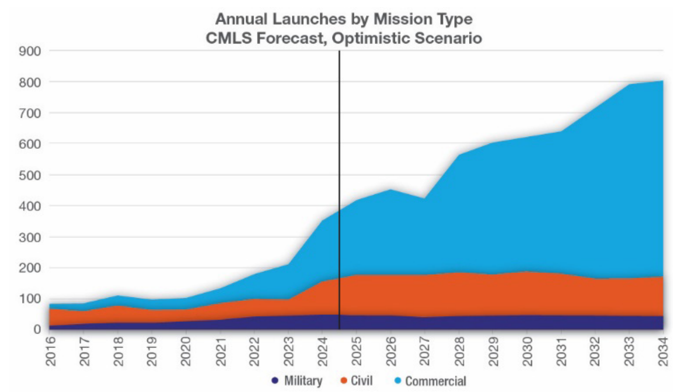

Figure 1. Worldwide launch history and forecast by sponsor type.

This era is characterized by a sharp paradigm shift from a system dominated by government investment and operations to one led by commercial space. This phenomenon is occurring worldwide, not just in the United States. Figure 1[*] shows how global commercial launches have surpassed both military and civil government launches. The story of commercial acceleration becomes even more dramatic when considering payload count, because commercial launches typically contain between dozens to more than 100 separate payloads, while military and civil systems often launch just a few payloads at a time.

Many more countries are sending payloads to orbit, often via their own launchers. In 2013, 38 countries launched 204 payloads. A decade later in 2023, 51 countries launched 2,674 payloads, a 13x increase.[†] Over a dozen countries now launch payloads using national providers. While the United States continues to dominate these statistics in both the number of payloads and the number of launches, China is steadily expanding both its government and commercial activity.

Two drivers for this new activity are the substantial drop in the cost of launch and the rise of alternative launch systems. Figure 2 shows a graphic from Our World in Data[8] illustrating the dramatic 10x drop in the cost of launching a kilogram to low Earth orbit (LEO), primarily driven by the reusability of the SpaceX Falcon 9, which has flown with exponentially greater frequency in recent years.[9] The SpaceX Starship, which completed successful suborbital test launches in March and June 2024, may drop the cost an additional order of magnitude to $10s/kg.

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[*]Data from The Aerospace Corporation's Compiled Master Launch Schedule (CMLS) as of May 22, 2024.
[†]From Spacetrack.org, May 2024.

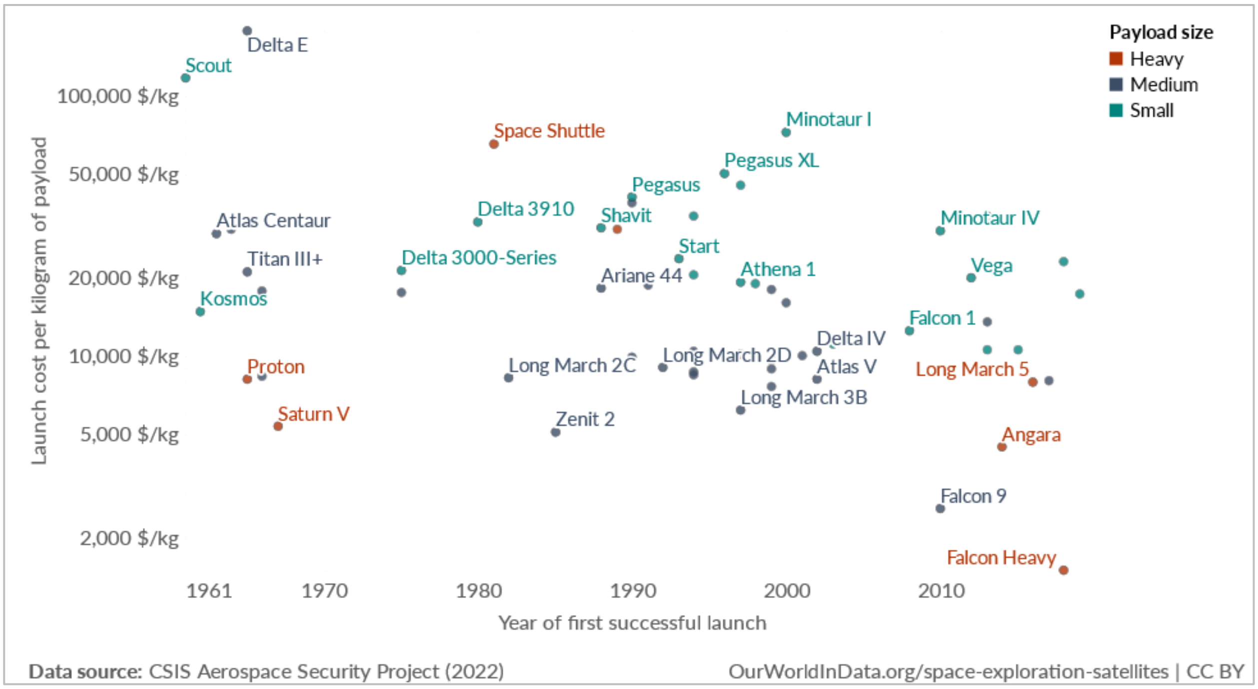


Figure 2. Cost of Launching a kilogram to LEO. Courtesy of [Our World in Data](#).[7]

This drop in cost has spurred intense competition within the burgeoning launch provider market, with virtually all providers seeking reusability, including established providers such as ULA, as well as international space organizations. The growth of additive manufacturing allows for printed engines and major vehicle components. One result has been a proliferation of launch providers for payloads of all classes, though the competition has already led some newer entrants such as Virgin Orbit to drop out of the market.

For payloads, ridesharing has become commonplace, and there have been numerous dedicated ridesharing launches. Rideshare launches may even offer services to deliver a payload to a specific orbit on these missions. There are also numerous opportunities for individual payloads to fly on host satellites, and government policy directly encourages the use of hosted payloads. At a broad stroke, there have never been more numerous or more affordable opportunities for companies, academic institutions down to the grade-school level, and even individuals to put their ideas into practice and operate and test them in space. This has been called ***the democratization of space***.

The ready availability of affordable transportation to orbit has led to an explosion of new space-based services and activity. Communication applications dominated the commercial market in the early decades of the space age, and that remains true today. However, the communication products being offered have expanded to include direct-to-device broadband internet, telephone, messaging, and machine-to-machine connectivity. Recent entrants such as SpaceX and OneWeb joined Iridium in challenging established players such as Intelsat and Viasat, and numerous competitors are in various stages of planning. Consumers now expect connectivity while traveling to other countries, on airlines, and onboard cruise ships. Space-based broadband internet can be available globally, wherever local authorities permit.

Table 1. Commercial Companies Offering Space-Based Services

Service Offered	Established	Emerging
Space-Based Imaging		
Electro-Optic (EO) imagery	26	67
Synthetic Aperture Radar (SAR)	16	34
Radio Frequency (RF) Sensing	15	21
Hyper-Spectral Imaging (HSI)	9	29
Light Detection & Ranging (LiDAR)		2
Space Situational Awareness		
Space-based SSA	2	30
Ground-based SSA	9	13
SSA Analytics	11	13
Communications		
Satellite Communications (SatCom)	23	26
Satellite Data Relay	4	12
Satellite Internet of Things (IoT)	5	25
Operations		
Satellite Alternative PNT		10
Ground Station as a Service (GSaaS)	7	3
Space-based Environmental Monitoring	1	12
Launch	19	29
Servicing, Mobility, and Logistics (SM&L)		
Satellite Propulsion Backpacks	1	6
On-orbit Refueling		14
Space Tug / Orbit Transfer Vehicle	11	31
Active Debris Removal		23
In-orbit Remove & Replace		6

Commercial imaging from space is also seeing enormous growth in electro-optical, synthetic aperture radar, and multi-spectral bands. Commercial "SIGINT-type" radio spectrum tracking, monitoring, and geolocation services are now available for the first time. Farmers and urban planners now have access to capabilities that would have been the envy of contemporaries just a half-generation ago. Table 1[10] shows that dozens of companies are already established in this market, and nearly triple that number are planning to enter it. Data consolidation and analytic services are offered to further exploit these changes. In early 2024, Privateer announced its intent to become the "Uber for space data."[11]

Table 1 also shows the growing commercial infrastructure for space operations: launch, space situational awareness, ground stations, and even an emerging capability for on-orbit serving in a variety of categories. This expanding infrastructure provides new options for mission and spacecraft designers.

New services and capabilities enable other new ventures and concepts. Ideas that were infeasible due to cost or communications limitations now become marketable. These new services build on and enable one another and create both other new services and new expectations. The designers of the Global Positioning System (GPS) and its kin were originally focused on the military applications, and surely did not imagine that pointing, navigation, and timing (PNT) services would become an essential global utility that would be in every phone and automobile.

This surge in new capabilities, possibilities, and activity in space has introduced new challenges, in part because it represents a step change from the space operations environment of previous decades. The regulatory and policy infrastructure in place today, intended to preserve safety and the public interests, was established in a very different environment. Some steps have been taken by governments to address this new environment; however, this is a work in progress, and the impact of those efforts is still to be determined. The policymaking process is innately slow and usually lags behind the needs of both the public and the industry sectors that policies govern.

Within the United States, the Department of Transportation and Department of Commerce have recently revised their regulatory frameworks for commercial launch, reentry, and remote sensing.[12] The Federal Communications Commission (FCC) is also developing new licenses to support large non-geostationary satellite orbit (NGSO) constellations, and the White House has recently published a proposal for a new framework to provide authorization and supervision for novel space activities.[13] Other countries have also been active, including the United Kingdom, Australia, New Zealand, Japan, and the European Union. Many are contemplating new initiatives for oversight of satellite servicing and active debris removal. There has been a surge of new proposals of best practices for operations and space sustainability.

One area of specific concern for the growing number of space objects is spaceflight safety and developing a system for space traffic coordination (STC) as the foundation for future Space Traffic Management (STM). In the United States, Space Policy Directive 3[14] was published in 2018 and directed the transfer of responsibility for spaceflight safety to the Department of Commerce (DoC) as the first step toward a U.S. domestic STC regime. Initial operations of the Office of Space Commerce's (OSC) Traffic Coordination System for Space (TraCSS) should begin later this year, and OSC has expressed it will maintain TraCSS in a transparent manner as an enabler of its vision for a global, coordinated space situational awareness (SSA) system.[15] As it happens, the European Union published its own "Approach to Space Traffic Management" strategy in 2022,[16] and several other countries are exploring their own national policies and regulations.

While many policy efforts are being made in good faith, there is still much uncertainty about their effectiveness. Part of this stems from the overall uncertainty of the actual risks and problems that will emerge as our collective use of outer space continues to evolve in new ways. The mere fact that much of what is happening is unprecedented creates fundamental challenges in determining what potential outcomes—negative as well as positive—may happen. At the same time, there are competing interests and substantial financial investments that are directly impacted by regulations. While there is growing consensus on some topics (e.g., transparency and data sharing), it is lacking on others.

This new era in space is creating exciting new services, opportunities, and possibilities, albeit with new challenges and uncertainties. Our challenge as a community is to embrace the benefits of this era while simultaneously preserving a safe and sustainable operations environment for everyone. Fortunately, most actors involved in this dynamic transformation offer frequent and public commitments to space safety and sustainability. The space community is actively engaged in addressing issues, as evidenced by the proliferation of best practices and shifting attitudes in norms of behavior. However, unknowns remain, and competing objectives must be balanced to ensure the continuing leadership of the U.S. space enterprise and the vitality of the space economy.

This *Compendium* seeks to illustrate and illuminate some of these challenges and includes recommendations to address them, based on the space community's collective understanding and wisdom. It is also a call for collaboration to balance competing interests and objectives, with the goal of forging a sustainable path to enable future innovation and reap the benefits of space for the benefit of all humanity.

TERMINOLOGY AND COMMUNITY FEEDBACK

To update our initial edition of the *Space Safety Compendium* from 2022, Aerospace solicited feedback on early drafts from government and industry stakeholders across the space community throughout 2024 via direct contacts and engagement activities, including a tabletop exercise at April's Space Symposium and listening sessions at the ASCEND conference in July.

We heard a common refrain from our reviewer community about using clear definitions when describing and discussing space safety issues. While laudable efforts are underway to more precisely define terminologies, create common vocabularies, and seek international consensus,[17] there is still disparity in this area. International consensus on precise terminology remains an aspirational goal, and retroactively applying any future agreement(s) on terminology to existing documents is unlikely to happen. We therefore aim to be clear on meanings and intentions within this document, but we cannot claim to be definitive for the entire community.

We define ***safety*** to mean ***the ability to continue to conduct operations without undue negative consequences or broader impact on the space environment***. Safety is about sustaining freedom of space activities and reducing risk. This usage sparked some discussion in our feedback sessions, in particular regarding the potential overlap between space ***safety*** and space ***sustainability***. From our perspective, safety is more of a near-term focus, while sustainability refers to access to and use of space over the long term. While many aspects of both space safety and sustainability intertwine, our specific intention remains for this *Compendium* to catalyze broader community discussion of the scope and boundaries of space safety.

> *"Safety" is defined as the ability to continue to conduct operations without undue negative consequences or broader impact on the space environment.*

Some reviewers thought we should narrow our definition of space safety, while others thought we should expand it. For example, it was observed that we do not address ground systems safety in this *Compendium*, though this area of work is certainly an important component of spaceflight which we will consider addressing in future research.

Another thread of discussion concerned how safety is measured, and how safe operations should be certified. This, in turn, raised the issues of who should perform certifications and how space professionals should be trained for safe operations. While these are worthy topics the community will need to address in the future, they are beyond the scope of this document. We have, however, included an initial list of safety-related training materials in the appendix.

Related to this question of scope, the impact of the increased pace and scope of space operations on astronomy and astronomical observation has fueled discussions about whether "dark and quiet skies" are a part of space safety.[18,19] By our definitions shared above, they are not safety related. However, steps to address these concerns might affect operations, and the scope of the term "space environment" could be expanded to include this kind of interference. Again, we will defer this topic to future work.

For decades, the community has used the term ***space traffic management*** (STM) as a general term for the day-to-day activity that watches objects in orbit, warns of close approaches, and facilitates actions to preserve safety and the environment.[20] It is certainly more accurate to describe current daily operations as ***space traffic coordination*** (STC), since activities of space actors are not managed in any real sense. “Management” implies authority and more broadly addresses policy and regulations and directed activity. In actuality, satellite operators are free to respond to close approach notifications as they think best. Some media outlets analogize current STC efforts with the function performed by civil air traffic controllers, and some within the community have even floated the idea of “control” as an ultimate goal.[21] Others see this as premature and problematic. However, both the U.S. Government and the European Union have clear policy goals of (eventually) moving to some form of true management of the space environment by entities and processes yet to be identified. In addition, a considerable body of writing exists that does not distinguish between these terms, and STC is a less familiar term than STM. For this reason, we will not completely avoid the use of STM, but acknowledge that it is more precise to refer to STC, particularly when discussing current operational activities.

A similar debate has also emerged within the community over the use of the term ***space situational awareness*** (SSA) following the U.S. military’s official shift to referencing ***space domain awareness*** (SDA).[22] This is not the U.S. military’s first major change in terminology on this capability: over a decade ago, Air Force Space Command evolved the term “space surveillance” to SSA.[23] Following the military’s most recent switch to SDA, many others within the community have followed suit, though the terms are not equivalent. SSA addresses where objects are, but SDA adds the dimension of “intent”. While the U.S. military’s use of SDA terminology is understandable for their specific national-security mission, there is still broad use of SSA to refer to non-national-security space dimensions, which is the focus of STC. Therefore, in the context of space safety, we will continue to use the term SSA throughout.

Similarly, there is an important distinction between the historical terms ***collision avoidance*** (COLA) and ***conjunction assessment*** (CA). In our 2022 *Compendium*, we used CA to describe a calculated close approach between two space objects and COLA to describe actions taken to mitigate the risk that a close approach will result in a collision. We can never be certain whether a given conjunction would have resulted in a collision, and indeed, the probability of collision for any given encounter is very low. Thus, in this edition we continue to use CA but have replaced COLA with ***risk mitigation maneuver*** (RMM) to better reflect the reality of current capabilities.

Finally, we also received some queries about the recommendations in this Compendium: to whom are they directed? Are they offered from the perspectives of policymakers or operators? How should they be prioritized? This discussion is exactly the purpose of this Compendium. We do not claim to be the authority on these issues; rather, we hope to spark continuing discussion about space safety and identify key areas for further work. There is no single perspective from which to view space safety. We believe a holistic approach to the topic with broad participation from the community is needed. Our recommendations are deliberately broad, and we expect them to evolve as the operations environment evolves.

1. SPACE SITUATIONAL AWARENESS

In recent years, commercial space companies have proposed, funded, and begun deployment of very large constellations of small- to medium-sized satellites. These constellations are adding greater complexity to space operations. Two dozen companies, when taken together, are planning to place nearly 90,000 satellites in orbit in the next 10 years, another 66,000 have been withdrawn, and 1 announced system would add another 337,000. For perspective, about 5,000 spacecraft had been launched in the first 60 years of the Space Age. The current total exceeds 13,000, and for the first time, the number of payloads exceeds the number of tracked fragmentation debris. This is an increase of about 50 percent from numbers cited 5 years ago.[24] It is not simply about numbers—the mass in orbit will increase substantially, and long-term debris generation is strongly correlated with mass.

By almost any metric used to measure activity in space, whether it is the number of payloads in orbit, the size of constellations, the rate of launches, the economic stakes, the potential for debris creation, or the number of conjunctions, this unprecedented growth in commercial space activity represents a fundamental change.

Although many of these large constellations may never be launched as proposed, if just half of the traffic comes to fruition, it would more than quadruple the number of payloads launched since the beginning of the Space Age. Most current space safety processes, such as space object tracking, conjunction assessment,, and debris mitigation, were designed for the previous population profile, launch rates, and density of low Earth orbit (LEO). These processes should be reconsidered based on a greater understanding of the changing space environment, and entities across the space sector have already begun such deliberations.

Space situational awareness (SSA) plays a foundational role in understanding the current space environment. SSA is broadly defined as the knowledge and characterization of space objects and their operational environment, including the process of tracking and identifying objects in space, establishing their orbits, understanding their operating environments, and predicting their future locations. SSA data is gathered by direct observation of objects in space via radars and telescopes and can also be supplied by onboard instrumentation or ranging on communications signals. Orbit propagation models are used to predict the motion of objects in space and can predict future conjunctions between objects for flight safety. Additional useful SSA insights are acquired by developing accurate and responsive tools and visualization techniques to simulate the space environment.

SSA is critical to all space safety activities, including space traffic coordination (STC), identifying operational threats, and enabling risk mitigation maneuvers. It is also critical to space domain awareness (SDA), which comprises efforts to understand the intent of other actors in current and predicted operating environments. Decisionmakers in the U.S. government and space sector use SSA and SDA to plan for future missions, warn operators of the possible threats, manage threats and uncertainty, and promote safe operations in space.

This chapter highlights several key recommendations to enable a holistic approach to SSA (see Recommendation 1.1). The recommendations include enhancing SSA data and analytics, improving satellite tracking, and accurately modeling an increasingly complicated space domain.

1.1 Compounding Effects of Better SSA, More Satellites, and New Operational Concepts

Figure 3 shows the LEO environment up to 2,000 km above Earth's surface, as a function of altitude.[25] As new constellations continue to be launched and smaller debris is tracked by the Space Fence[‡] and newer sensors, the problem of space congestion becomes more pronounced. A common feature of many of these constellations is their concentration of satellites into tightly controlled altitude regions of LEO. As can be seen by the horizontal lines representing new systems, which push far beyond the level of what is currently tracked (purple field), these new systems will alter the density of their local neighborhoods. As a result, the number of close approaches and conjunction alerts that both the constellation owners and neighboring LEO operators must address has and will continue to increase substantially as large constellations continue to be launched.

Fortunately, the operators of large LEO constellations (LLCs) recognize the challenges and are implementing procedures to cope with the new environment. Some large constellations, such as Starlink, have taken a largely autonomous approach to conjunction risk mitigation, in which conjunction assessment (CA) information is uploaded to individual satellites, and the satellites themselves make risk assessment decisions and formulate and execute mitigation maneuvers.

Autonomy can be effective in mitigating collision risk with inert objects and most strains of active payloads, but it can become problematic when two autonomous constellations occupy the same general orbital location, because both spacecraft might maneuver. In such cases, some sort of active communication between the two constellations is needed, aided by a very low-latency CA screening capability and an automated mechanism for indicating which constellation should maneuver to mitigate risk in a conjunction. Starlink and a NASA experimental constellation (ironically named Starling) have encountered this; in response, they have entered into a partnership to develop a low-latency CA screening ground node and conjunction responsibility management capability. Both constellations will submit their predicted ephemerides to the ground node, which will implement negotiated bilateral rulesets. The active experiment to demonstrate these capabilities is currently underway and is expected to conclude in December 2024. If successful, SpaceX intends to continue to operate this ground node and make it available to all interested satellite owners/operators so they can leverage the low-latency screening results to avoid close approaches among satellites from different large constellations.[26]

[‡]The Space Fence is a second-generation space surveillance system operated by the U.S. Space Force. Its mission is to track artificial satellites and orbital debris in Earth orbit. It is expected that it may track an order of magnitude more objects than the first-generation space surveillance system. Initial operations doubled the previous catalog.

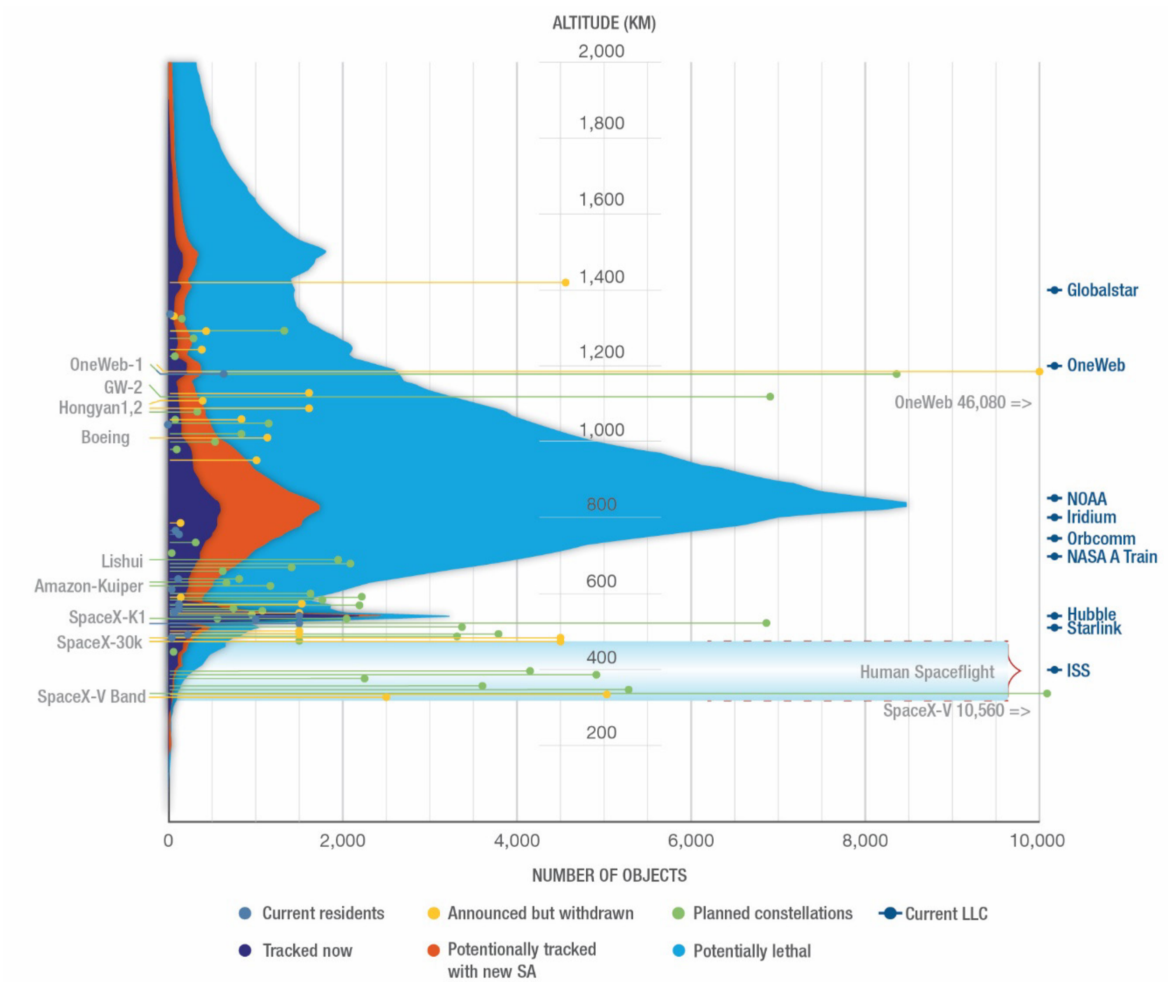


Figure 3. Objects by altitude compared to LEO residents. The purple region on the left shows what is currently tracked by the Air Force Space Surveillance Network. This includes both active satellites and debris. The orange region shows the distribution of objects potentially trackable with recent improved tracking capabilities. The blue region shows the distribution of potentially mission-ending objects down to 1 cm in size. Objects in the blue region can be observed and are estimated from models, but not specifically tracked and avoided. Background data from ADEPT[27], updated April 2024.

Even if this experiment is successful, a challenge remains to extend the lessons and techniques to other autonomous constellations, particularly non-U.S. systems. Figure 3 reveals how much of the potentially lethal population is currently untracked. Modeling and simulating the space environment is a necessary capability, given the predicted population growth in LEO satellite constellations and to further enable the safe operations of spacecraft.

In addition, it should be noted that the current space safety system relies almost entirely on the Department of Defense's (DOD's) Space Surveillance Network (SSN). Per Space Policy Directive 3 (SPD-3)[14], issued in 2018, the National Oceanic and Atmospheric Administration's (NOAA's) Office of Space Commerce (OSC) is working to transition the safety service to a civil operation that will incorporate commercial SSA data and owner-operator data into its Traffic

Coordination System for Space (TraCSS)[28]. There is also value in examining the potential contribution of satellite tracking by international partners.

Consider a predicted close-approach event with estimated significant risk. Combining data at the observation level will produce an improved state estimate for both objects, with two specific benefits to the conjunction computation. First, combining data from two geographically separated surveillance systems will likely increase the percentage of the orbit observed, which will give an overall better orbit prediction. Second, the likelihood of obtaining tracking close to the inertial position of the predicted conjunction will increase with the combined data. This can have significant safety benefits.

Recommendation 1.1: **Utilize a holistic approach to SSA.** As the space environment increases in complexity with diverse mission types and increasing congestion, it is imperative to apply a holistic approach to SSA. Risks to space operators are far more than just the objects we can see and track, which is the focus of most SSA efforts. Instead, a holistic examination of the space environment requires the space community to also understand both debris effects and the future environments created by current space activities. The space community should support the following U.S. government activities:

- Acquire and incorporate available commercial and international tracking data into TraCSS to enable improvement in SSA metrics. It is important to ensure that the quality of this data is consistent with quality of the data collected by existing operational systems.
- Explore improved algorithms for orbit determination, orbit propagation, conjunction prediction, and collision probability estimation used by the U.S. space enterprise's operations. Explore novel or nascent technologies, such as artificial intelligence.
- Support sharing of SSA data, including owner-operator data, via mechanisms such as Space-Track.org, the Unified Data Library (UDL), and TraCSS. Explore the need for developing new or novel mechanisms.
- Continue to incorporate commercial SSA data and owner-operator data into space safety processes.
- Establish norms of behavior and best practices for safe operation of space assets.
- Use the regulatory processes to encourage or even require broad information sharing.

Recommendation 1.2: **Enhance SSA data analysis, services, and tools.** An important factor for safe space operations is fully understanding the SSA data that we obtain and using it to improve decision-making.

Probability of collision (P_c) is usually considered the best single factor in deciding whether to maneuver to reduce the chance of a collision, but it is a complex calculation that can be strongly influenced by variations in SSA measurements and knowledge of the conjuncting objects.[29] A plot of daily predictions of the P_c for a given conjunction may or may not be predictive of later assessments of the probability. Figure 4 shows an innovative visualization developed by the Commercial Space Operations Center's (COMSPOC's) Center for Space

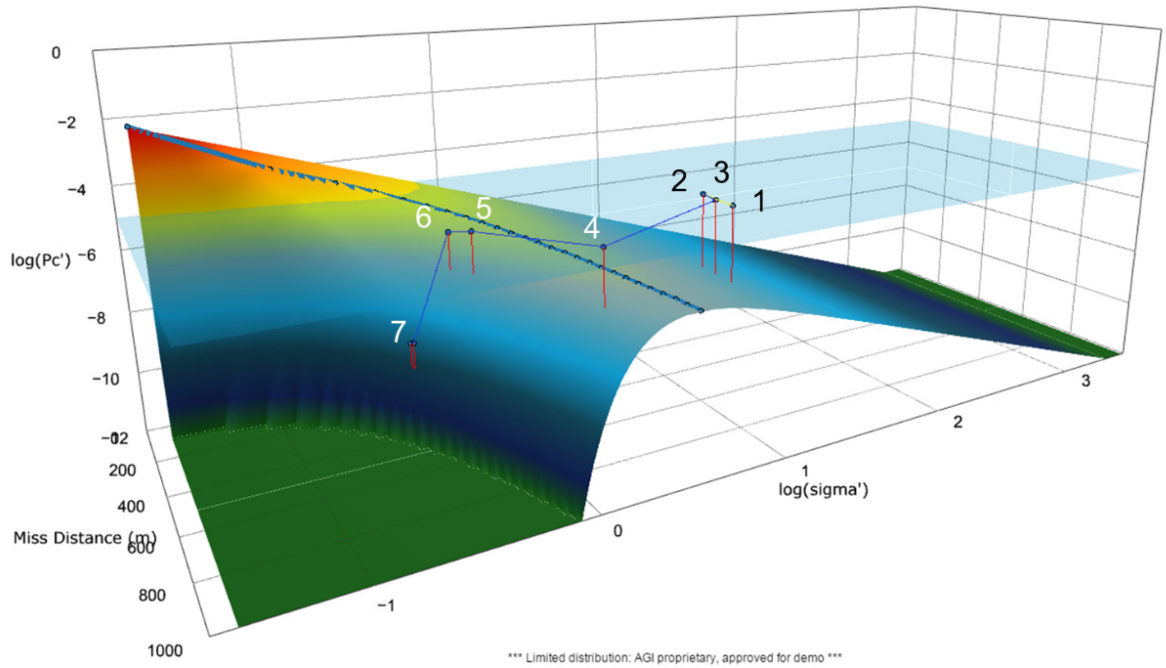


Figure 4. Visualization of the probability space for a conjunction over several days. The numbers indicate successive updates over 4.5 days. The dotted line is the maximum probability for that miss distance, and the plane is the decision threshold. The falling P_c indicates that no maneuver is necessary. [19]

Standards and Innovation (CSSI) that plots the probability in a three-dimensional space, indicating that the falling probability does not require a maneuver.

The visualization in Figure 5 provides decisionmakers with enhanced information about the situation immediately following an on-orbit breakup, yet before the actual debris from the breakup can be tracked. The on-orbit breakup is characterized by “pinch points,” where the satellite fragments from the breakup will pass through. The level of risk and the boundaries of the debris field are shown, permitting operators to understand the specific risk to their vehicles (i.e., when a vehicle is or is not at risk).

Various organizations have developed various software tools and techniques for analyzing potential collision and explosion scenarios, reentry breakups of upper stages and spacecraft, and debris objects in space. To support a holistic approach to SSA, tools should also encompass a vast array of space operations, including:

- Predicting possible collisions during launch and on orbit.
- Predicting hazards to spacecraft after collisions or explosions in space.

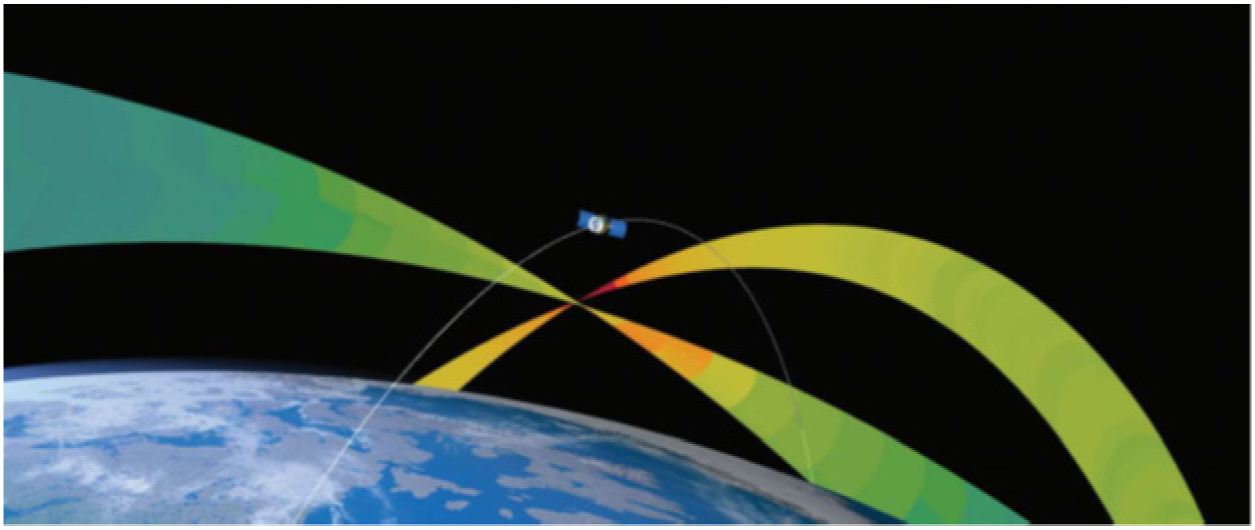


Figure 5. Visualization of the debris risk of a newly created debris field from a collision. The passage of a spacecraft near the pinch point (highest density) can be seen as safe since boundaries of the risk are also shown.[30]

- Simulating breakup of reentering debris and estimating when it might occur.
- Estimating survivability of satellite components reentering Earth's atmosphere and determining their risk to life and property.

The addition of the Space Fence and commercial SSA sensors for tracking space objects may also improve conjunction analysis to better locate currently untracked objects and improve tracking for other objects currently in space. These tools and practices enhance our understanding of SSA, STC, and space-debris impacts.

1.2 Accurate Satellite Tracking in the Era of Large Constellations

A common feature of newer large constellations is their concentration in LEO, a region where traffic density heightens risks to spacecraft residing nearby or passing through the altitudes of other satellites. Sufficiently large constellations can be seen as creating a "shell," where conjunctions with members of the shell are common. As a result, the number of conjunctions and conjunction alerts that both constellation owners and other LEO operators will have to deal with, and the need for risk mitigation maneuvers, has increased and will continue to increase.[31, 32]

One concern for some in the space community is the large number of conjunction alerts that are expected to be generated by SSA tracking systems as these satellites are operated and deorbited.[33] Studies estimate thousands of conjunction alerts occurring per day, depending on the threshold violation criteria that is selected. The goal of any SSA system is to correctly identify high risk conjunctions with sufficient accuracy to support mitigation decisions, including risk mitigation maneuvers.

Alerts should be "actionable" to the greatest extent possible. Actionable information usually means state and covariance estimates that are sufficiently accurate and durable to serve as a basis for risk assessment calculations. It is usually not taken to mean that alerts should recommend an action. Ideally, an operator would receive alerts days ahead of time to enable stronger predictions of what will be present at the maneuver commitment point, when a decision must be made. The task of risk assessment is to assimilate all this information and initiate planning activities when prudent so that the appropriate decision can be made.

It should be noted that the volume of alerts is primarily an issue for small operators and some legacy operations. New and larger systems are incorporating automation to deal with the volume of conjunction alerts and may even welcome additional, less critical alerts. Commercial SSA companies have automated this process and provided it to smaller operators as a service. Some operators of large constellations have also volunteered to take on the full burden of any risk mitigation maneuvers with their systems.[34] However, issues of "right of way" and responsibility/liability are not yet fully settled, and the question of trust remains.

Aerospace has examined the tradeoff between the level of tracking and the number of alerts for an actively managed STC system. Results indicate that it is not sufficient to reduce the uncertainty on the primary LLC satellites only; improvements are necessary for all cataloged objects. Understanding the relation between tracking accuracy and alerts is crucial in developing requirements for a future SSA system to support SPD-3.[13]

One of the concerns is that any SSA system will need to produce data products useful to spacecraft operators. If operators are overwhelmed by the number of conjunction messages they receive, the notifications may be ignored, since almost all alerts are low probability in an absolute sense. Additionally, in the past, incomplete information sharing has been an issue. For example, post-event analysis of the Iridium-33/Cosmos-2251 collision in 2009 indicates that this conjunction could have yielded a high probability of collision or an unacceptably close approach distance if current tools and processes were available.

Using the tools of the time, the probability of collision's value and the danger of the conjunction did not stand out from many other conjunctions faced by Iridium that day (Figure 6). Covariances and maneuver plans were not shared between the operators and the Joint Space Operations Center (JSpOC); only the two-line element (TLE) data for satellites common for the time was shared. Subsequent analysis[35] showed that had current practices been followed, the conjunction would have been flagged and acted upon, and planned station-keeping maneuvers might have been altered or skipped. This illustrates the importance of sharing high-quality information in a timely fashion and incorporating operator maneuver plans.

It is also important to note the significant progress the community has made since the Iridium-Cosmos collision in putting in place additional capabilities and processed to reduce the likelihood of additional collisions. The mere fact that constellations of several hundreds to thousands of satellites are operating safely in orbit today – something that was viewed by many as impossible a decade ago – should be celebrated as a major success within the community. To date, no long-term orbital debris has been generated by the large new constellations. There are still areas that need improvement, as outlined in this document, but we should not lose sight of the efforts by governments and industry to make progress since 2009.

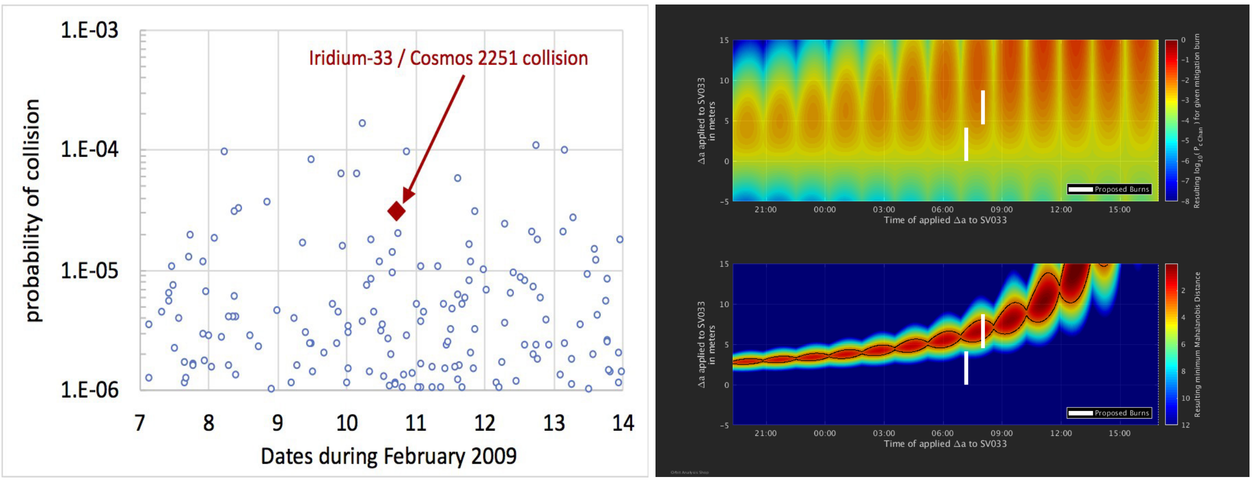


Figure 6. Two displays of the Iridium-Cosmos collision data. The display on the left shows the Iridium constellation conjunction probabilities computed during the week of February 7, 2009. Under then-current information sharing, the actual collision between Iridium-33 and Cosmos 2251 did not stand out from other conjunctions that week as being noticeably dangerous. The display on the right shows the conjunction and maneuvers using current Iridium software and higher accuracy tracking data. Current practices using full information sharing would have flagged the event.[25]

When a collision between two objects occurs and debris clouds are created, the newly created debris is relatively concentrated and may take weeks or months to be cataloged. The debris cannot be specifically avoided until it is cataloged, and it may be impossible for a spacecraft to avoid the region of the debris cloud. Even when the debris is cataloged, it may create a “debris squall” where alerts are concentrated over a short period. For example, the November 2021 Russian anti-satellite (ASAT) test created a large cloud of debris that still is actively threatening the Starlink constellation. Fortunately, Starlink automation was able to handle the load, but it could still only avoid objects that are actively tracked and cataloged. These debris clouds also pose a risk to other satellites flying in the vicinity. SpaceX reported that, in the first months since the November 2021 Russian ASAT test, their Starlink satellites had to maneuver 1,700[36] times to avoid debris from the test. Indeed, on August 6, 2022, Starlink experienced more than 6,000 close approaches, involving 841 Starlink satellites or about 30 percent of the constellation.[37]

In the two 6-month intervals between December 2022 and December 2023, Starlink satellites maneuvered 25,299 and 24,410 times, respectively, to avoid potential collisions, averaging about 1 maneuver per satellite per month.[38] Automation helped Starlink deal with the load, but less-prepared operators might be overwhelmed.

Some in industry have commented that the volume of alerts is not an issue for them, and that they consider it data. This is not necessarily the case for smaller, academic, or legacy operators whose systems were designed in an earlier era, or who are in an extended phase of their mission with limited funding, or who face other operational constraints. Regardless of the capabilities of individual operators, it is clear that timely, high-accuracy assessments that support quality decision-making are of benefit to the community.

Recommendation 1.3: **Reduce tracking uncertainties to make more informed STC decisions.** The data that SSA systems produce on satellite locations, debris, and potential collisions is integral to STC decisions that require maneuvering satellites to avoid collisions and ensure safe operations. Decreasing the size of tracking uncertainties improves the identification of collisions and reduces unnecessary alerts. Figure 7 shows how using a standard external tracking tool (shown on the left) would result in a conjunction notification and possible risk mitigation maneuvers, while smaller uncertainties using onboard data (shown on the right) would not.

Aerospace examined which kind of tracking uncertainties would have to be reduced to produce an effective STC service.[§] The study found that, in total, over 67,300 alerts per year would be generated, all in trying to properly identify 8 to 9 truly dangerous conjunctions per year. Reducing the covariance by an order of magnitude would reduce most of the unnecessary alerts and, even for the largest of the examined constellations, the number of alerts would be on the order of one every week or two. This is a much more manageable situation, particularly for legacy systems and smaller operations.[21]

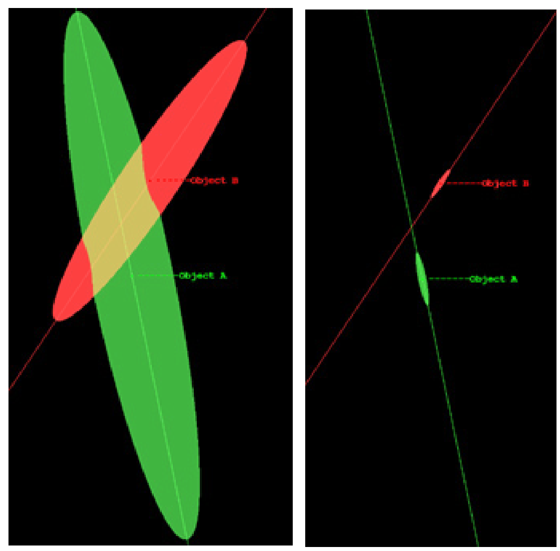


Figure 7. The covariances for a conjunction using external noncooperative tracking are compared to those from an onboard GPS receiver. The situation on the left would result in a conjunction notification and possible COLA maneuver, but the situation on the right would not trigger an alert.

However, based on the results of the simulation, in addition to improving the tracking accuracy of primary satellites by whatever means possible (e.g., internal positional determination, ground tracking, or improved tracking and dynamical models), it is necessary to also improve the tracking accuracy of other objects, such as debris and other satellites that operate in the neighboring environment (see Recommendation 1.2).

It should also be noted that orbit propagators cannot include the effects of unknown maneuvers. Even very small maneuvers reduce the accuracy of a prediction. As illustrated in the Iridium-Cosmos incident discussed previously, the effects of maneuvers must be included to identify dangerous conjunctions. Moving one of the objects a distance equivalent to its own body width (i.e., meters) is sufficient to change a collision to a very near miss, or vice versa.

[§]Aerospace looked at two different simulation backgrounds: one with the current space environment and the other with smaller objects included since inception of the Space Fence initial operational capabilities in March 2020.

Recommendation 1.4: **Expand and improve the use of owner-operator data.** Tracking new space activity and large constellations will require the use of owner-operator data. If the largest of the proposed constellations is launched, then the tracking uncertainty on all objects, including "dead" satellites and cataloged debris of all tracked sizes, may need to be on the order of meters. Tracking aids, such as transponders and owner-operator data, will help with the problem but only in a minor sense since the probability of collision is driven by both objects' uncertainty and the "dead" satellites and debris that currently dominate the population.

The last decade has also seen an increase in the number of mass deployments of satellites from a single launch. This occurs both via ride-sharing missions with dozens of payloads, such as the Indian PSLV or SpaceX's Transporter missions, and via the deployment of large constellations, such as OneWeb and Starlink. It can take a substantial amount of time for the deployed vehicles to separate sufficiently for accurate external tracking and avoiding cross-tagging (misidentification) of adjacent spacecraft. This "COLA gap[**]" can be quite problematic for systems operating in the vicinity of the deployment, including the deployed vehicles themselves. The use of onboard information can provide a substantial improvement in operational safety for these mass-deployments.

Space operators should establish and implement tracking accuracy goals on the order of meters (Figure 7). This can be accomplished by tracking enhancements, such as corner reflectors, or by using onboard GPS receivers. The accuracy of these tracking errors is time dependent—the older the tracking solution, the larger the error since drifting is not accounted for, making the uncertainty grow. The age of the tracking solution should be included in the calculation as well to further minimize the tracking errors.

In addition, risk mitigation maneuvers to date have relied on the assumption that the position of objects can be accurately predicted far into the future. This assumption no longer holds when objects actively maneuver. The most effective way to address this is by owner-operators actively sharing planned maneuver information in advance and in realtime for autonomous systems.

Note that the effective use of onboard owner-operator plans, and information implies not only that operators actively share such information but also that STC systems actively make use of the data. While standards have been declared for some data,[39] the space enterprise should continue to develop standards and processes for sharing maneuver plans, improving SSA accuracy, and collecting and making use of the information. These standards should also include sharing other information, such as hard-body radii or antenna and appendage orientation, that can reduce the need to make overly conservative assumptions.

One possibility for improvements in tracking is the use of onboard GPS to actively report an object's location, whether by broadcast or in response to a query. These space "transponders"

[**] The "COLA gap" for newly deployed vehicles should not be confused with the long-established term "LCOLA gap", which refers to pre-launch analysis and actions to avoid creating conjunctions with the ISS and other human-occupied systems, prior to the newly launched objects being cataloged. The two terms are related, but often used in different contexts.

might be equivalent to aviation's Automatic Dependent Surveillance–Broadcast, or ADS-B, system. Numerous concepts for "tagging" or identifying space objects and their locations have been proposed and tested. It seems clear that low-impact technology exists that could enable space objects to have the equivalent capability of consumer tracking devices (e.g., Apple AirTags) operated independently of the spacecraft as a fail-safe, though numerous systems engineering and policy decisions need to be explored.

Recommendation 1.5: **Actively explore the design and establishment of a space transponder system.** A system concept needs to be developed, and numerous questions addressed, primarily from the government side. Unanswered questions include:

- How are the signals collected?
- Who collects them, and when?
- How will they be used?
- What frequencies should be used?
- Are the signals encrypted?
- Who must carry these transponders?

All of this will require collaboration and cooperation between government and industry.

2. SPACE OPERATIONS ASSURANCE

Space operations are in the midst of an accelerated evolution that will only continue to expand in the coming years. New scales of operations, more diverse operators, and entirely new space missions are all being developed and implemented. The development of small satellites and nanosatellites, like CubeSats, and the use of standardized deployment systems have enabled a wider range of organizations to perform innovative space activities when previously they could not have considered operating a satellite. New missions leveraging in-space servicing, assembly, and manufacturing (ISAM) capabilities—including satellite life extension and active debris removal (ADR)—are expanding the possibilities in space and how satellites interact with each other. These new and maturing activities and capabilities have, in part, shifted the dominance in space operations from government to commercial actors, changing dominant mission priorities and operating parameters in the process.

These changes present many new opportunities but also pose different types of safety challenges on different scales than those the enterprise has previously dealt with. Balancing the potential of new space activities while maintaining a safe operating environment requires a combination of technical, organizational, legal, regulatory, and political solutions. The rapid pace of these changes means that there is little time to act on these issues before introducing and implementing new, preferred norms of behavior, which becomes onerous on existing systems.

This chapter examines issues related to the challenges of new activities in space operations, such as STM, ADR, and rendezvous and proximity operations (RPO), and proposes practical solutions.

2.1 STM: Challenges of Large Constellations and Debris

Recent space activity is stretching conventional approaches to safe space operations. In the previous chapter, we highlighted the need to improve SSA to better understand the changing space environment. This section emphasizes U.S. leadership in the development and implementation of good space traffic coordination and management based on sound SSA data to encourage safe space operations, which are intrinsically international in nature.[14]

The following recommendations for implementing effective STM and safe space operations will assist the space enterprise in establishing the organizational and technical capabilities needed to develop safe space practices.

Recommendation 2.1: **Continue to authorize and support the OSC to perform space traffic coordination and support its rapid and effective implementation.** The president's fiscal year (FY) 2023 budget pursued a significant investment of $87.7 million for the OSC to stand up a civil program with an operational SSA and STM capability to meet the U.S. commercial space industry's needs.[40] The final enacted FY 2024 budget, however, appropriated a total of $70 million to OSC after FY 2023 funding levels were extended via multiple continuing resolutions.[41] The previous budget included funding for several SSA activities, and TraCSS should create a minimum viable product by late 2024. In March, the White House released the President's FY 2025 budget, proposing $75.6 million for OSC.[42] Congress should continue to authorize funding so the OSC can ramp up its capabilities to facilitate STM coordination and SPD-3 implementation. How active the OSC is regarding the management of space traffic will in large part depend on the resources available.

Recommendation 2.2: **Establish mechanisms for international coordination and cooperation between stakeholders.** Bad actors affect all users of space. U.S. leaders should work with international allies and good-faith international counterparts to harmonize global STC practices and regulations.

Currently, few international, legally binding agreements exist that constrain a country's freedom of action in space[††] except for regulations for the use of the electromagnetic spectrum by the International Telecommunications Union (ITU), prohibitions on nuclear weapons tests in space, and a prohibition on the placement of nuclear weapons (or other weapons of mass destruction) in space. In April 2022, the United States pledged to stop testing destructive, direct-ascent ASAT missiles in a unilateral moratorium. A series of other national pledges have followed, beginning with Canada in May 2022 and, most recently, Costa Rica and Norway in October 2023, bringing the total number of states up to 37.[43] This means no state can presume to "manage" space traffic on behalf of other countries without consent and cooperation. Moreover, in the current context of growing geopolitical tension, it is difficult to foresee a new, legally binding, international treaty regime emerging to address the issues of growing space traffic. Once international mechanisms are developed, they can be used to collaboratively develop internationally accepted, voluntary standards, guidelines, and best practices between commercial, government, and international stakeholders.[44]

2.2 Building Norms as the Foundation for Space Traffic Management

Earlier in this document we discussed the reality of today's STC efforts as compared to a potential future STM regime. One of the challenges in progressing from STC to STM is developing consensus around what the "rules" should be. Many governments and industry actors alike are reluctant to sign up to specific rules at this stage in the process as there is still a large degree of uncertainty as to what the right approach is. This challenge is made even more difficult by the polycentric nature of space governance – power and authority are distributed at the international and national levels, with no single entity being in charge.[45]

There is a rising consensus among the international community that norms are necessary to protect the safety, stability, security, and sustainability of the space domain and are part of building international consensus on future STM rules.[46] This is also reflected in current U.S. policy, as the U.S. State Department's 2023 Strategic Framework for Space Diplomacy[47] indicates, leading the development of international space norms is key for promoting U.S.

[††]The 1967 Outer Space Treaty, "Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies," establishes in international law that all states are equally free to use space and have the right of freedom of access to space. It also establishes that no state can claim sovereignty over any part of space.

foreign policy, economic, and national security interests. Additionally, there is a growing number of private sector initiatives to develop best practices for various categories of space activities, including orbital debris mitigation, large constellation operations, and satellite servicing. Yet how these various governmental and private sector efforts will coalesce into global consensus on future "rules" is unclear and uncertain to happen.

To assist in this process, Aerospace has developed a strategic framework for "building normentum" that lays out a process for how thew U.S. government can support and enable the process. This framework emphasizes four strategic decision points involved in successfully developing norms of behavior for space:

1. Establishing domestic buy-in through interagency coordination
2. Selecting initial international negotiating partners
3. Choosing diplomatic mechanisms for generating international commitment
4. Setting a target for which and how many states need to support the proposal for it to be considered a norm, referred to as achieving a critical mass.

There is no "one-size-fits-all" solution to norm development—especially not for space activities. Different international norms of behavior for space can be paired with the approaches that have the best suited strengths and weaknesses. The framework proposed in Figure 8 can help analyze and compare these tradeoffs while demonstrating how different decisions in norm development will interact with each other.

Recommendation 2.3: **Match norm characteristics to development approaches.** Space norm development will proceed along numerous lines of effort, and each effort can be made more effective if it is paired with the right potential norm. Factors that could affect the suitability of different development approaches include the perceived costs of complying with the proposed norm, the sense of urgency or necessity, the norm's relationship to space sustainability versus security, the perceived or expected rate of change in relevant technologies, the level of international agreement on key definitions and concepts, and the distribution of capabilities to norm compliance.[48] Considering how these factors apply to each norm proposal can aid decisions, such as whether to introduce the proposal to allies first or to a large multilateral organization first, the degree of political or legal commitment needed to establish a norm, and how broad the target for international support should be.

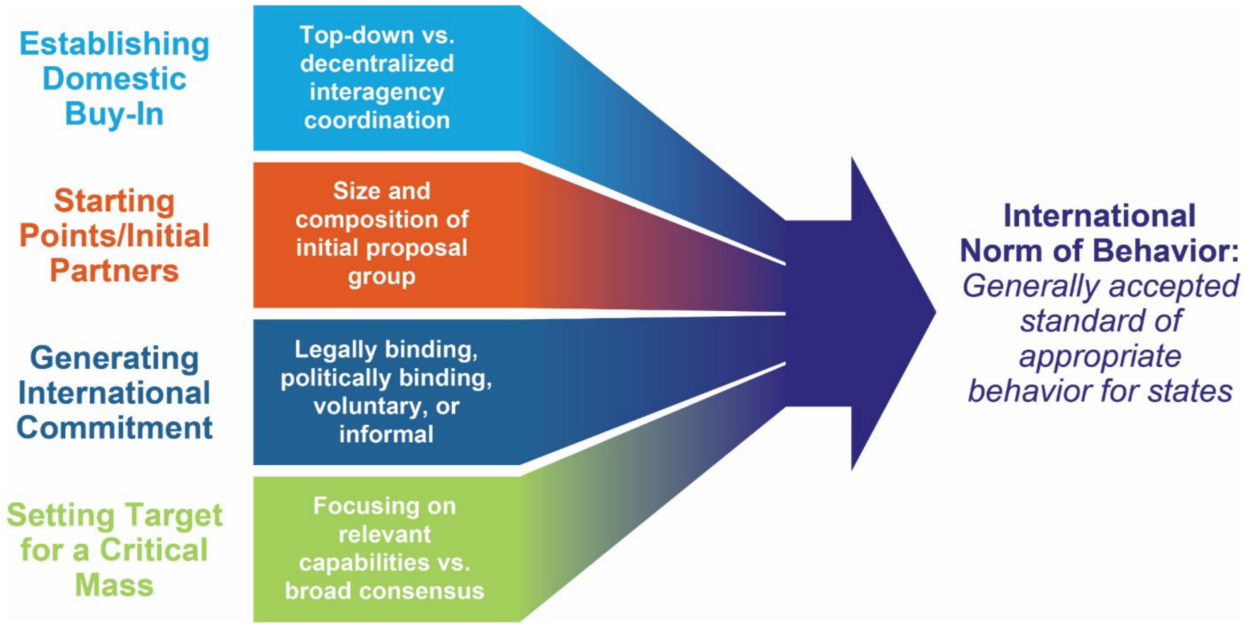


Figure 8. The norm development decision point framework. The analysis for this framework uses generally accepted standards of appropriate behavior for states, a definition for international norms of behavior with several elements common to norms discussions.

Recommendation 2.4: **Consider the whole lifecycle of norm development.** Strategic decision-making for norm development should look beyond questions of the diplomatic venue and type of agreement to use for creating the norm. Policymakers will also need to consider their criteria for success, which could vary for different norms, and how the norms will be implemented once they are agreed upon. Norms can have many different purposes, ranging from identifying irresponsible actors to coordinating international standards, and the starting points and intermediate efforts can be better identified if the underlying assumptions and aims about what the norm is supposed to accomplish are laid out first.

2.3 Active Debris Removal: Legal, Policy, and Technical Feasibility

Over the last few decades, as the complexity of space operations has grown, the amount of space debris has increased to a degree that interferes with space operations and frequently requires satellites to maneuver to reduce the risk of potential collisions. Such maneuvers are becoming more common in certain orbital regimes.

The most critical way to address the debris issue is to perform effective debris reduction and mitigation[‡‡] to control the debris environment.[49] Reducing the total amount of debris already in space through remediation is also becoming an increasingly important proposal for improving the safety of high-population orbits. Active debris removal (ADR) is one of the tools for remediating existing debris. Studies by the National Aeronautics and Space Administration (NASA) and others have shown that at least five major satellites or rocket bodies should be

[‡‡]This includes post-mission disposal.

removed annually to flatten the curve in the space debris population.[50] Since many of these studies were done, the pace of on-orbit activity has substantially grown the LEO population, which has increased the need for active removal. Removing more than five objects per year would decrease the overall number of debris even more, moving toward a more sustainable model for space.

Interest within the U.S. government about ADR has grown. ADR featured in a major element of the 2021 National Orbital Debris Research and Development Plan[51] and the July 2022 National Orbital Debris Implementation Plan[52]. In October 2023, the U.S. Senate unanimously passed the ORBITS Act of 2023[53], which calls for NASA to establish an active debris remediation program. In March 2023, NASA's Office of Technology, Policy, and Strategy released a report examining the cost and benefits of different approaches for ADR.[54] Other organizations, including the European Space Agency (ESA), the UK Space Agency, and the Japanese Aerospace Exploration Agency (JAXA), are pursuing on-orbit demonstrations of ADR technology. JAXA's Commercial Removal of Debris Demonstration program, leveraging the Astroscale ADRAS-J spacecraft, conducted successful RPO maneuvers in April 2024 to approach an orbiting rocket upper-stage—a precursor to an attempt to remove and deorbit the debris.[55] Yet viable options for ADR remain largely elusive due, in part, to technical, economic, and legal challenges. This section will focus on legal and technological questions associated with ADR, which are often described as seemingly insurmountable.

A variety of international and national policies and laws govern space operations, some of which are directly or indirectly applicable to ADR (see Table 2). For example, Article VI of the Outer Space Treaty (OST) requires that all states party to the treaty provide authorization and continuous supervision over the operations of entities under their sovereignty.[56] U.S. national law, policy, and regulations from the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC), and NOAA further incorporate and aim to accomplish that obligation.

Due to these examples, it is important to explore the following questions that are often highlighted in ADR discussions:

- What would international obligations look like for an ADR mission?
- Does ADR require a transfer of ownership?
- How will issues of liability be addressed internationally while abiding by international treaties?

Recommendation 2.5: **Implement a principles-based ADR framework.** To address the legal and policy questions on ADR, the following two principles should be applied:

1. Consent between two parties (debris owner and ADR service provider)
2. Legally binding contract between both parties that incorporates domestic law and international obligations.

By applying the above two principles as well as provisions such as Article VI of the OST, ADR could be a simple legal matter to address.

Table 2. Summary of Applicable Laws, Regulations, and Policies

<table>
<tr><th></th><th>U.S. Government-Owned Debris</th><th>U.S. Commercially Owned Debris</th><th>Internationally Owned Debris</th></tr>
<tr><td rowspan="4">U.S. Government as the ADR Service Provider (e.g., DARPA Mission)</td><td colspan="2">Legal:
• No specific applicable laws to ADR</td><td>Legal:
• MOU or bilateral agreement recommended</td></tr>
<tr><td>Regulatory:
• Not applicable, any issues would be addressed in interagency deliberations on policy</td><td>Regulatory:
• Debris: follow existing regulations; update any licenses
• Service provider: no specific regulations applicable</td><td>Regulatory:
• U.S.: Not applicable and would be handled through interagency deliberations.
• Follow any applicable foreign laws and regulations</td></tr>
<tr><td colspan="3">U.S. policy:
• U.S. space policy
• U.S.G. ODMSP
• NTIA/FCC frequency assignment
• Export issues unlikely</td></tr>
<tr><td colspan="3">International:
• IADC guidelines
• OST and registration convention
• Solid messaging campaign recommended</td></tr>
<tr><td rowspan="4">U.S. Commercial Service Provider</td><td colspan="2">Legal:
• Remote Sensing Policy Act
• Space Launch Act</td><td>Legal:
• MOU or bilateral agreement recommended</td></tr>
<tr><td colspan="2">Regulatory:
• NOAA (to license camera)
• NTIA/FCC spectrum deconfliction
• FAA payload review, if applicable</td><td>Regulatory:
• NOAA
• FCC
• FAA payload review, if applicable
• Follow any applicable foreign law and regulations</td></tr>
<tr><td colspan="3">U.S. policy:
• U.S.G. ODMSP
• SPD-3</td></tr>
<tr><td colspan="3">International:
• IADC guidelines
• OST and registration convention
• Solid messaging campaign recommended</td></tr>
<tr><td rowspan="4">International Service Provider</td><td colspan="2">Legal:
• No specific applicable laws, treaties, or international agreements to ADR</td><td rowspan="3">ADR without U.S. involvement will need to follow applicable laws and regulations from the debris owner and service provider nation.</td></tr>
<tr><td>Regulatory:
• Not applicable</td><td>Regulatory:
• Debris: follow existing regulations; update any licenses; export control, if applicable
• Service provider: no specific regulations applicable</td></tr>
<tr><td colspan="2">U.S. policy:
• Export issues possible
• U.S. space policy
• U.S.G. ODMSP
• SPD-3</td></tr>
<tr><td colspan="3">International:
• IADC guidelines
• OST and registration convention
• Solid messaging campaign recommended</td></tr>
</table>

Legal | Regulatory | U.S. Policy | International

Many potential prohibiting factors (such as export concerns, liability, and ownership concerns) could be addressed in a binding contract between parties. Such contracts between both parties would build the foundation of making ADR a common practice for the future.

A contract between a debris owner and an ADR service provider could address:

- ADR service provided and reentry mechanism (controlled or uncontrolled)
- Retention of debris ownership
- Liability issues
- Licensing responsibilities
- Amount of technical data exchanged, if any
- Export and International Traffic in Arms Regulations (ITAR) control issues, if any
- Intellectual property transfers, if any
- Messaging and public communication responsibilities

If multiple nations are involved, a second agreement in the form of a bilateral memorandum of understanding (MOU) may also be useful to incorporate to address any cross-national issues, such as export control and differences in national regulations. Using the principles of consent and permission, Table 2 shows a matrixed overview of potential legal, policy, and regulatory issues to address. In general, two scenarios exist: (1) debris removal occurring within a single nation-state's responsibility and (2) involvement of two or more states.

Furthermore, using a pathfinder mission to demonstrate this principles-based framework would establish a U.S. commitment to the remediation of space debris and, more broadly, to the long-term sustainability of outer space. A pathfinder ADR mission based on permission and consent would also greatly facilitate transparency, confidence-building measures, and best practices and help transition ADR into a common practice.

Recommendation 2.6: **Enable commercial ventures and establish public-private partnerships to increase the technology readiness level (TRL)[§§] of ADR.** In addition to the legal and financial difficulties of ADR, there are myriad hurdles concerning the technical feasibility of rendezvous, grappling an uncontrolled object, and safely deorbiting. However, due to the level of interest in space sustainability, government agencies and industry are both encouraged to actively pursue missions designed to test and demonstrate technologies for all phases of ADR. Several nations are already pursuing this.

Recommendation 2.7: **Encourage provisions for on-orbit servicing as a first step toward ADR.** On-orbit servicing concepts must solve many of the same technological problems as ADR: rendezvous, grappling and/or controlling a consenting but possibly noncooperative[***] target, and modifying the target's orbit. Government and industry are encouraged to pursue and enable on-

[§§]TRLs measure the maturity level of a particular technology. The technology is assigned a level from 1 to 9, with a level 9 technology exhibiting the highest level of maturity through proven success in mission operations.
[***]"Noncooperative but consenting" refers to when information transfer between the chaser spacecraft (vehicle performing the rendezvous operation) and target object is one way only. The target object will not actively provide information regarding its own state to the vehicle performing rendezvous. Efforts to service dead satellites or deorbit orbital debris are examples of noncooperative but still consenting operations.

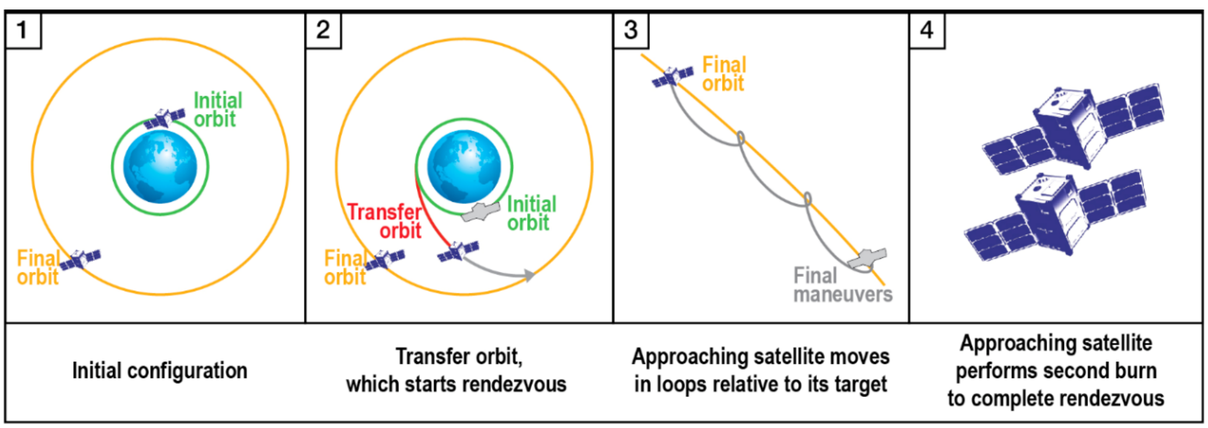
orbit servicing technologies as a first step toward ADR, including rendezvous aids, such as radar and optical reflectors, and grapple fixtures to facilitate possible future retrieval.

2.4 Learning from Past RPO

As orbits become increasingly crowded due to proposed LLCs, mission lifetime extension technologies, such as on-orbit servicing, will require internationally sanctioned rules for safe and transparent interactions. On-orbit servicing and other services like ADR utilize RPO, which generally refers to orbital maneuvers in which two spacecraft arrive at the same orbit and approach at a close distance. This rendezvous may or may not be followed by a docking procedure.

Using rules and procedures developed for the International Space Station (ISS) and other on-orbit examples, this section draws on lessons learned and makes recommendations for future RPO concepts,[57] shown in Figure 9.

Rendezvous and Proximity Operations



Sequence of events that comprise RPO:

Definitions

- **Rendezvous:** The process of bringing two (or more) satellites close in position and velocity, typically by matching the orbital plane, orbit size and shape, and phasing of the satellites
- **Proximity operations:** Two (or more) satellites performing maneuvers while close in position and velocity.
- **Docking:** Subset of proximity operations where one satellite intentionally performs maneuvers to physically join with another satellite
- **Cooperative RPO:** Two (or more) satellites performing a coordinated RPO pursing a mutual objective (e.g., docking with the ISS)
- **Noncooperative RPO:** Two (or more) satellites performing an RPO while pursuing independent (but not opposing) objectives (e.g., ADR)

Figure 9. Key RPO concepts.

The ISS provides a compelling RPO case study due to the wide number of international agencies that work together to create a safe and transparent environment through bilateral and multilateral agreements and clearly outlined technical specifications. The ISS includes a crew-habitable environment mounted on a space platform about the size of a football field in LEO that has been continuously occupied since 2000. It is a cooperative effort involving the United States, Russia, Canada, Japan, and ESA. Principally, a space station program document (SSP 50235)[58] defines performance and interface requirements for myriad vehicles that need to interface with the ISS, whether in its construction or for the transportation of astronauts and supplies.

In addition, NASA's 2005 Demonstration of Autonomous Rendezvous Technology (DART) and the Defense Advanced Research Projects Agency's (DARPA's) 2007 Orbital Express missions provide important technology demonstrations with valuable lessons learned. NASA's DART demonstration was designed to autonomously rendezvous with and maneuver around a designated communications satellite, but, after eight hours of the demonstration, it started using more propellant than expected, and then actually collided with its target. A subsequent mishap report found a series of issues, such as poorly managed risk posture and inadequate guidance, navigation, and control software development processes. The DART spacecraft was completely autonomous, so even if ground operators had accurate navigation information, they could not have sent commands to intervene. While errors such as these can affect any spacecraft when in an RPO environment, these errors can produce drastically worse consequences.[59]

Orbital Express sought to validate the technical feasibility of autonomous RPO pertaining to on-orbit servicing. The mission called for a servicing vehicle to rendezvous and dock with a target client satellite, then transfer fuel and battery power as a demonstration of servicing technologies. However, a major failure in the sensor computer onboard one of the participating spacecraft, which lost the relative navigation estimate after a reset, resulted in unplanned vehicle motion that nearly ended the demonstration prematurely. A key finding from a NASA postmortem technical report was that mission designers often make implicit assumptions about the navigation state and the performance of the guidance and control systems, which could lead to unanticipated behavior if not adequately tested on the ground.[60]

A key issue with space-based navigation is that the precise state of a system (such as the relative position, velocity, and orientation of two spacecraft performing RPO) is never known perfectly. The intrinsic errors in relative navigation require redundant, robust navigation systems with highly trained ground operators standing by during critical moments of the mission. Examining these three case studies (NASA ISS, DART, and Orbital Express) highlighted the importance of ground operations, flight navigation software, risk mitigation maneuvers and relative navigation, autonomy, cooperative agreements, and technical specifications. Today, technology innovation has advanced the field, and several commercial entities are pursuing various RPO missions.

Recommendation 2.8: **Continue to promote U.S. leadership in RPO norms development.** Recognizing the need for agreed-upon norms of behavior, DARPA established the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) in 2017. Now an independent, not-for-profit trade association, CONFERS is developing industry-led voluntary consensus standards and guiding international policies and standards for satellite servicing.

In 2023, NASA sponsored the formation of the Consortium for Space Mobility and In-Space Servicing, Assembly, and Manufacturing (ISAM) Capabilities (COSMIC). The United States Space Priorities Framework sets many strategic civil, commercial, and defense priorities that will rely on ISAM capabilities. The 2022 National ISAM Implementation Plan calls for NASA and the U.S. DOD to jointly lead U.S. advancement of these capabilities. RPO success and safety are highly reliant on ISAM technologies and the technical standards that shepherd their use. There is also a strong need for mission processes utilizing those technologies to align with policies that ensure responsible operations and mitigation strategies for contingencies.

Guided by these considerations, the United States should continue to facilitate the development of industry consensus standards for how RPO is conducted. The standards and norms of behavior should be dynamic to adapt to new lessons learned and future ideas of on-orbit activities. CONFERS and COSMIC serve as models for coordination across government, industry, and academic stakeholders.

2.5 Integrating Constellation Impact in Space Operations

The regulatory and policy frameworks currently in place are based on spacecraft designed and launched as individual objects. An important characteristic of more recent constellations is that spacecraft are now designed to be mass-produced and mass-deployed as part of a larger constellation. Standards for launch, on-orbit, and post-mission reliability have been established for individual spacecraft. However, even a low-probability event can become a near certainty when multiplied by thousands or tens of thousands of spacecraft.

It should also be noted that most of the most recent constellations have relatively short spacecraft lifetimes (e.g., five years) to enable rapid technology refresh and lower weight and cost and are designed for lower levels of individual spacecraft reliability. This implies that for a viable business model, the constellation must not only be launched but must also be replaced continuously over time. For example, from what is recorded in Space-Track.org as of September 17, 2024, the SpaceX Starlink system has launched 6857vehicles in 3 versions and deorbited 560. In 3 years (2021, 2022, and 2023), SpaceX launched Starlinks at a rate of nearly 200 per month and deorbited them at a rate of about 12 per month. The vehicles in each generation have grown significantly in both size and capability, and the number on each launch has been reduced. OneWeb has launched 636 vehicles and deorbited 2, and it has completed its initial constellation.

Recommendation 2.9: **Explore the assessment of risk at the constellation level.** The space community should reassess debris mitigation, reliability standards, and norms of behavior, taking the impact of the entire constellation into account. A standard that is acceptable for a single spacecraft may not be viable when multiplied by hundreds or thousands of small satellites.

Of course, any new metrics or standards for constellation risk must be backed by careful analysis and studies to show that proposed changes are superior to considering individual spacecraft risk. It will be important to consider the effect changes in the "rules" have on the safety and sustainability of the operations environment, and whether the advantages outweigh the costs and disadvantages.

One advantage of considering the constellation as a "system" is that system-level risk mitigations can be considered. The well-traveled axiom, "space is hard," helps set the expectation for some degree of failure. At the system level, a mitigation plan that is separate from the individual spacecraft's onboard systems or reliability can be considered. For example, a "tow truck" satellite or tug may be considered as a system-level backup plan to address failures.

Recommendation 2.10: **Establish performance-based regulatory approvals for constellations**. As discussed previously, many constellations will be continuously launched and replenished over many years or even decades. When a company seeks regulatory approval for a system, it is common to outline plans and present analyses to show compliance with standards. However, once a system has been placed in orbit, performance data becomes available. Given the long timespans under consideration at the system or constellation level, it would be prudent to make regulatory approval an ongoing process that also considers the performance of the earlier elements of the system. The details and terms of the reassessments will need careful examination to balance the desired space environmental outcomes with the burden on the operators, but the stakes are high. Ongoing performance-based rolling approvals could prove a useful approach to deal with a rapidly evolving environment. The FCC has begun requiring reporting on the actual performance of some constellations, and this practice should be expanded to other sustained constellations.

Recommendation 2.11: **Promote effective post-mission satellite disposal methods to offset collision possibility.** Nonfunctioning satellites, used rocket bodies, and debris from the operation of large constellations will pose a risk to other spacecraft operating nearby. Therefore, proper safety and disposal of spacecraft near the end of their operational life and practices that minimize the creation of superfluous debris should be undertaken to help maintain a robust and usable space environment.

One of the most important principles created internationally for satellite disposal is from the Interagency Space Debris Coordination Committee (IADC) and is drawn from the 2002 IADC Space Debris Mitigation Guidelines.[61] It recommends that satellite operators should remove spacecraft and orbital stages from useful and densely populated orbit regions no more than 25 years after mission completion. However, under its newly issued National Orbital Debris Implementation Plan (July 2022),[40] the White House has called for a reevaluation of the 25-year rule due to the growing risk to orbital operations by space debris.[62]

An Aerospace study of the potential of long-term debris generation found that LLCs can cause an increase in the spatial density by a factor of roughly two over that expected from business as usual.[63] It also found that satellite failures could increasingly become an issue. Therefore, how these satellites are removed from the environment and how reliable the satellites are will be important considerations for the future of the near-Earth debris environment. To control debris growth, satellite operators will need to reliably ensure post-mission disposal of dead satellites at the constellation level.[64, 65, 66]

All spacecraft and upper stages in LEO should be removed from orbit as soon as possible at the end of mission life. The preferred method for this is through controlled reentry since uncontrolled reentry requires the satellite to naturally decay, which may take longer than the 25 years recommended by the IADC and Orbital Debris Mitigation Standard Practices (ODMSP)[6] if the satellite begins its natural decay above 600 km altitude. In late September 2022, the FCC announced a requirement for a 5-year deorbit, which lowers that ceiling by about 135 km.[67] In October 2023, the FAA issued a notice of proposed rule-making that required commercial launches to follow rules very similar to the government's ODMSP document and its 25-year rule but specifically requested comments on whether the rule should be shorter. However, for controlled reentry, spacecraft must remain under active control and perform risk mitigation maneuvers until located in a safe long-term disposal orbit or final reentry.

It should be noted that all U.S. large-constellation operators have publicly embraced sustainability and appear committed to safe operations. In February 2024, SpaceX simultaneously announced a public commitment to space sustainability and a plan to deorbit 100 Starlink satellites due to a higher-than-planned risk of failure while controlling them until close to reentry.[68] These are currently operational satellites being deorbited early as a precaution. Historically, it has been a common practice to allow satellites to fail in place to obtain the maximum service life, and such precautions were rare. OneWeb has similarly made a public commitment to "leave no trace in space."[69]

3. LAUNCH AND REENTRY

For most of the space age, LEO satellites were one of a kind and were used for scientific research, land remote sensing, and similar endeavors. Satellite designers faced a relatively open environment: collisions were rare, operators could expect to manage satellites with minimal interference, and satellite lifetime would not be seriously degraded by impacts with debris or other human-made items while in orbit. In addition, mission designers virtually had a free hand in where they could place satellites, particularly in LEO, and when and how to decommission them.

To date, the most common method of disposal has been to simply let a satellite's orbit degrade from atmospheric drag and then disintegrate in Earth's atmosphere. Some large objects might survive reentry and be recovered, but many space practitioners believed that objects would simply "burn up" due to reentry heating without issue. This is not the case. Debris from the satellite breakup at reentry can continue to fall and impact aircraft in the sky and people on the ground. With LLCs, possible impacts from debris are amplified as the number of satellites being launched and disposed of increases.

Additionally, it should be noted that even when a reentering object fully "demises," the disintegrating rocket stage or spacecraft does not simply turn to harmless gas or "sand." Demise, in this context, means that the rocket stage or spacecraft does not produce any objects that individually will deliver enough energy to harm an unprotected human. Between 10 and 40 percent of an object's mass[†††] will survive reentry and fall to the surface, scattered over a long, thin footprint that covers an area potentially as large as 140,000 km2, or roughly the area of Iowa. The material that does not survive reentry is vaporized and processed into particles that mix into the global atmosphere. The metallic fingerprint of reentering spacecraft has been detected in 10 percent of particles in the background stratospheric aerosol layer.[69] Little is understood about how hot reentry plumes mix into the global atmosphere, the ultimate fate of vaporized spacecraft materials, or their cumulative effects on the global atmosphere (see 3.6).

3.1 The Iridium Constellation Case Study

Between May 1997 and May 1998, Iridium established the first major LEO satellite constellation, launching 66 factory-built satellites plus 6 "spares" into orbit. The constellation provided voice and data communication services to users worldwide. Two more were launched in August 1998, and by 2002, 95 had been launched in the first generation.

Within 14 months of being operational, possible bankruptcy forced Iridium to consider disposing of all current satellites in the constellation (then 74)—a possibility that raised the first concerns about hazards to people on the ground should a constellation be disposed of by

†††The percentage of surviving mass is highly dependent on the specific design of the rocket body or spacecraft. "Design for demise" is a principle often applied to spacecraft. Many developers of LLCs specifically design for complete demise; i.e., no surviving pieces sufficiently large enough to be a hazard to unprotected people.

reentry. Iridium planned to dispose of the satellites by lowering each satellite's orbit to an altitude where aerodynamic forces would bring it into the atmosphere in a few months, shortening the time it would take if simply left in its operational orbit. The location of the satellite's final reentry point would be uncontrolled, and surviving debris could land anywhere under the satellite's orbital path.

While the probability of striking an aircraft was not estimated at that time, an unpublished NASA study, validated by independent Aerospace analysis, predicted that reentering all 74 satellites would lead to an estimated probability of 1 in 249 of striking a person. Some analysts felt that estimate was too conservative, which illustrates the importance of using hard data and accurate models in decision-making. Fortunately, though Iridium did go bankrupt, its successor company did not deorbit the satellites but continued operations. In the last few years, as the constellation was refreshed, the first-generation satellites reentered, but no injuries were reported. This was consistent with the low-probability 1:249 expectation.

Today, several commercial companies plan to launch or have launched constellations with thousands of satellites in LEO. Satellites at the end of their operational lives would be disposed of into the atmosphere, potentially with little or no control over where their surviving debris might land. If a constellation comprises 10,000 satellites, it may be disposing of 1,000 or more satellites on a yearly basis—several each day on average. For reference, 2016 was prior to the start of the large-constellation era, and 62 objects larger than 1 m^2 in cross-sectional area reentered. In 2023, there were 203 such reentries, prior to the large-scale reentries anticipated when large constellations begin replenishment. Large constellation designers generally "design for demise" to prevent debris dangerous to unprotected humans, but this does not mean that *all* debris simply "burns up."

The addition of these constellation satellites certainly changes the LEO environment and may pose an increased risk to people on the ground or in aircraft. This chapter highlights key actions for policymakers and regulators to develop strategies for safe operations of satellite launches, disposal, and reentry.

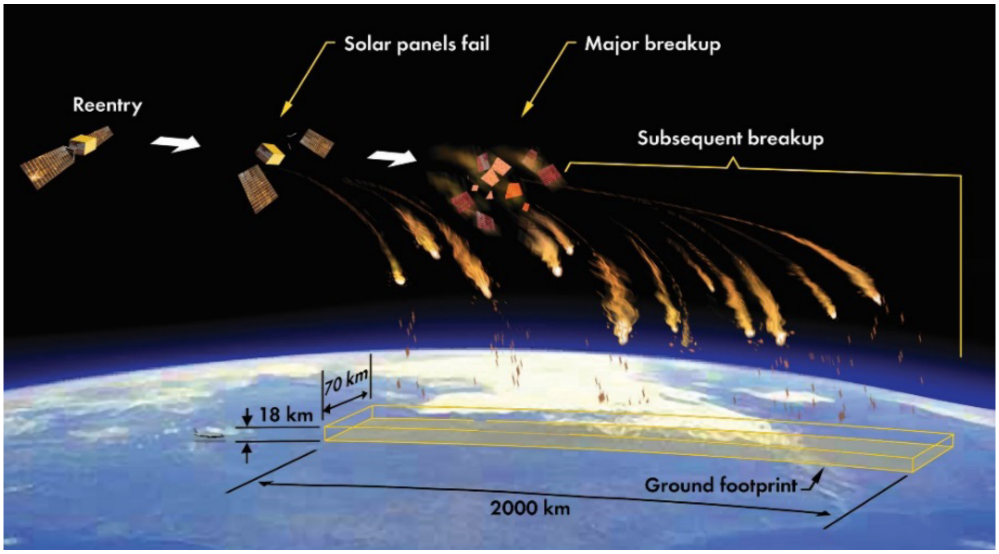


Figure 10. The final reentry breakup process, showing that debris surviving reentry would fall through airspace potentially occupied by aircraft (commercial airspace extends to 18 km above ground) and could spread over a long, narrow path as it impacts the ground, possibly causing human casualty.

3.2 Airspace Integration of Launch Operations

Rockets launching into space only briefly intersect with commercial aviation flight levels. Nonetheless, launches can have noticeable impacts on air traffic and ground safety and typically require a significant amount of airspace to be cordoned off as regions that should be avoided due to possible risks during launch. These risks include potential objects dropped during launch and failure modes that might produce debris or other hazards. Historically, launch rates were low enough that these disruptions could be tolerated. Newer space systems, particularly those of commercial operators, are significantly increasing launch rates, adding new ranges from which rockets may be launched and adding entirely new operations like flyback of launch vehicle first stages. All these changes put a strain on existing launch safety practices and can overburden them if changes are not implemented.

To date, space launch has been *accommodated* in the National Airspace System (NAS) rather than *integrated into* that system.[70] That is, a launch operator determines a launch day and time based on mission needs and secures a launch window from the relevant range authorities, generally regardless of the impact on the NAS. Hazard areas are identified by the launch provider and reported to range safety authorities, and the FAA issues a notice to alert aircraft pilots of potential hazards due to launch activities, such as flight of the launch vehicle itself, hardware jettisoned from the launch vehicle, or debris in the event of vehicle breakup or explosion. These hazard areas can cover the airspace over many hundreds of square miles and last for substantial periods of time (i.e., hours), again depending on mission needs. The hazard areas can bring with them restrictions on air and shipping traffic, which can have economic effects. If regulators use assumptions that are too conservative, the economic and non-space operational impacts can be out of proportion to the actual risk.

This kind of accommodation is burdensome for today's commercial operators and regulators alike, but at earlier launch rates of approximately 20 per year (from Cape Canaveral Air Force Station, for example), it was manageable. In addition, most space launches have historically been for government customers, so acceptance of this process by other users of the NAS has traditionally held some sense of being "for the greater good." With the recent accelerated pace of launch and the anticipation of increased launch rates from commercial customers (Figure 11),[71] there is a need for better integration of space launch activities in the NAS.

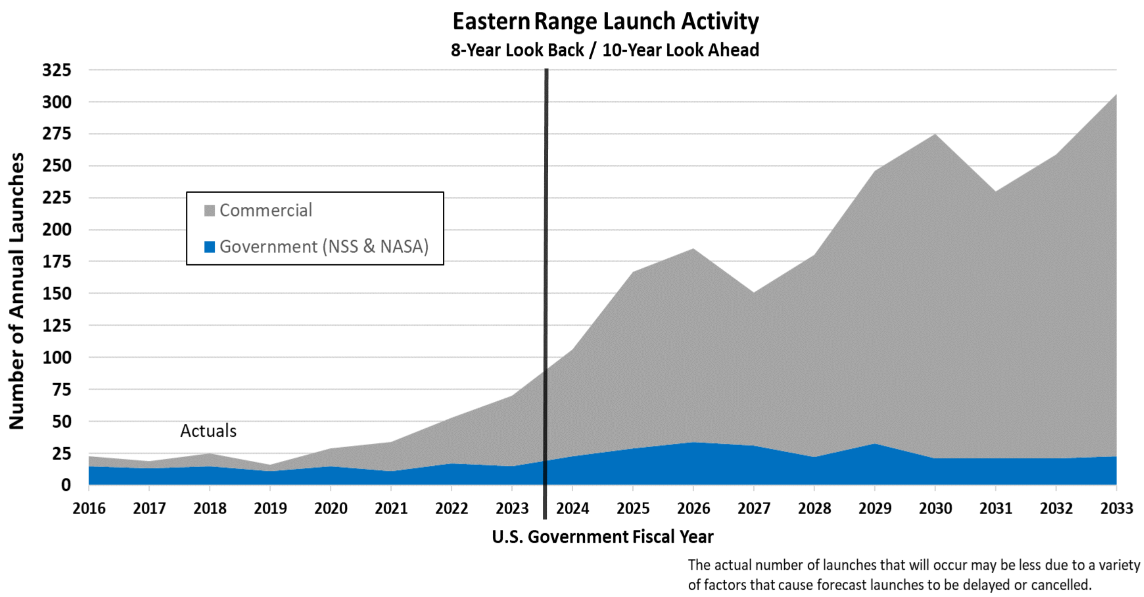


Figure 11. Eastern Range launch activity as of January 18, 2024, derived from several data sources, in particular, FCC filings for planned satellites, which telegraph a large potential increase in future launch rates.

Any integration strategy should recognize characteristics of orbital space launch that constrain the solution space. These characteristics fall into the broad categories of launch timing (rocket launch times are not chosen arbitrarily), launch system reliability (space launch rockets are inherently less reliable than aircraft), and launch trajectories (because of the physics of the problem, space launch rockets affect the NAS for thousands of miles and are "un-steerable" around other users of the NAS).

Recommendation 3.1: **Implement a comprehensive NAS integration strategy for launch and reentry.** While the total integration of space launch rockets as "just another user" of the NAS would appear to be impossible given the differences between aviation and space systems, improvements can be made in the areas of situational awareness, data exchange, and automation to minimize the impact of space launches on the NAS. These include:

- Improving data sharing between launch providers and NAS managers. More efficient communications can reduce launch impacts on other NAS operations.

- Examining the use of technologies such as automatic dependent surveillance-broadcast (ADS-B) for use in space launches. This could facilitate better integration of launches into normal NAS operations as it offers improved shared situational awareness.
- Revisiting conservative assumptions about defining special activity airspaces (SAAs) to identify areas where better analysis and more experience with space launches could decrease the SAAs.
- Designing space hardware for demise in reentry to reduce interference with the NAS on return to Earth.[‡‡‡]
- Considering the implementation of a "fee for use" to the FAA. For launch systems, this would be determined based on the area of the NAS affected, duration of usage, etc. to encourage more efficient use by stakeholders.

3.3 Collision Analyses for Satellite Launch and Disposal

While much of the focus of satellite tracking is on satellites in orbit, the role of launch and satellite deorbit (disposal) in collision assessments has received less consideration. The uncertainties associated with launching vehicles are far greater than those related to orbiting objects. Improved tracking of on-orbit assets alone will not noticeably improve launch collision avoidance (LCOLA).

Decay, failures, and/or disposal of constellation satellites could also pose a threat to satellites operating at altitudes other than a constellation's original altitude. Particularly, while proposed LLCs are currently planned to reside at distinct, well-defined altitudes, they could affect smaller operators during disposal. Previous studies[72] have shown that, over the long term, a wide range of collision rates for LLCs with lethal debris can be expected. This, however, depends on the LLC traffic and success rate of debris mitigation practices.[51] These collisions can occur both during operations and during disposal phase. The relative proportion of each is dependent on the types of disposal mechanism used, which can also affect other missions outside of their operational regions.

Recommendation 3.2: **Consider a larger risk posture to make more informed decisions regarding launch risks.** It is important to reconsider current launch practices to allow for a better understanding of launch risks. The growing population of on-orbit satellites can result in some launch windows being entirely closed due to LCOLA concerns using current practices.

The goal of any LCOLA system is to identify high-probability conjunctions between launch trajectories and orbiting tracked objects. In doing so, operators can avoid launch opportunities that have a higher risk of collision. Conceptually, a simple launch hold for a short interval is a low-impact way to avoid a potential threat. However, too low a threshold can result in an entirely

[‡‡‡]The exception to this recommendation is the use of reusable launch vehicles that return to Earth through controlled reentry.

closed launch window, which incurs different costs. LCOLA is useful as a risk-reduction tool; its implementation should not prohibit the ability to launch.

An Aerospace study found that improved data collection from the Space Fence or other lower-size threshold tracking systems, which increased the amount of tracked debris by more than 50 percent, plays a greater role in LCOLA than adding new large constellations to the space environment. Since improved tracking systems will see more objects than just the large constellations that are expected to deploy, the smaller objects will be more likely to influence LCOLA systems. Compounding this effect is that newly tracked objects less than 10 cm may only be observed by single or few sensors and will have much larger orbit uncertainties than the constellation satellites.

The study also found that under current LCOLA processes, missions to LEO will be much more affected than missions to higher altitudes. However, it must be noted that much of the "new" risk comes from the debris newly tracked by improved systems. These objects were already in orbit, but were untracked, so launch providers have been accepting this risk unknowingly. By adding these objects to the catalog, LCOLA systems can provide additional risk reduction.

Additionally, Aerospace found that while "safe corridors" through which launching vehicles can traverse do *not* exist, "regions to avoid" do. For example, launching directly to an orbit whose altitude range corresponds to one of the large constellations should be avoided. Aerospace is examining modified trajectories that could launch to a more "open" region of space and maneuver to the more crowded altitudes using improved on-orbit knowledge.

To have a more holistic and contextual approach to launch risk, LCOLA systems should address questions such as:

- How does the risk from a launch conjunction compare to other risks in the operation?
- Does holding the launch, changing the trajectory, or modifying a launch process add or subtract overall risk?
- Should LCOLA screening only be performed on a subset of the space catalog, such as operational satellites, or should it also include other high-value space assets?

LCOLA is a risk assessment and reduction tool that can be used to enhance flight safety at minimal cost[73]; i.e., hold the launch momentarily to wait for a pause in traffic along the launch vehicle trajectory. There is a flight safety risk between the end of the LCOLA process when the payload(s) and stage(s) are in orbit and the accurate tracking of the deployed spacecraft that enables the on-orbit COLA process to begin. This "LCOLA gap" has for several years been a primary concern for human spaceflight safety, and various techniques have been developed to ensure that the launch will not be a concern for the ISS, or other human-occupied vehicles.[74] The delay in accurately cataloging and tracking mass deployments of spacecraft creates a different kind of COLA gap in that routine flight safety processes cannot reliably warn of potential conjunctions possible from these deployed "clouds" of spacecraft.[75] The use of owner-operator data or transponders would be useful in addressing this gap.

3.4 Large Constellation Disposal Hazards

While satellite disposal has historically involved a deorbit where it "burns up" in Earth's atmosphere, Figure 12 shows that some hazardous fragments do survive reentry. In fact, the objects in the figure are large enough to cause human casualty, which we define as the death or injury resulting from the collision between a human and a surviving portion of a reentering space object, or catastrophic damage to an aircraft.[76]

Figure 12. Recovered composite overwrapped pressure vessels (COPVs). The left photo shows debris from the Centaur stage of an Atlas V booster, and the right photo shows the SpaceX Falcon 9 stage.

Aerospace conducted a first-order assessment of potential risks to people and aircraft associated with random reentries of large numbers of satellites from large constellations in LEO. The analysis considered constellations totaling approximately 56,000 new satellites that must be routinely replenished, leading to approximately 9,800 reentries per year. Aerospace concluded that risks to aircraft posed by small debris surviving a reentry might also pose a problem for disposal of satellites from large constellations. That study predicted a risk of aircraft worldwide striking a reentering debris fragment of 1 impact every 1,400 years. Hazards to people on the ground from larger debris objects will be a more pronounced problem, with expectations as high as one casualty somewhere on Earth every other year for uncontrolled reentries.[64] Actual risks will be strongly dependent on real satellite demisability.

Since that initial assessment, the number of satellites in proposed LEO constellations has increased, and the masses of many spacecraft have also increased. Typically, larger spacecraft can introduce much greater risk per reentry. Disposal of satellites from these constellations via random reentries could increase the risk to people and aircraft as a result.

Recommendation 3.3: **Design spacecraft components and features and disposal plans to limit disposal hazard risks and ensure fewer hazardous fragments survive reentry.** Moving forward, regulators could direct constellation owners to provide information on disposal plans and estimates for the maximum yearly hazards associated with disposal of their satellites. Test ranges provide some guidance relative to the acceptable yearly risks for hazards from surviving debris but not for yearly reentries thus far.

It should be noted that most operators rely on government-provided models to assess the hazards of reentering debris from their spacecraft. It is critical to provide the enterprise with accurate models of reentry risk to accurately assess compliance with standards and regulations while not overly constraining operators.

Recommendation 3.4: **Control reentry points.** Controlling the point where satellites reenter so all surviving fragments make impact in a safe region (e.g., the Pacific Ocean) should be the preferred option from a safety perspective. If a satellite is deemed to fully demise, then its reentry point could be uncontrolled and anywhere. Currently, there is limited hard data on actual debris survival, and collecting radar observations of actual reentries could provide more information. More refined hazard estimates are needed to improve constellation satellite designs, lifetimes, and disposal strategies.

Recommendation 3.5: **Improve and validate reentry hazard models.** Applicants for FCC licenses frequently use the NASA Debris Assessment Software (DAS) to show compliance with reentry risk requirements. However, software like DAS is designed to provide general assessments of compliance with requirements and may not always accurately reflect the details of risky surviving debris from a reentry, so when large numbers of vehicles are considered, the total risk from a given constellation may be quite different from what was predicted. Efforts should be made to validate and, if necessary, improve the models used for regulatory purposes.

One of the issues with predicting the risk from a reentry is the difficulty in predicting the location of a randomly reentering object. This is due to the extreme variability of the tenuous upper atmosphere and the orientation of the often-defunct reentering object, making drag prediction highly problematic. A generally accepted rule of thumb in predicting the time, and therefore the location, is 20 percent of the “time to go” (e.g., a 1-day uncertainty for a 5-day prediction, or a 12-minute uncertainty for a 1-hour prediction).

This is another area where more diverse geographic locations of international and commercial sensors can make a distinct contribution. The last site to observe a decaying satellite is the most important because it strongly contributes to more accurate computation of the impact point. Having tracking data from more partners increases the likelihood of getting a track very near the decay time.

3.5 The Impact of Modeling and Data Sharing

The effectiveness of any given approach to space safety is dependent on the accuracy of the models the approach is based upon. As discussed above, the risk from reentry is based on several important models. How much material from a spacecraft will survive a reentry? How many pieces, how much mass, scattered over how large a footprint? Where will this debris footprint fall, who is at risk, and are the people sheltered or exposed? What level of risk is “acceptable”? A change in the model or a change in the assumptions and inputs to the model can produce quite different conclusions on the risk. Spacecraft designs may be altered based on these outcomes.

Compliance with regulations for licensing often requires use of a standard or widely recognized and accepted model, and government-provided models play a critical role. For example, both the NASA Orbital Debris Engineering Model[77] (ORDEM 3.2) and DAS[78] are used by industry for assessing debris impact likelihood, survivability, and reentry risk both in design and compliance with U.S. regulations. The extent to which models such as these over- or underestimate risk directly impacts the success or failure of the regulatory intent and directly impacts the design of the system.

The space industry is heavily dependent on models and simulations. Long and sometimes bitter experience teaches us that models and reality are not always as closely matched as we might wish. Hard data is golden. Models must continuously be compared against the reality the model attempts to emulate.

Recommendation 3.6: **Implement model development strategies.** When considering strategies to develop and implement policies to achieve some goal related to space safety, consider how it will be measured. What metrics will be used, and what models will be used to assess these metrics? How will these models be shared and made available? How will they be maintained? What is the strategy for continuously assessing the validity of the model and the continuing validity of the assumptions? Models are living things—they must evolve and must be maintained.

It is a long-standing truism in the modeling and simulation world that “garbage in equals garbage out.” The correct data and inputs must be used to get useful results, and the assumptions behind the model must be valid for the application. If models are used to show successful compliance with a safety or regulatory goal, extra care must be taken to ensure successful application of the model. This is also true when an organization is modeling someone else’s system.

How do we ensure that the correct input data is used and that the assumptions are valid? The most common approach is to make a conservative assumption when we don’t know something for certain. For example, in collision risk assessment, the actual risk depends on the physical dimensions and relative orientation of the two objects. We usually use the longest dimension as the “hard-body radius” and assume that the object is spherical to eliminate the need to know the orientation. If we don’t know the actual dimensions, the radar-cross-sectional area is sometimes used a substitute. This practice usually overestimates risk and is “conservative” in that it errs in the direction of safety. But it would be better to use actual data, and the developers and owners of a system are the best source.

Also, to the extent possible, a knowledgeable third party should independently validate the use of these models. Long experience in comparing the results from different models shows that the differences are often due to different assumptions. This can reveal which assumptions are critical to results and sparks closer scrutiny. All models make assumptions and have inherent “error bars” on the results, even when we cannot accurately assess the implied error. Many or most models contain discontinuous steps and nonlinear processes. In the case of the reentry risk modeling discussed in section 3.1, the difference in 100 percent demise (no risk) and 99.5 percent demise (small risk) can lead to notable levels of impact when multiplied over numerous launches. Independent validation is an excellent process for illuminating this phenomenon and improving our understanding of a system and its impact.

Recommendation 3.7: **Develop strategies and processes to maximize data sharing.** A best practice for operators is to be as transparent as possible in their operations and in the details of the system. Regulatory and other agencies can and should facilitate data sharing in the name of safety. This might be done by establishing standards for data sharing and databases for storage and sharing. Recognizing that some data might be considered sensitive or proprietary, these databases and processes should also address data protection and access control.

Finally, the nature of assessing the success of safety approaches relies heavily on statistical analysis. Most safety rules use probabilities or rates of outcomes. The space safety community must recognize that success is when a low-probability negative event does NOT occur. The absence of a negative outcome does not (necessarily) indicate that the model or process is too conservative or even wrong. But the safety community must nevertheless continuously assess the validity of models and assumptions.

3.6 The Impact of Space Operations on the Atmosphere

We recommend taking a holistic view of the entirety of space operations that considers how each spaceflight phase and system affects the environment, the coupling between systems, and total lifecycle impacts. Launch vehicles and reentering spacecraft emit gases and particles that affect Earth's atmosphere locally and globally. Although spaceflight emissions are not currently regulated, if the space industry grows large enough, it is conceivable that launch or reentry emissions will conflict with efforts to manage stratospheric composition. Emissions are coupled with spacecraft design choices such as propellants, materials, reusability, and operations. Nearly all the mass that characterizes a space mission (propellant, engines, antennas, electronics, stages, and sensors) is ultimately emitted into the atmosphere and so must be considered as a unified whole.

Launch vehicle rocket engines emit combustion products across every layer of the atmosphere from Earth's surface to LEO. Destructive satellite and stage reentries emit mostly metallic particles into the mesosphere and stratosphere. Most of these emissions accumulate in the stratosphere and come entrained into the global circulation. Models show that the most impactful emissions on the atmosphere are the particles black carbon and metal oxides, rather than the combustion gas emissions. The particles absorb and scatter sunlight in the stratosphere and serve as sites for chemical reactions and cloud-forming nuclei. The overall emissions and global atmosphere processes shown in Figure 13 generally cause slight surface cooling, stratosphere warming, and ozone depletion.[79] The scientific community studying this issue thinks that spaceflight's global impacts are

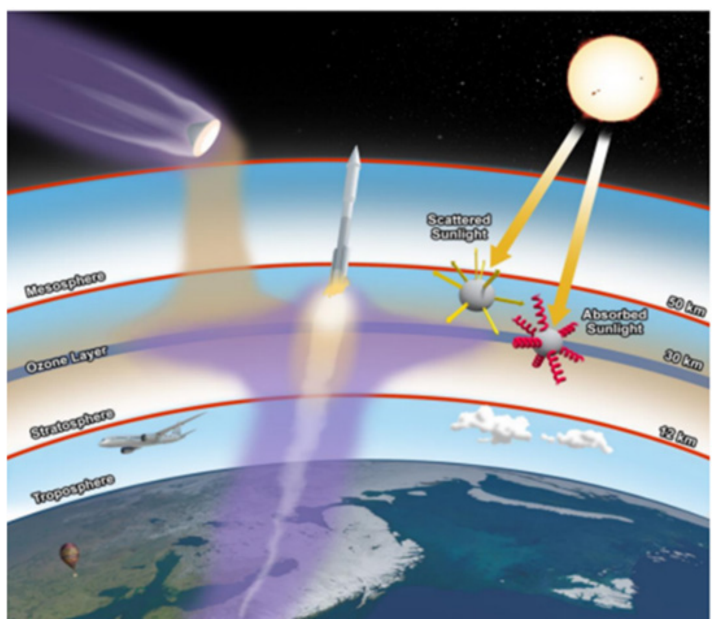


Figure 13. The impact of the space enterprise on global atmospheric processes.

smaller than those from global aviation, though uncertainties are sufficiently large to warrant further research.[80] Aerospace's own studies support this view.

Transient, regional impacts from launches and reentries include ozone holes, ionospheric holes, mesospheric clouds, and thermospheric airglows lasting up to several days. The cumulative impacts of these transients are not significant today, but at much higher operational rates, the transient effects could merge and become global ones with potentially important impacts on radio propagation, astronomical observations, and remote sensing.

Launch emissions were long assumed to play a larger role in the atmosphere than reentry. The dominance of LLCs and requirements for disposal via reentry means that global reentry emissions will exceed launch emissions by mid-decade. Recent measurements obtained in the stratosphere showed that in 2022, even before the expected increase in reentries, 10 percent of the background aerosol population contained metallic inclusions attributed to reentering spacecraft.[81] What this surprising result says about climate or ozone impacts, or how the stratosphere will respond to the anticipated increase in reentry emissions when the first generation of LLCs reaches end of life and reentry emissions rapidly increase, is unknown.

Figure 14 compares calculated future reentry mass flux, historical background reentries, and the natural meteoritic mass flux as a function of a global population of LEO satellites.[82] The figure shows that future spaceflight emissions will be dominated by the LLCs that would exceed the natural meteoritic background.

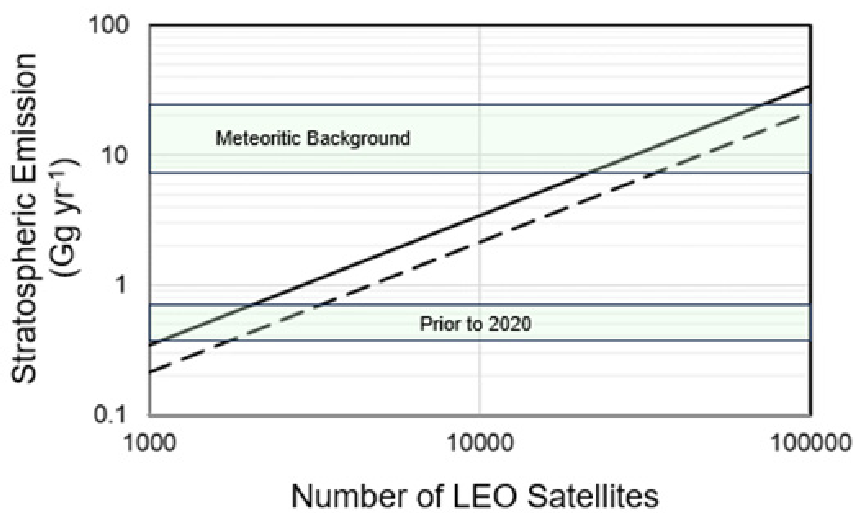


Figure 14. The number of LEO satellites compared to the meteoric background.

Though spaceflight emissions are not now regulated, scientific and regulatory interest is increasing as concern over stratospheric pollution more generally increases. Recent research has focused on mitigation by controlling emissions that map to technology and operations options. Reentry impacts, for example, are a function of reentry latitude and therefore could be minimized using controlled reentry latitude. The changes in design and operations that would follow regulation of disposal latitude could be significant.

To avoid "surprise" environmental impacts that require costly modifications of newly deployed systems, clarify how spaceflight differs from other particle sources that might be regulated, and support policymakers in their effort to manage the stratosphere, it is in the space industry's interest to better understand what is emitted by rocket engines and vaporizing spacecraft and how these emissions affect the atmosphere. NASA, NOAA, and the FAA are already carrying out research to better understand spaceflight's impacts on the global atmosphere.

Recommendation 3.8: **Support scientific investigation of spaceflight emissions and their global impacts.** Ongoing interagency scientific research requires supporting technical and operational data that can only be supplied by the space industry. Space industry players should be prepared to provide information such as engine design, test stand data, launch and reentry logs, propellant composition, and vehicle construction. Engineering tools routinely used by industry to predict engine performance or reentry survival can be modified to provide input to atmosphere simulations. Commercial spaceflight stakeholders could cooperate with the academic and technical research communities to provide this information, which increases the accuracy and efficacy of the science.

Recommendation 3.9: **Include environmental impacts into design considerations.** New research has focused on the relationship between space system architecture and operations and space system environmental impacts. Constellation design from launch vehicle choice (propellant-specific emissions) to following active disposal regulations (reentry emissions) and other mission aspects together determine environmental impacts. A more holistic analysis of space systems from launch to end of life that includes the couplings and influences of regulation, performance, cost, and schedule with respect to mitigating or minimizing environmental impacts would serve to prepare the industry for a future that will likely include some degree of regulation.

4. CYBER AND SPECTRUM

Space systems operate in a physical realm as well as a cyber realm. A complete space system has multiple components: ground network/infrastructure, launch infrastructure, up-and-down data links, space vehicle, space bus, and cross-data links. All these components are subject to cyber vulnerabilities and cyberattacks. To defend against these, proper cybersecurity should be integrated into the spacecraft and, from the beginning, into the ground infrastructure.

The following three sections and associated recommendations address one or more of the key aspects of cybersecurity—confidentiality, integrity, and availability (CIA)—defined by the Committee on National Security Systems Instruction (CNSSI) Glossary (no. 4009)[83] as follows:

1. **Confidentiality:** Preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information.
2. **Integrity:** Guarding against improper information modification or destruction, including ensuring information nonrepudiation and authenticity.
3. **Availability:** Timely, reliable access to data and information services for authorized users.

Cybersecurity should be tailored to fit the unique space system by the system designer/builder from the beginning of the lifecycle and through any modification and upgrade based on specific vulnerabilities and threats. Since no space system program has unlimited resources, a risk management approach helps the space system designers and operators to prioritize the resources against vulnerabilities and threats.

4.1 Establishing Space Cybersecurity Policy Standards and Risk Management Practices

Space threats are changing at an incredibly rapid pace. Cyber threats pose a significant and complex challenge due to the absence of a warning and the speed of an attack by an adversary, the difficulty of attribution, and the complexities associated with carrying out a proportionate response.[84]

In response, the U.S. government has given significant prominence to cybersecurity concerns. SPD-5[85] is the major directive that drives the core premise to design and integrate cybersecurity into our space systems. SPD-5 states, “The United States considers unfettered freedom to operate in space vital to advancing the security, economic prosperity, and scientific knowledge of the Nation. […] Therefore, it is essential to protect space systems from cyber incidents to prevent disruptions to their ability to provide reliable and efficient contributions to the operations of the Nation’s critical infrastructure.”

Based on SPD-5, our future space systems, which include spacecraft and payloads, must be made cyber-resilient and secure. It is critical to define robust cybersecurity principles and cyber requirements for space systems; engineer them into initial designs; use threat-informed, risk-based systems engineering; and apply defense-in-depth principles throughout space systems, particularly on the spacecraft themselves.

Recommendation 4.1: **Properly support and promote cybersecurity best practices.** SPD-5 serves as the foundation for the U.S. government approach, which includes working with the commercial space industry and other nongovernment space operators to further define best practices, establish cybersecurity-informed norms, and promote improved cybersecurity behaviors.

Space system owners and operators should promote the development of best practices to the extent permitted by applicable law. In collaboration, they should share threat, warning, and incident information, using venues such as information sharing and analysis centers (ISACs).

These best practices should be included early on to achieve a "built-in" cybersecurity approach instead of "bolt on" and promote a full lifecycle approach to cybersecurity. As per SPD-5, a "space system" is a combination of systems, to include ground systems, sensor networks, and one or more space vehicles that provides a space-based service. This includes integrating cybersecurity into all phases of the space system development.

Recommendation 4.2: **Provide cybersecurity requirements and guidance on next-generation platforms.** Increasingly, more systems are moving to the cloud or cloud-hybrid architectures, but not much cybersecurity guidance is provided for cloud security implementation. Providing cloud security requirements and implementation guidance for ground systems is essential for preventing threats to spacecraft and enhances overall security of the lifecycle. In addition, exploring cyber resiliency through self-healing artificial intelligence (AI) networks and machine-learning-driven platforms and providing related guidance in future implementation will set the path for future success.

4.2 Spacecraft Defense in the Cyber Domain

This section focuses on principles aimed at decisionmakers, acquisition professionals, program managers, and system designers to consider while acquiring and designing cyber-resilient spacecraft. These include issues such as onboard intrusion detection and prevention systems, hardware/software supply chain, and onboard logging. [86]

Current policies do not address the intersection of space and cyberspace, especially for spacecraft. Some examples of cyber threats to a typical space system are shown in Figure 15. These cyber threats occur across the entire space system and architecture. Therefore, cybersecurity specialists must apply a total system engineering approach that integrates and implements protections across the entire space system and architecture.

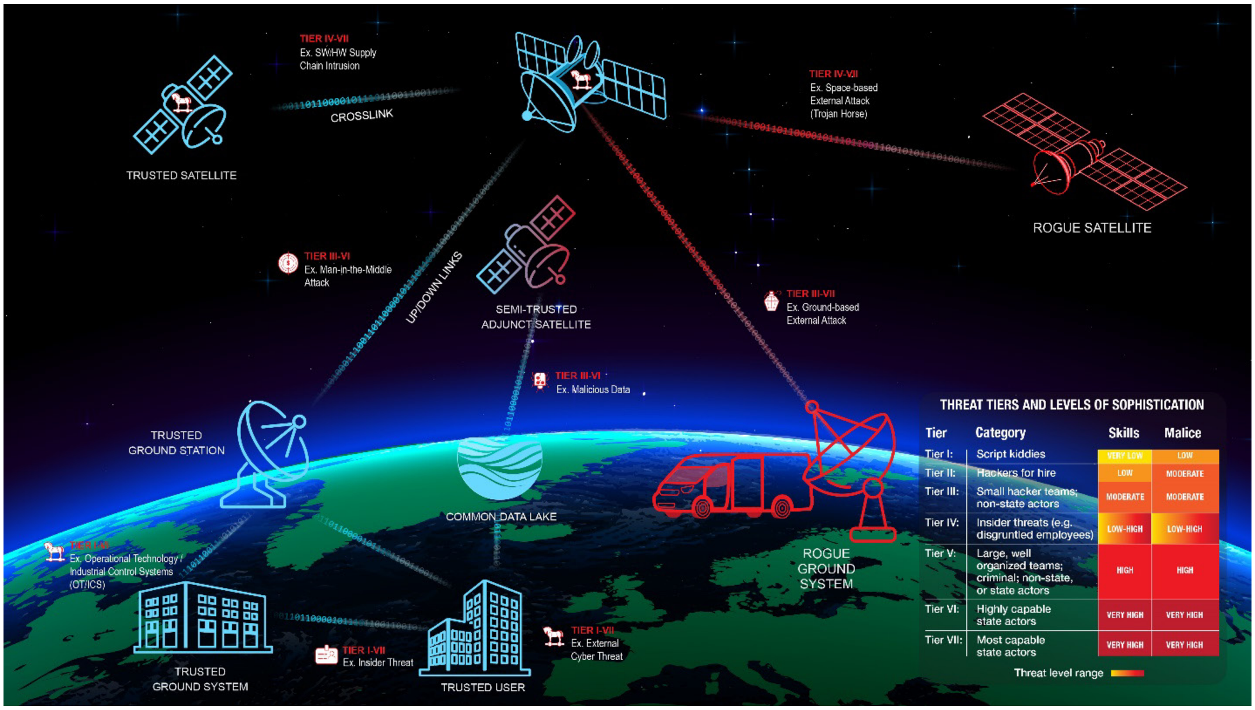


Figure 15. Cyber threats across space systems, including threat tiers and levels of sophistication.

Space systems operators should also implement additional spacecraft defenses to address emerging threats. Historically, spacecraft have been considered relatively safe from cyber intrusions. However, threats from adversary nation-state actors have made spacecraft a direct target. While space-centric cybersecurity standards and governance are lacking, utilizing defense-in-depth (DiD) techniques for spacecraft protection will help ensure the spacecraft is resilient to a cyber intrusion.

In 2022, Aerospace created the Space Attack Research and Tactic Analysis (SPARTA) framework to address the information and communication barriers that hinder the identification and sharing of space-cyber TTPs—tactics (high-level descriptions of behaviors), techniques (more detailed descriptions in context of behaviors), and procedures (highly detailed descriptions). SPARTA also provides a common language to facilitate information sharing and describe attacks on space systems (both theoretical threats as well as those documented in space or in laboratory settings) and mitigation methodologies. The framework is open source, allowing contributions from space stakeholders across the enterprise on novel, nascent, or evolving TTPs, including those involving AI.[87]

The Space ISAC is a nonprofit organization launched in 2019 to enable all-threat security information transfer between the public and private space sectors on vulnerabilities and incidents. It provides guidance to its members on threat mitigation and opened a watch center in March 2023, which leverages SPARTA in many ways, including its common lexicon.[88]

New developments that could contribute to spacecraft and network defense include many governments supporting secure-by-design principles. Shifting more security into technology manufacturing avoids placing security responsibility on the consumer. For example, many breaches have been caused by default passwords, such as administrator accounts with elementary or simplistic passwords (e.g., username "admin" and password "admin123"). While technology producers might blame consumers for inadequate cyber hygiene, it makes sense for manufacturers to simply remove these default passwords or insist they be changed to more complex passwords upon setup. These security-by-design concepts will also improve cybersecurity of space systems.[89]

Recommendation 4.3: **Develop and deploy DiD cybersecurity principles**. In the absence of formal policy and regulations, industry and government alike should implement DiD[§§§] and recoverability principles and cybersecurity plans throughout the ground and space vehicle architecture.

Implementation of meaningful cybersecurity hygiene is based on sound systems engineering approaches and allows the space system to operate through attacks to support mission-essential functions as much as possible for quick recoveries.

Recommendation 4.4: **Integrate onboard cyber-intrusion detection and prevention techniques.** Operators can identify and block cyber intrusions by leveraging signature-based detection, which assigns a unique identifier to known threats, allowing them to be detected more quickly in the future and helping facilitate machine-learning techniques. Additionally, integrating onboard logging can aid to verify legitimate operations and investigate anomalies.

Recommendation 4.5: **Apply robust supply chain risk management (SCRM) in cybersecurity and counterfeit-parts prevention planning.** Proper cybersecurity planning must include a SCRM program to protect against malware inserted into electronic components and modules. The program should follow best practices for software assurance methods within the software supply chain to reduce the likelihood of cyber vulnerabilities.

Without robust SCRM, counterfeit parts or components (hardware, software, or firmware) can be introduced into space systems. They may contain malicious code or be imitations or "knockoff parts" that do not function as intended by the system designer or owner, which can then affect mission assurance or even hasten mission failure.[90]

While policies and guidance are important, they can also be piecemeal and can almost immediately become out of date. To effectively counter modern supply chain threats, organizations must be flexible and responsive. An evolvable framework can be applied to identify and counter emerging cyber threats within a range of dynamic supply chain landscapes and circumstances, including pandemics like COVID-19, natural disasters, security risks associated with corporate entities (e.g., Huawei), and more. Getting and staying ahead of a

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[§§§]DiD principles offer an approach to cybersecurity that layers a series of defense mechanisms in order to protect valuable data and information. This approach will provide space system owners robust protection of space assets through multiple layers of security and through the acquisition and operations lifecycle.

constantly shifting threat environment will require a culture of collaboration guided by information-sharing, risk tolerance, process, and technology practices that highlight the targeted states of SCRM governance. This will allow organizations to proactively leverage and exchange peer knowledge, processes, and best practices. It also prompts analysis of future threats and effects across economic, geopolitical, and technological aspects that can help inform today's decisions.

4.3 Terrestrial Radio Interference to Space-Based Services

Terrestrial wireless service providers and equipment manufacturers have been lobbying for more spectrum to meet the growing demand for mobile data usage.[91] Calls for sharing spectral bands previously allocated for space-based services and encroachment of high-power terrestrial transmitters into the frequency bands adjacent to space-based services could place many critical national security, navigation, and weather- and water-monitoring systems at risk.

The increasing demand for spectrum and its finite supply will continue to present tough choices for regulators and commercial communications companies. A series of Aerospace papers illustrate the context of this ongoing debate and examine various policies for managing spectrum sharing.[92, 93]

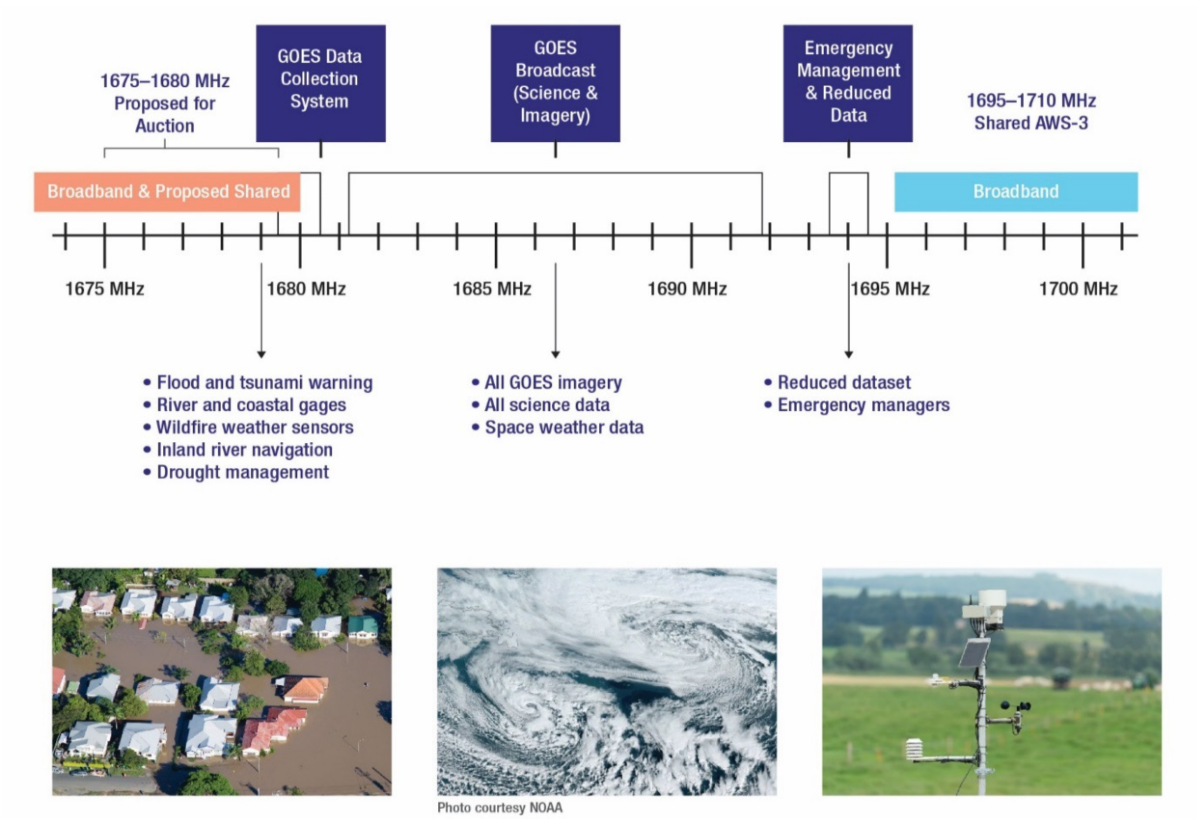

Figure 16. An example of the potential interference of Geostationary Operational Environmental Satellite (GOES) communications/transmissions.

Expanding spectrum sharing to include new entrants is often viewed as encouraging innovation in commercial communications. However, benefits to and from new entrants versus incumbents should be weighed fairly. With greater spectrum sharing, operators and users of space-based systems can no longer presume interference-free operation guaranteed by the FCC and the National Telecommunications and Information Administration (NTIA).[****] Space operators should prepare to mitigate against service degradation or interruption. All space-based systems and their users, including the aviation, weather, science, national security, and intelligence communities, need to "brace for impact."

Recommendation 4.6: **Conduct cost-benefit analyses of spectrum sharing and reallocation.** The current and future costs to agencies, industry, and the American public should be weighed against the revenue benefits to the U.S. Treasury and future licensees. Ideally, the FCC and its spectrum policy decisionmakers should fully consider the significant network investments already made by aviation; weather satellite; and PNT stakeholders and the benefits that they are producing for society.

Considerations should include:

- Economic benefits of existing satellite-based services
- Technical feasibility of mitigating terrestrial interference and the cost of mitigation
- The time it takes to develop, test, manufacture, and install technical mitigations.
- The consequences of abrupt changes to traditional spectrum allocations that contradict decades of careful planning. There could be unintended consequences to waivers or ad hoc, impromptu service rules.
- The unique physics of space-based services compared to terrestrial radio services, including potentially large differences in received signal power.

Recommendation 4.7: **Design space systems responsive to spectrum changes.** In light of the evolving spectrum environment, space system operators will need to design robust systems that are responsive to changes. In order to do so, they need to be aware of the radio frequencies they will operate in and monitor and participate in regulatory activities potentially affecting those frequencies.

[****] Rather than the loss of exclusive spectrum allocations, the greater challenge for space operators is the effect from terrestrial-based spectrum allocations in or near space allocations. These space allocations have historically been relatively quiet, and growth of new and adjacent terrestrial service spectrum allocations cause interference to long-standing, space-based spectrum allocations.

5. HUMAN SPACEFLIGHT SAFETY

How the United States operates in space has been undergoing dynamic transformation for several years. This trend is applicable as much to human spaceflight as it is to satellites and constellations, robotic missions and in-space servicing, or the development of infrastructure in LEO and cislunar space. Over the next decade, there are plans for five novel and distinct types of human spaceflight missions, four of which will be primarily driven and evolved by the commercial space sector:

1. NASA missions to the moon in support of the Artemis program
2. Suborbital commercial spaceflights that take off from and land at the same location, either for research purposes or for space tourism
3. Commercial missions to LEO
4. Commercial missions to the moon
5. Commercial point-to-point missions for high-speed, long-distance transportation

As human spaceflight evolves from a solely government-based arena to one of joint government and private industry, the U.S. government needs to ensure a defined and timely implementation of related regulations. These include:

- New approaches to mishap investigation and revising the legislative language in the NASA Authorization Act of 2005 to better integrate the current space environment.
- New performance-based regulations using the safety-case methodology, which would provide a flexible approach for operators to ultimately prove to the FAA how they intend to ensure the safety of their passengers.
- A "future-proof" safety framework focusing on people, safety culture, data collection, and analytics.
- Reassessment of current space rescue efforts and policies that accommodate a multi-vehicle, multi-orbit operating environment and proactively incorporate in-space rescue plans.

These efforts will result in a more resilient human spaceflight industry that is better able to reduce the risk involved in an accident, should one occur, and improve the viability of the industry.

5.1 Human Spaceflight Safety Regulatory Moratorium and Mitigating Concepts

Since 2004, the FAA has been under a moratorium from Congress that prohibits the issuing of regulations intended to protect the health and safety of crew, government astronauts, and spaceflight participants, which was recently extended again[94] through the end of 2024.

The moratorium, or learning period, was originally put in place in 2004 for eight years to help ensure that government regulations did not stifle the industry and that government and industry had the opportunity to gain experience adequate enough to inform the development of an appropriate set of regulations. At that time, eight years was considered enough time for sufficient data to be gathered for the FAA to institute at least some top-level regulations. Congress and other policymakers assumed that suborbital commercial spaceflights would begin soon after Scaled Composites won the XPRIZE in 2004, becoming the first private company to launch people to the edge of space. With the advent of commercial spaceflight taking longer to manifest, Congress extended the moratorium numerous times.

Figure 17. Active private crew-carrying spacecraft. Shown are SpaceX's Crew Dragon, Virgin Galactic's VSS Unity, and Blue Origin's New Shepard.

Meanwhile, commercial human spaceflight has increased rapidly in frequency since its eventual emergence, albeit with its own pauses. Blue Origin's New Shepard initially flew three suborbital flights in 2021 and 2022, carrying up to six passengers on each flight, but an anomaly on a September 2022 uncrewed flight caused the program to pause flights before resuming uncrewed operations in December 2023. Crewed flights resumed in May 2024, after a 22-month standdown. The Virgin Galactic spacecraft *VSS Unity* carried its first passengers in July 2021, but it paused operations for nearly two years before resuming flights approximately monthly in May 2023. SpaceX's Crew Dragon has flown private flights roughly annually since 2021, with several more planned for 2024 and beyond. Some of these, such as Polaris Dawn, extend private spaceflight into new territory, such as high-altitude and spacewalks.

In June 2024, Boeing's Starliner successfully conducted its first crewed flight to the ISS for NASA. However, after anomalies with the thrusters caused some concern for astronaut safety, a decision was made to err on the side of safety and return the vehicle uncrewed. Starliner returned safely to Earth in September, landing in New Mexico. NASA's plan is for the astronauts to remain on board the ISS until 2025 and return on a SpaceX Crew Dragon.

As the current licensing authority for commercial space launch and reentry, the FAA may be directed to assume additional regulatory responsibility for commercial human spaceflight should an accident occur before the moratorium expires. Meanwhile, the FAA has encouraged the voluntary development of industry consensus standards. Additionally, in April 2023, the FAA formed the Human Space Flight Occupant Safety Aerospace Rulemaking Committee for the Commercial Space Transportation Industry with the intent to engage the "commercial space industry to provide consensus information, concerns, opinions, and recommendations to the Department of Transportation."[95] The following recommendations may help better prepare the FAA and the industry writ large for ensuring human spaceflight safety in the future.

Recommendation 5.1: **Update human spaceflight mishap investigation requirements**. Mishap investigations are a pillar of human spaceflight safety as they are one of the most useful mechanisms of discovering and resolving problems in space systems design and manufacturing. There are three main mechanisms for investigating human spaceflight accidents, mishaps, and other incidents: the FAA, the National Transportation Safety Board (NTSB), and presidential commissions. There are also several interagency agreements that govern the investigation process. Despite the involvement of these various authorities, mishap investigation remains a fraught and uncertain process.

To begin, the NASA Authorization Act of 2005 required the president to establish an independent, nonpartisan commission to investigate any incident that results in the loss of either a U.S. space vehicle owned or contracted by the federal government or a passenger on that vehicle. This provision may have been appropriate for the Space Shuttle era but has outlived its usefulness within the current commercial environment. A presidential commission is unlikely to apply to commercial space vehicles and passengers; in fact, no such commission has been established under this statute to date.

The FAA does outline a mishap investigation process for its commercial space licensees. Mishaps include serious injury or fatality, or a high risk of it; malfunction of a safety-critical system; failure of safety operations; substantial damage to property; permanent loss of vehicle; impact of hazardous debris; and launch or reentry failure. A hurdle for human spaceflight mishap investigation at the FAA is its potentially conflicting dual mandate, which is to (1) oversee, authorize, and regulate launch and reentry of vehicles to ensure public health and safety, safety of property, national security, and foreign policy interests of the U.S. and (2) promote commercial space launches in the private sector, including those that involve spaceflight participants.

The NTSB is an independent investigatory agency that is charged with determining the facts, circumstances, and causes of all transportation accidents and incidents. In this role, the NTSB investigates and reports on aviation accidents and incidents, certain types of highway crashes, ship and marine accidents, pipeline incidents, bridge failures, and railroad accidents. It is also responsible for investigating any commercial space launch accidents that result in damage outside of the launch facility, such as was accomplished during the STS-107 accident. However, unlike the FAA, the NTSB has no regulatory authority to provide an independent assessment prior to launch.

On September 9, 2022, the FAA and the NTSB agreed that the NTSB will take the lead in investigating any accidents involving a "fatality or serious injury to any person, regardless of whether the person was on board the commercial space launch or reentry vehicle, or damage to property not associated with the commercial space launch or reentry activities or the launch site, from debris that could reasonably be expected to cause death or serious injury." The FAA will handle other commercial space mishap investigations.[96] While this is an important step forward, several issues must still be addressed either through updated interagency agreements or expanding the scope of current rules and regulations. These issues include:

- Statutory authority and regulation must be clear to avoid regulatory uncertainty and outline roles and responsibilities among involved agencies.
- Regulation must balance industry goals with public safety.
- Independence and transparency of this process will be critical in developing a successful human spaceflight industry that values and sustains the public's trust.

Recommendation 5.2: **Implement a safety-case approach to human spaceflight**. Government regulations can be prescriptive or performance based. When the U.S. Air Force crafted the original safety requirements for the Eastern and Western Ranges, most were very prescriptive, specifying precisely how flight safety systems were to be designed, tested, inspected, and operated. In recent years, performance-based regulations have become more popular and desirable due to their flexibility in accommodating new commercial approaches and technologies. With this approach, government launch regulators specify what the end objective is rather than how to achieve that objective. The downside of this approach is that contractors may not understand exactly what the government is looking for or how to demonstrate that their systems satisfy the stated requirements. The government, in turn, may have a more difficult time determining whether its requirements have been met.

One promising approach for implementing performance-based regulations is the safety-case methodology, which has been widely used by other industries and national governments, most notably the UK. A safety-case approach can be defined as "a structured argument, supported by a body of evidence that provides a compelling, comprehensible, and valid case that a system is safe for a given application in a given environment."[97] In other words, the burden of proof is on the launch provider to use whatever means is most effective.

To implement a safety-case approach, the FAA could allow launch license applicants to choose between complying with existing regulations or following an alternate process. The alternate process would require applicants to fully implement a performance-based regulatory philosophy, along with the requirement for launch operators to accept responsibility for operating safely and the necessity of advocating for safety. The alternate process could also consist of a voluntary audit of the applicant's safety and risk management program, followed by the development of a safety case in which the applicant would present evidence, in the form of engineering analysis and test data in their own format, showing how public crew and spaceflight safety would be protected. In terms of who would conduct the safety audit, the FAA could either conduct the safety audit and safety-case assessment itself or obtain the support of a knowledgeable, experienced, and independent third party to carry out those responsibilities.

Recommendation 5.3: **Develop and implement a future-proof safety framework.** As commercial space activities in human spaceflight continue to evolve, they will include a variety of transportation means (e.g., horizontal launch, vertical launch, balloon launch) and destinations (e.g., point-to-point, suborbital, orbital, geostationary orbit [GEO], cislunar, and even interplanetary). A safety framework for commercial human spaceflight should be performance-based and non-prescriptive in order to accomplish that goal.

Based on Aerospace's analysis of case studies of other analogous sectors, any successful safety framework should focus on the most fundamental components, which include prioritizing people, a positive safety culture, and data and analytics to help continuously improve safety. The SSI presented a recommended framework for commercial human spaceflight safety to the FAA in 2023 based on these analyses, taking into consideration current and future commercial activities regardless of the development status of individual spaceflight companies. The developed safety framework is flexible in order to recognize new developments, new transportation mechanisms, and new spaceflight destinations as they emerge.[98]

5.2 The In-Space Rescue Capability Gap

In accordance with the Commercial Space Launch Amendments Act of 2004, which initialized the spaceflight regulatory moratorium, current FAA policy does not regulate the safety of the space participant. The policy simply mandates that the participant be informed of associated risks. Therefore, in the absence of voluntarily crafted rescue plans and dedicated resources, today's spaceflight participants journey entirely at their own risk.

One of the risks spaceflight participants undertake is the fact that they might not have access to a timely rescue in the event of danger or an emergency situation. Neither the U.S. government nor commercial spaceflight providers currently have plans in place to conduct a timely rescue of a crew or participants from a distressed spacecraft in LEO or anywhere else in space.[99]

Apollo 13 demonstrated the lifesaving properties of two spacecraft capable of sustaining the crew during the journey to the moon. In similar fashion, historical maritime explorers, such as Ferdinand Magellan, sailed with multiple ships. NASA's Artemis missions, however, will use a single spacecraft for transiting the crew between Earth and lunar orbit. During all Skylab missions and the final space shuttle Hubble Space Telescope servicing mission, NASA had rescue rockets and spacecraft ready in the event that an on-orbit spacecraft were to be disabled in space.

The space enterprise is well reminded of the safety lessons learned from the Apollo, Skylab, and Space Shuttle programs with respect to the rescue of astronauts, especially as the number of humans in space will undoubtedly continue to rise in the era of commercially provided spacecraft, space tourism, and the return of U.S. astronauts to the moon. Though there are currently no rescue plans in place for any U.S. crewed space missions, this is a hard problem worthy of our immediate and collective attention.

The June 2023 implosion of OceanGate's *Titan* submersible[100] while diving to inspect the wreck of the *Titanic* provides an interesting analog of issues similar to those we are facing for space safety. The submarine was of a novel design and was operating in international waters where it was not subject to the safety regulations of any nation. The company's founder and vessel's inventor, Stockton Rush, had seemingly fostered a safety-averse corporate culture, having repeatedly stated that the U.S. Passenger Vessel Safety Act of 1993 needlessly prioritized passenger safety over commercial innovation." [101] Mr. Rush refused to have OceanGate vehicles certified by outside experts, according to testimony before a U.S. Coast Guard panel investigating the *Titan* incident.[102]

OceanGate had no capability to rescue the crew and passengers in the event of an emergency. Multiple nations with submarine rescue capability immediately sent aid and provided considerable resources to locate and attempt to rescue those on board, but the aid arrived well after the incident, possibly too late even if the *Titan* had been merely disabled. Even if the passengers on the *Titan* had survived in a disabled vessel, the design would have prevented any of the existing rescue vessels from docking and removing the crew.

The present posture of not planning for in-space rescue and not having responsive in-space rescue capabilities needs to be addressed before the need for a rescue materializes, not after. Potential solutions are available and need to be established with a sense of urgency. Key capabilities for in-space rescue include common docking mechanisms for all crewed spacecraft, timely availability of a rescue spacecraft or a safe haven to escape to, and charters and sufficient resources for organizational entities—government, commercial, and/or international—to plan for, train for, and conduct in-space rescues.

Recommendation 5.4: **Address the in-space rescue capabilities gap.** Government, commercial, and international organizations should account for and develop proactive capabilities for in-space rescue. OST Article V (1967) alludes to the potential need to rescue astronauts in space. It says, “In carrying on activities in outer space and on celestial bodies, the astronauts of one State Party shall render all possible assistance to the astronauts of other State Parties.” It does not require nations to proactively develop capabilities to enable rescue of astronauts in space nor does a second treaty, the “Rescue and Return Agreement” of 1968, which focuses on the rescue and return of astronauts that have made emergency landings somewhere on Earth.[103, 104] Both of these agreements are affirmed by the Artemis Accords, a set of shared principles for the safe and peaceful exploration of space developed by NASA and the U.S. Department of State and signed by 41 other nations as of this writing.[105]

While the aforementioned treaties and accords do not require nations to develop space rescue capabilities, Article 98 of the United Nations Convention on the Law of the Sea (UNCLOS) requires every coastal state to promote the establishment, operation, and maintenance of an adequate and effective search-and-rescue service regarding safety on and over the sea and, where circumstances so require, by way of mutual regional arrangements with neighboring states for the purpose of search and rescue. The United States, while not having ratified UNCLOS, nonetheless abides by its principles. U.S. leadership among the spacefaring nations can be demonstrated by promoting effective search-and-rescue capabilities.

Recommendation 5.5: **Ensure that operators utilize common docking systems for spacecraft**. Common docking systems can support and improve in-space rescue efforts. In October 2010, NASA, ESA, the Canadian Space Agency, JAXA, and the Russian Federal Space Agency jointly developed the International Docking System Standard (IDSS), derived in part from the Apollo-Soyuz test project. The preface to the standard states that the IDSS Interface Definition Document (IDD) “establishes a standard docking interface to enable on-orbit crew rescue operations and joint collaborative endeavors utilizing different spacecraft.” Adhering to this standard will mean that any spacecraft with a compliant international docking system can dock with any other spacecraft with such a docking system. It is important to ensure that all crewed spacecraft have an IDSS-compliant docking adapter so they can easily dock with rescue spacecraft.

NASA has already taken the first steps along these lines by developing a draft document (at the request of the commercial companies) aimed at providing the companies as much flexibility as is possible in a common docking system. This document, CLDP-STD-1101, Commercial LEO Development Program (CLDP) Common Docking System Standard (CDSS), was based off the previously existing IDSS and will be released before the end of this calendar year.

Recommendation 5.6: **Integrate rescue plans into launch plans.** Having the ability to integrate a rescue spacecraft with the next available rocket ready to launch could provide a modest rescue capability for distressed spacecraft in Earth orbit. Orbital launches are occurring with increasing frequency worldwide; there is, on average, a rocket available within approximately three days of launch at any given time of the year. If rescue plans were integrated into launch plans, rockets sitting on launch pads could be utilized for in-space rescue as well. This requires prelaunch determination of the various vehicles’ orbit compatibility, including whether there is enough propulsive capability onboard the rescue spacecraft to dock in the necessary orbit and accomplish a successful rendezvous in a timely fashion.

6. CISLUNAR SPACE

While this compendium has focused extensively on LEO and safety in the context of LLCs, we must not lose sight of the reach of the space enterprise to higher orbits. Today, there is growing emphasis on much higher orbits, including cislunar space, and this will only increase over the next decade.[††††]

The term "cislunar" can have multiple definitions—including only the region near the moon or the region of space between Earth and the moon. We define cislunar space here as the region of space within Earth's gravitational influence, which includes both Earth and the moon, the lunar surface, and several other orbits of interest, out to an approximate altitude of 550,000 km.

In November 2022, the White House released the National Cislunar Science and Technology Strategy,[106] whose purpose is to provide a vision for realizing U.S. leadership in the responsible and sustainable utilization of cislunar space. The strategy includes a directive that "the U.S. government will support development of best practices related to debris mitigation, minimizing the hazard of Lunar landing ejecta, end-of-life operations, mishap reporting, collision avoidance, and other events associated with safety of flight."

The White House's strategy clearly signals the importance of cislunar space's sustainability, but the government's primary means of influencing sustainable behavior as it pertains to debris—the ODMSP[6]—was composed without cislunar operations in mind. Many aspects of operating in the cislunar regime are incompatible with ODMSP requirements as initially written, and unless or until they are updated in correlation with the uptick in cislunar space activity, forthcoming cislunar missions for NASA, defense organizations[107], and the commercial space industry[108] must plan sustainable operations despite this ambiguity. The Artemis Accords—established in 2020, one year after the last ODMSP review cycle—do commit signatory nations in the meantime "to plan for the mitigation of orbital debris…as part of their mission planning process" and "to limit the generation of new, long-lived harmful debris…by taking appropriate measures such as the selection of safe flight profiles and operational configurations as well as post-mission disposal of space structures."

Orbital motion in cislunar space (Figure 18) is more challenging to predict and control than orbits close to Earth. At and below GEO, Earth's gravity dominates a spacecraft's motion, which follows an elliptical orbit. These "Keplerian" orbits obey Kepler's laws of planetary motion and admit straightforward solutions for their behavior. Even if other small perturbing forces act on a Keplerian orbit, the motion remains approximately elliptical and hence predictable. However, as the orbit's altitude increases, the moon's gravity becomes another meaningful force. At around 100,000 km altitude, which is roughly three times higher than GEO, the moon can no longer be considered a small perturbation. In this "three-body problem," the comparable gravitational attractions from Earth and the moon cause more complex behavior that does not allow for

[††††]The National Cislunar Science and Technology Strategy and this paper define cislunar space as "the three-dimensional volume of space beyond Earth's geosynchronous orbit that is mainly under the gravitational influence of the Earth and/or the Moon."

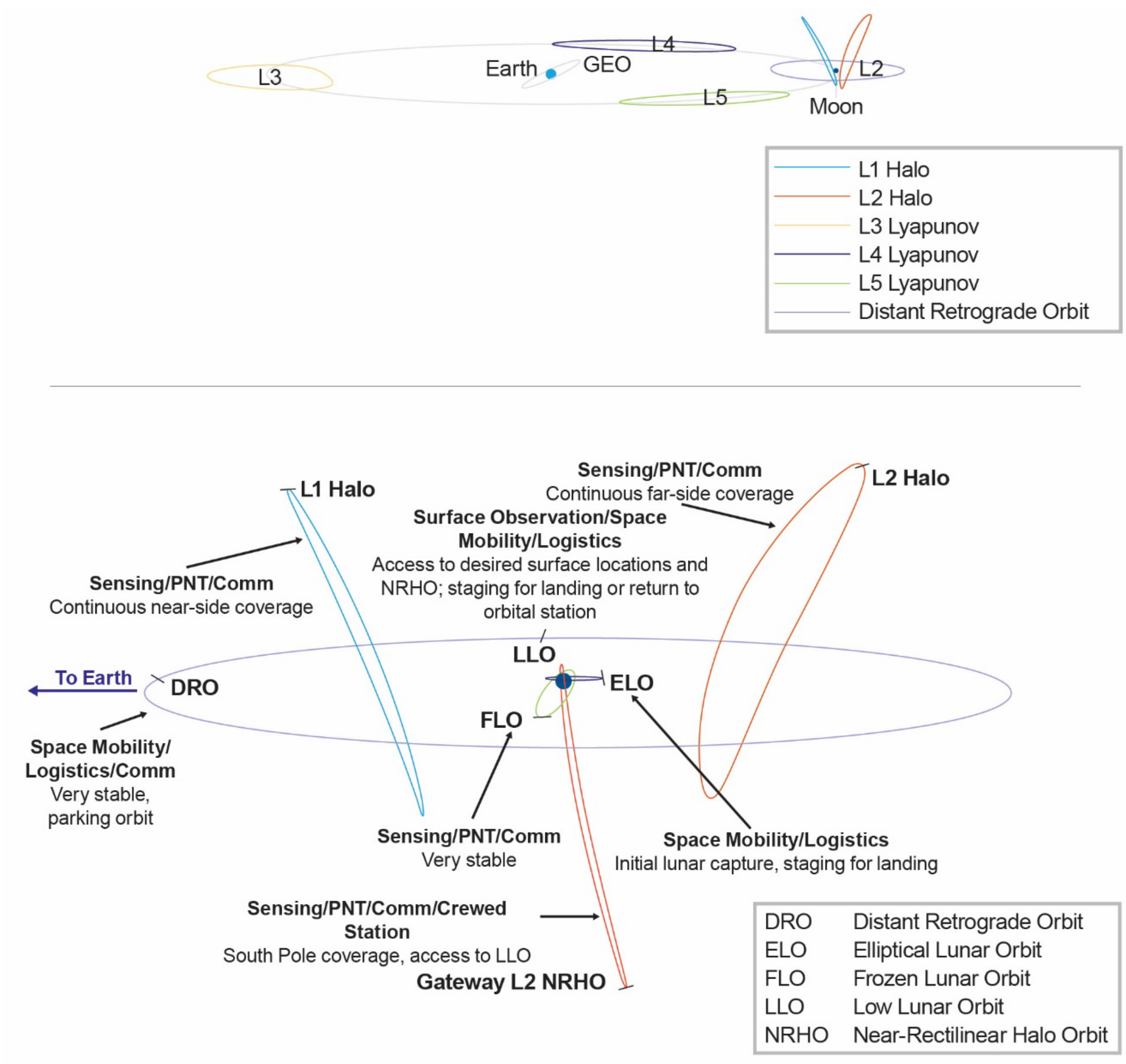

Figure 18. Cislunar space, showing the Earth-moon system and its Lagrange points. This is the region where both Earth and lunar gravity must be considered for orbit prediction. Key orbits for cislunar missions are shown.

simple solutions. Gravitational interactions with Earth and the moon in this cislunar regime destabilize the system from familiar Keplerian ellipses and can cause chaotic behavior. Although periodic orbits—such as "halo orbits" near Lagrange points and "distant retrograde orbits" at the moon—do exist in the cislunar regime, the complicated dynamics make it very difficult in general to predict the future position of a spacecraft even if its initial conditions are known with high precision.

The fundamental difference in behavior between cislunar and near-Earth orbits has substantial implications on the composition of rules and policies related to debris mitigation, safety of flight, and disposal. If you cannot predict long-term behavior in cislunar space, how can you write a rule about disposal that should apply to a spacecraft for a century or more? If cislunar orbits are extremely sensitive to initial conditions, how can a spacecraft vent its propellant tanks at the end of its life without upsetting its targeted disposal orbit? What role should the moon itself have in cislunar spacecraft disposal, as we allow atmospheric reentry at Earth today? These questions and others largely remain open.

This section offers recommendations on several notable issues surrounding the development and implementation of policy for sustainability in the cislunar regime. Resolving many of these issues will require a whole-of-government approach buoyed by extensive analysis, with input from civil, national security, and commercial stakeholders as well as the international community of stakeholders committed to the Artemis Accords. As the number of U.S. and international missions to cislunar space continues to grow, ad hoc agreements and waivers are not sustainable options. In June 2022, Aerospace called for the establishment of a cislunar master planning effort.[109] Without a new effort to revise policies and rules like the ODMSP to account for cislunar operations, the enterprise runs the risk of setting bad precedents with a patchwork of exceptions, waivers, and idiosyncratic interpretations of the rules that will imperil the long-term sustainability of space beyond GEO.

6.1 Space Domain Awareness in Cislunar Space

The currently deployed architecture for space domain awareness (i.e., the U.S. SSN, foreign SSA systems, and newer commercial SSA systems) has insufficient sensitivity and coverage to ensure adequate flight safety in a highly populated cislunar regime. Section 0 of this compendium has already noted in detail how SSA is foundational for understanding the space environment and is critical to all space safety activities. The safe and sustainable exploitation of the cislunar regime will require the same foundation. However, cislunar missions operating 10 times farther away than GEO cannot be detected except by the most powerful of the SSN's assets, and the volume of cislunar space is so large that discovery and custody maintenance are a considerable challenge. Most actors in cislunar space to date have entered the regime in a spirit of collaboration and coordination, but the proliferation of nations and commercial operators there will strain the scalability of one-on-one interactions for flight safety. Also, the extension of economic interests to the moon may introduce incentives not to be forthcoming about behavior in space or on the lunar surface. The United States should have a means of monitoring noncooperative activity in this regime.

Recommendation 6.1: **Extend the nation's SSA architecture to cover cislunar space.** A cislunar SSA architecture should be capable of the same functions as its geocentric counterpart, including detection, discovery, tracking and custody maintenance, identification, and characterization. All these functions, supported by a combination of ground- and space-based assets, should feed into a data-integration and -exploitation ecosystem that provides safety-of-flight services (e.g., CA and RMM) to operators in cislunar space, as is currently offered in LEO and GEO. The size and scope of this architecture is an area of ongoing analysis and discussion. The opportunity is open today to establish a roadmap and funding for a cislunar augmentation of the SSN, before the demand for safety-of-flight services becomes overwhelming and potentially forces operators to seek options that are less in the interest of the United States.

6.2 Cislunar Collision Risk and Mitigation

Close approaches and mitigation maneuvers are becoming relevant beyond Earth's orbit. The growing population of spacecraft in cislunar and Martian space is increasing the risk to all operators there. In November 2021, the Lunar Reconnaissance Orbiter and the Indian research satellite Chandrayaan-2 had a conjunction close enough to prompt a risk reduction maneuver (RMM).[110] This RMM in cislunar space had become necessary with only a small number of active objects in lunar orbit, due to the use of similar orbits. As the population increases from a growing community of international, commercial, and military actors, and as the monitoring of cislunar space debris begins with the arrival of new space domain awareness capabilities, frequent RMM may become the norm in cislunar space as it is at Earth.

The U.S. government does not have an operational capability for tracking, cataloging, and producing RMM products for cislunar or lunar orbits. The heritage capabilities and data products developed for geocentric safety of flight do not admit a ready translation to another central body or another multi-body reference frame, even if there were a process to use to produce these products. The leading alternative for cislunar flight safety is the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP), an operational process at the NASA Jet Propulsion Laboratory that screens ephemerides for spacecraft not orbiting Earth.[111] Participation in MADCAP is voluntary for operators outside of NASA, and MADCAP screens ephemeris data from those volunteers. MADCAP's conjunction assessments have prompted several RMM actions, beginning with maneuvers between Mars orbiters in 2005. Once objects in cislunar space can be tracked non-cooperatively, a scalable close approach screening system using that catalog of data will be possible. Since debris at the moon cannot currently be tracked, it is important for operators to share their ephemerides with MADCAP to prevent collisions and thus protect other spacecraft and future astronauts.

Recommendation 6.2: **Develop and deploy upgraded collision-risk-assessment and RMM capabilities that are valid in the cislunar regime.** Conjunction assessments and RMM have extensive heritage in LEO, medium Earth orbit (MEO), and GEO, but many of the underlying algorithms and processes include assumptions that do not apply in the cislunar regime. Furthermore, actionable conjunction assessments require realistic estimates of orbit uncertainty, which today are largely unavailable in cislunar space and may not become available until a more extensive architecture of space domain awareness assets comes online.

6.3 Disposal on the Lunar Surface

Current disposal rules and policies do not directly address the acceptability of lunar impact as a disposal option. Impact with the lunar surface has been a favored disposal option since the beginning of the Space Age, both for NASA (e.g., GRAIL, LCROSS, LADEE, etc.) and other nations (e.g., Japan's Kaguya and China's Longjiang-2). The advantages of impact are two-fold: it permanently removes the spacecraft from the space environment, and it provides an incidental opportunity to advance lunar science via observation of the impact ejecta. For spacecraft in lunar orbit or cislunar orbits near the moon, the only practical disposal option may be impact. The large propulsive change in velocity necessary to depart the moon again for heliocentric escape, return to Earth, or other disposal options might be achievable for only the largest space missions. Figure 19 shows the cost in ΔV for departing lunar orbits for other cislunar orbits, whence a mission might proceed to final disposal. Any departure from low lunar orbit (LLO) requires at least 500 m/s of ΔV, and even from higher frozen lunar orbits (FLOs) or elliptical lunar orbits (ELOs), the necessary ΔV is measured in hundreds of meters per second. Most smaller missions, especially those in micro- and nanosatellite form factors, would be incapable of supplying sufficient propulsion capacity to achieve these changes in velocity.

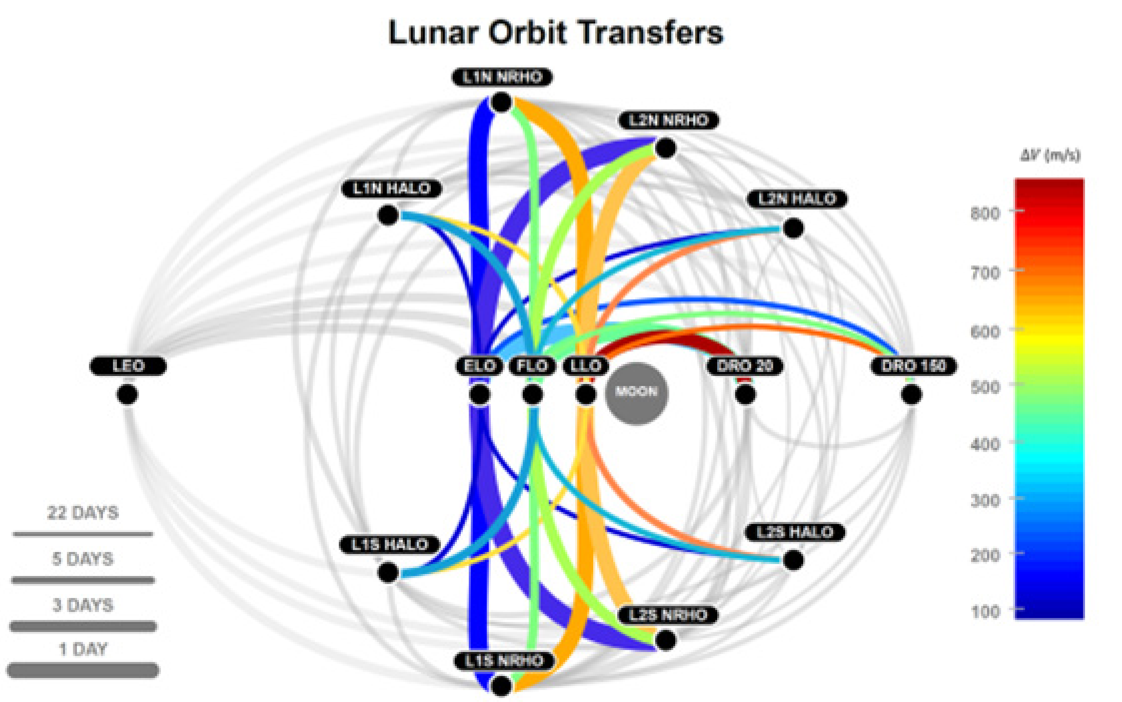

Figure 19. Lunar "transit map" showing ΔV required for transit between various types of orbits. The ΔV required to exit a location to another orbit for disposal may be substantial.

With a growing cislunar population, it is unclear how a higher frequency of lunar impacts would affect the lunar environment. Lunar impacts will eject dust, debris, wreckage, and potentially toxic propellants in all directions that could endanger other lunar orbiters and activity on the surface. The OST obligates the United States to protect the moon from "harmful contamination" and to avoid "potentially harmful interference"[44] to other nations' activities. But the scope of such contamination or interference remains unclear. Future activity at the moon will depend on finding the appropriate balance in policy between preserving the moon's pristine condition for posterity and encouraging the development of human interests there.

Recommendation 6.3: **Develop policy and requirements that address the validity and acceptability of lunar impact as a disposal option.** New requirement language should explicitly address lunar impact, either introducing it as a valid disposal option or restricting or prohibiting its use under specific conditions, such as damage to a scientifically critical impact site. This new option should address whether it is limited to natural orbital decay or only to controlled impact, limitations on post-mission lifetime, if and how missions should comply with planetary protection, and how to evaluate and mitigate casualty risk on the moon.

6.4 Other Cislunar Disposal Options

Missions to cislunar space need disposal options that are consistent with the realities of operating there. Cislunar space is vast, and it may not be feasible or affordable for most missions to default to currently sanctioned disposal options, such as reentry at Earth or transferring to approved graveyard orbits (e.g., near GEO). However, the great volume of cislunar space does not mean that derelict missions should be left in place, which was the historical practice for geocentric missions until the late 20th century. In the multi-body gravity of the Earth-moon system, objects tend to traverse the entire volume of cislunar space over years-long timescales. A mission abandoned in a random state in cislunar space has a high probability of passing through regions of great interest, such as Lagrange points, at random intervals and posing a risk to active spacecraft there.

Recommendation 6.4: **Update current disposal options to be consistent with cislunar operations.** The ODMSP recognizes a valid disposal option of "storage above GEO," where a spacecraft must maneuver "sufficiently above GEO to ensure the structure remains outside GEO for >100 years." We recommend that the next ODMSP update revisit the current equal treatment of all space above GEO. "Storage above GEO" likely requires a ceiling.

Furthermore, the ODMSP offers "heliocentric Earth escape" as a disposal option, but no further guidance or definitions are provided. "Earth escape" has meaning in the Keplerian two-body sense, but in the three- and multi-body problem, it is possible to have escaped in the Keplerian sense but still return. This behavior has been observed several times, including an Apollo 12 upper stage, Apollo 10 lunar module, and others. The ODMSP should include a new definition of "heliocentric Earth escape" to capture the spirit of the original requirement, namely, to ensure that disposed vehicles do not return to the Earth-moon system for decades or even centuries.

Recommendation 6.5: **Determine the viability of new disposal orbits in cislunar space and develop policy to guide their potential adoption.** The ODMSP should identify new long-term disposal orbits in the cislunar regime, if any are appropriate and meet criteria for sustainability. The viability of a candidate cislunar disposal orbit will require an evaluation of:

- The orbit's sustainability, which includes whether the region is stable enough to ensure the confinement of derelicts over a long period of time, whether the derelicts in the graveyard pose a risk to active missions nearby, and what the carrying capacity of the graveyard may be.
- Opportunity costs to using the orbit in light of active missions that may want to use the same region of space.
- The disposal orbit's reachability and costs in terms of transfer time, propellant, and operational complexity for insertion, which would affect the graveyard's palatability to mission planners regardless of its sustainability.

Even if all three assessments indicate that a cislunar disposal orbit is viable, the underlying normative question remains whether the disposal orbit should be exploited at all. New policy will therefore be needed to guide the appropriate adoption of notional cislunar disposal orbits.

Recommendation 6.6: **Develop definitions of cislunar protected regions for post-mission disposal and flight safety.** Many cislunar orbits in the Earth-moon system have great utility for human and robotic spaceflight, but no policy exists to codify whether or how they should be protected. The ODMSP clearly defines LEO, MEO, and GEO regions where flight safety and long-term disposal rules apply, but no such definitions yet exist for useful cislunar orbits, including Lyapunov or halo orbits near the Earth-moon or sun-Earth Lagrange points; near-rectilinear halo orbits and distant retrograde orbits near the moon; or frozen orbits around the moon. These regions of high utility in cislunar space are vast—far larger than the protected volumes of LEO, MEO, or GEO—and do not admit easy definitions in terms of altitude bounds. Orbital elements have no meaning in the multi-body regime. Action should be taken to determine how best to categorize cislunar orbits into regimes that are general enough to be documented succinctly in policy but are also quantitative enough for flight safety and disposal purposes.

7. NEXT STEPS – COLLABORATION AND BALANCING RISKS

This *Compendium* has often referenced the idea that actions in one area can directly impact another, and that the approach to space safety should be holistic. An example of this is the trade between on-orbit safety and reentry risk. ADR focuses on removing objects from orbit to reduce the risk of collision and damage to active spacecraft and to create a more sustainable space environment. However, almost all ADR approaches accomplish this by having the debris reenter the atmosphere, usually in a random, uncontrolled location. ADR improves space safety, albeit while potentially degrading reentry safety. Even if the debris "burns up" with little risk to people on the ground, it might have a negative or at least unknown impact on the atmosphere. How should we balance or prioritize on-orbit risk against reentry risk?

In the example above, the risk to people comes from random reentry, which can be mitigated by performing a controlled reentry. But controlled reentries almost always require a large, impulsive maneuver to bring the object down steeply enough that it reenters in a known, remote location. This may mean adding an extra motor to a spacecraft and could complicate command and control. It adds mass, testing, and risk to operations and constrains disposal. Potentially, an on-orbit failure would have greater debris consequences. Again, the benefits of reducing reentry risk must be balanced against increased complexity, on-orbit risk, and cost implications.

In addition, there is often a sharp difference between the statistical risk and the public perception of risk. Much of science and government policy is driven by statistics, but public perception and politics are more often driven by anecdotes and incidence. For example, 2009's Iridium-Cosmos collision dramatically changed the public perception of space debris and orbital risk, even though such an incident was statistically expected. One serious injury to a person or damage to a structure from falling reentry debris could similarly and drastically change the public perception without altering the statistical risk. For example, on March 8, 2024, a bolt about the size of a soda can from a disposed battery pallet from the ISS punched through the roof and second floor of a home in Naples, Florida.[112] No one was injured, but a resident was home and close to the point of impact. This sparked a flurry of media interest and speculation on the responsibility and liability of space operations. The average person already would likely be more concerned about the risk to people (i.e., themselves) on the ground than the risk to a robotic spacecraft in orbit.

It is important to consider all the ways in which our actions in one arena might impact other aspects of safety. The space enterprise has been growing rapidly because the benefits of space activity are so important to society. But how should we balance risk and make trades when they need to be made? How do we make certain that a sufficient number of stakeholders participate and that we have a sufficiently diverse set of viewpoints? Since no one entity "owns" the inter-related problems or controls the space and Earth environment, the only feasible way appears to be broad collaboration.

Aerospace seeks broad collaboration from all stakeholders addressing the inter-related issues concerning space safety and operations.

As we stressed earlier in this *Compendium*, safety is a broad, shared objective, and it invites a number of distinct yet interconnected challenges that no single individual or organization can solve alone. An impressive array of associations and consortia of varying makeup, scale, and scope are already hard at work addressing these challenges, including but not limited to the Aerospace Industries Association, American Institute of Aeronautics and Astronautics (AIAA), Commercial Spaceflight Federation, CONFERS, COSMIC, International Association for the Advancement of Space Safety, IADC, International Organization for Standardization (ISO), Space Safety Coalition, and Space ISAC. These various groups do often feature a cross-section of small to large commercial, government, nonprofit, and international space organizations among their respective memberships.

However, as referenced throughout this *Compendium*, there are technical and policy areas and specific capability gaps that are not receiving holistic consideration from an integrated space enterprise perspective. Aerospace is exploring the formulation of a consortium or organization to fill these gaps and unify enterprise efforts to advance space safety. This consortium would be synergistic with and broadly inclusive of U.S. government agencies, commercial companies, consortia, researchers, and other organizations involved in some facet of supporting the long-term sustainable use of outer space. A proposed consortium would provide stakeholders with:

- Physics- and engineering-based analyses and databases to inform safe space operations, governance, policy, and management.
- Shared safety lexicon to harmonize communications and enable the collaborative development of standards, norms of behavior, and policy for the entire community.
- Advanced modeling and tools development for community access.
- International coordination informing regulatory, policy, and standards development; conformance assessment; and evolution.

Aerospace is actively engaged in discussions with representatives across all sectors of the community on this topic, and we are eager for feedback, insights, or suggestions on the concept of a consortium tackling space safety from an integrated space enterprise perspective, including feedback to expand the comprehensiveness of research products such as this compendium. Queries and comments should be sent via email to SSI@aero.org.

8. CONCLUSION

The 1920s are sometimes referred to as the "Golden Age of Aviation." During that period, there were plenty of barnstorming and air races, and Charles Lindbergh made his nonstop flight across the Atlantic. Perhaps someday, the 2020s will be referred to as the "Golden Age of Commercial Space," a distinction better-earned through partnerships and focused collaboration on improving safety than through the reckless feats of daredevil pilots and wing-walkers.

This *Space Safety Compendium* highlights many of the challenges the space sector faces in this era of enhanced commercial space activity. It covers policy implications of challenges, issues, and opportunities within our core mission areas and offers key actions and recommendations for decision- and policymakers to tackle those challenges.

These recommendations are based on a collection of Aerospace and community studies, policy papers, and presentations that offer some pathways forward to address these challenges. These are by no means comprehensive but rather offer some next steps to continue to build the knowledge base and policy frameworks needed to address the increasingly complicated question: How do we keep space safe so that Earth and its inhabitants continue to benefit?

The SSI hopes to work across these areas with all stakeholders to foster collaboration and help enable norms of behavior, best practices, and integrative strategies for public and space safety.

ACRONYMS

ADR	Active debris removal
ADS-B	Automatic dependent surveillance-broadcast
AI	Artificial intelligence
AIAA	American Institute of Aeronautics and Astronautics
ASAT	Anti-satellite
CA	Conjunction Assessment
CDSS	Common Docking System Standard
CIA	Confidentiality, integrity, and availability
CLDP	Commercial LEO Development Program
CMLS	Consolidated Master Launch Schedule
CNSSI	Committee on National Security Systems Instruction
COLA	Collision avoidance
COMSPOC	Commercial Space Operations Center
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COPV	Composite overwrapped pressure vessel
CORDS	Center for Orbital and Reentry Debris Studies
COSMIC	Consortium for Space Mobility and In-Space Servicing, Assembly, and Manufacturing Capabilities
CSPS	Center for Space Policy and Strategy
CSSI	Center for Space Standards and Innovation
DARPA	Defense Advanced Research Projects Agency
DART	Demonstration of Autonomous Rendezvous Technology
DAS	Debris Assessment Software
DiD	Defense-in-Depth
DOC	Department of Commerce
DOD	Department of Defense
ELO	Elliptical lunar orbit
EO	Electro-optic
ESA	European Space Agency
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FLO	Frozen lunar orbit
FY	Fiscal year
GEO	Geostationary Orbit
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSaaS	Ground Station as a Service
HIS	Hyper-Spectral Imagery
IADC	Interagency Space Debris Coordination Committee
IDD	Interface definition document
IDSS	International Docking System Standard
IoT	Internet of Things
ISAC	Information sharing and analysis center
ISAM	In-space servicing, assembly, and manufacturing
ISO	International Organization for Standardization

ISS	International Space Station
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union
JAXA	Japanese Aerospace Exploration Agency
JSpOC	Joint Space Operations Center
LCOLA	Launch collision avoidance
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LLC	Large LEO Constellation
LLO	Low lunar orbit
MADCAP	Multimission Automated Deepspace Conjunction Assessment Process
MEO	Medium Earth orbit
MOU	Memorandum of understanding
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NGSO	Non-geostationary orbit
NOAA	National Oceanic and Atmospheric Administration
NTIA	National Telecommunications and Information Administration
NTSB	National Transportation Safety Board
ODMSP	Orbital Debris Mitigation Standard Practices
ORDEM	Orbital Debris Engineering Model
OSC	Office of Space Commerce
OST	Outer Space Treaty
P_c	Probability of collision
PNT	Positioning, navigation, and timing
RF	Radio frequency
RMM	Risk mitigation maneuver
RPO	Rendezvous and proximity operations
SAA	Special activity airspace
SAR	Synthetic Aperture Radar
SatCom	Satellite communications
SCRM	Supply chain risk management
SPARTA	Space Attack Research and Tactic Analysis
SPD	Space Policy Directive
SSA	Space situational awareness
SSI	Space Safety Institute
SSN	Space Surveillance Network
SSP	Space Station Program
STC	Space traffic coordination
STM	Space traffic management
TLE	Two-line element
TraCSS	Traffic Coordination System for Space
TRL	Technology readiness level
TTP	Tactics, techniques, and procedures
UDL	Unified Data Library
ULA	United Launch Alliance
UNCLOS	United Nations Convention on the Law of the Sea

SPACE SAFETY REFERENCES

Aerospace received community feedback requesting we provide in the *Compendium* a list of useful references for training new space safety professionals. The following can be considered a preliminary list of useful material, but it should not be considered comprehensive, or to be listed in order of priority. In addition, we do not necessarily endorse every position taken in these materials. We welcome specific feedback and additional suggestions from the community.

In addition to the list below, the Space Safety Institute works with the AIAA to maintain a Space Governance Database. The space governance database contains industry best practices, norms, treaties, principles, recommendations, and guidelines focused on safety of flight, radio frequency interference (RFI), space situational awareness (SSA), and space traffic management (STM). The Space Safety Institute hosts and periodically updates this international body of knowledge, developed in collaboration with AIAA, to aid existing and new entrants into the space enterprise.

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