AEROSPACE | Space Safety Institute

# 2022 SPACE SAFETY COMPENDIUM

## GUIDING THE FUTURE OF SPACEFLIGHT

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THE AEROSPACE CORPORATION

# *2022 SPACE SAFETY COMPENDIUM*

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Edited by Samira Patel and Josef S. Koller

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# ACKNOWLEDGMENTS

The *2022 Space Safety Compendium* was made possible by numerous experts at the Space Safety Institute (SSI) who have considerable expertise in the subjects discussed herein. These experts include William Ailor, Brandon Bailey, Danielle Bernstein, Grant Cates, Robin Dickey, Michael Gleason, Lee Graham, Lori Gordon, Matthew Hejduk, Samuel Liberto, Ted Muelhaupt, Samira Patel, Glenn Peterson, Rebecca Reesman, Andrew Rodgers, Marlon Sorge, Ryan Speelman, David Spencer, Colleen Stover, Wai Troyer, Tyler Way, and Rob Unverzagt.

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

# EXECUTIVE SUMMARY

The space sector is undergoing an unprecedented period of growth that expands the scope of what is possible in space and who is involved. We have shifted away from the 1960s and 70s model of centralized, government-led space activities to a new model that increasingly leverages the dominating commercial space market. Furthermore, new actors in space represent a wide array of international actors, partnership and business models, and commercial entrants. They have expanded the scope of missions and capabilities in space that include everything from commercial human spaceflight to growing industrial activity such as mining and pharmaceutical development.

As a result, new activities have called into question current regulatory frameworks and policy standards for managing space that were largely developed for an outdated model. We are seeing increasing uncertainty in regulation and, in some cases, not even a clear picture of which U.S. government agencies bear the responsibility of handling which issues. There is also friction between regulators and new actors as regulations could become more burdensome for new entrants, giving a competitive advantage to those who have long been in space.

At the same time recent events have called into question current safety measures and norms in space. The FAA's Human Spaceflight Moratorium, or learning period, is set to expire in October 2023. With the historic number of commercial human spaceflights that took place in 2021, now is the time to consider the future of this moratorium and its related safety concerns for private citizens who might consider traveling to space. We must also consider any unintended consequences to public safety here on Earth from space activities. In November 2021, we also saw risky space behavior, including Russia's direct-ascent anti-satellite (ASAT) test to destroy one of its own satellites. This ASAT test created a field of at least 1,500 trackable pieces of debris in low Earth orbit (LEO), threatening space operations and human spaceflight. Following the Russian ASAT test, the United States decided to set an example and issued a self-imposed ban on debris-generating, direct-ascent ASAT missile tests and called on other nations to make similar commitments to responsible behavior in outer space.

The space domain is an international domain that is predicated on cooperation and partnerships enabled by safe space operations. In order to manage this domain and address growing challenges, the space sector needs to look at a holistic approach. The space domain is like a Rubik's cube; in order to align each color correctly to its corresponding side, all the other sides need to match up. For a safe space domain, each mission area will have to be properly managed for all of them to work together correctly.

It is with this holistic approach in mind that The Aerospace Corporation (Aerospace) decided to stand up the Space Safety Institute (SSI). The SSI leverages long-standing Aerospace expertise on issues of space safety to provide more targeted and impactful thought leadership across the range of challenges described in this *2022 Space Safety Compendium*.

Based on this new age of commercial space activities, we have identified five mission areas at SSI. Each must work together in order to build a holistic space safety approach. The mission areas are:

1. Space situational awareness
2. Space operations assurance
3. Launch and reentry
4. Cyber and spectrum
5. Human spaceflight safety

Each chapter of this compendium describes key high priority areas that should be addressed over the next few years. Each subsection covers an issue topic that the Space Safety Institute has examined extensively and concludes with specific recommendations for space operators, regulators, and other decisionmakers. Some recommendations are broad outlooks for the future, others are concrete next steps that the space sector can take. The variety of scope and scale of these recommendations reflects the diverse set of space safety challenges we are facing today.

We hope that 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 space economy and the value that space provides to society depends on safe and sustainable operations in space.

*Uma Bruegman*
*Josef Koller*

# SUMMARY OF RECOMMENDATIONS

## SPACE SITUATIONAL AWARENESS

**Recommendation 1.1:** Utilize a holistic approach to SSA.

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

**Recommendation 1.3:** Reduce tracking uncertainties to make more informed space traffic management (STM) decisions.

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

## SPACE OPERATIONS

**Recommendation 2.1:** Fund and authorize the Office of Space Commerce (OSC) to perform STM coordination and support its rapid and effective implementation.

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

**Recommendation 2.3:** Implement a principles-based active debris removal (ADR) framework.

**Recommendation 2.4:** Enable commercial ventures and establish public-private partnerships to increase the technology readiness level (TRL) of ADR.

**Recommendation 2.5:** Encourage provisions for on-orbit servicing as a first step toward ADR.

**Recommendation 2.6:** Continue to promote U.S. leadership in rendezvous and proximity operations (RPO) norms development.

**Recommendation 2.7:** Assess risk at the constellation level.

**Recommendation 2.8:** Establish performance-based regulatory approvals for constellations.

**Recommendation 2.9:** Promote effective post-mission disposal methods to offset collision possibility.

## LAUNCH AND REENTRY

**Recommendation 3.1:** Implement a comprehensive national airspace system (NAS) integration strategy for launch.

**Recommendation 3.2:** Consider the 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.

## CYBER AND SPECTRUM

**Recommendation 4.1:** Properly fund and promote cybersecurity best practices.

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

**Recommendation 4.3:** Develop and employ defense-in-depth (DiD) principles to cybersecurity.

**Recommendation 4.4: I**ntegrate onboard cyber intrusion detection and prevention applications.

**Recommendation 4.5:** Apply robust supply chain risk management in cybersecurity 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.

## CROSS-CUTTING SPACE SAFETY ISSUES

**Recommendation 6.1:** Invest in STEM education and continuous training.

**Recommendation 6.2:** Improve the narrative of a space career.

**Recommendation 6.3:** Expand to school-to-space workforce pipeline.

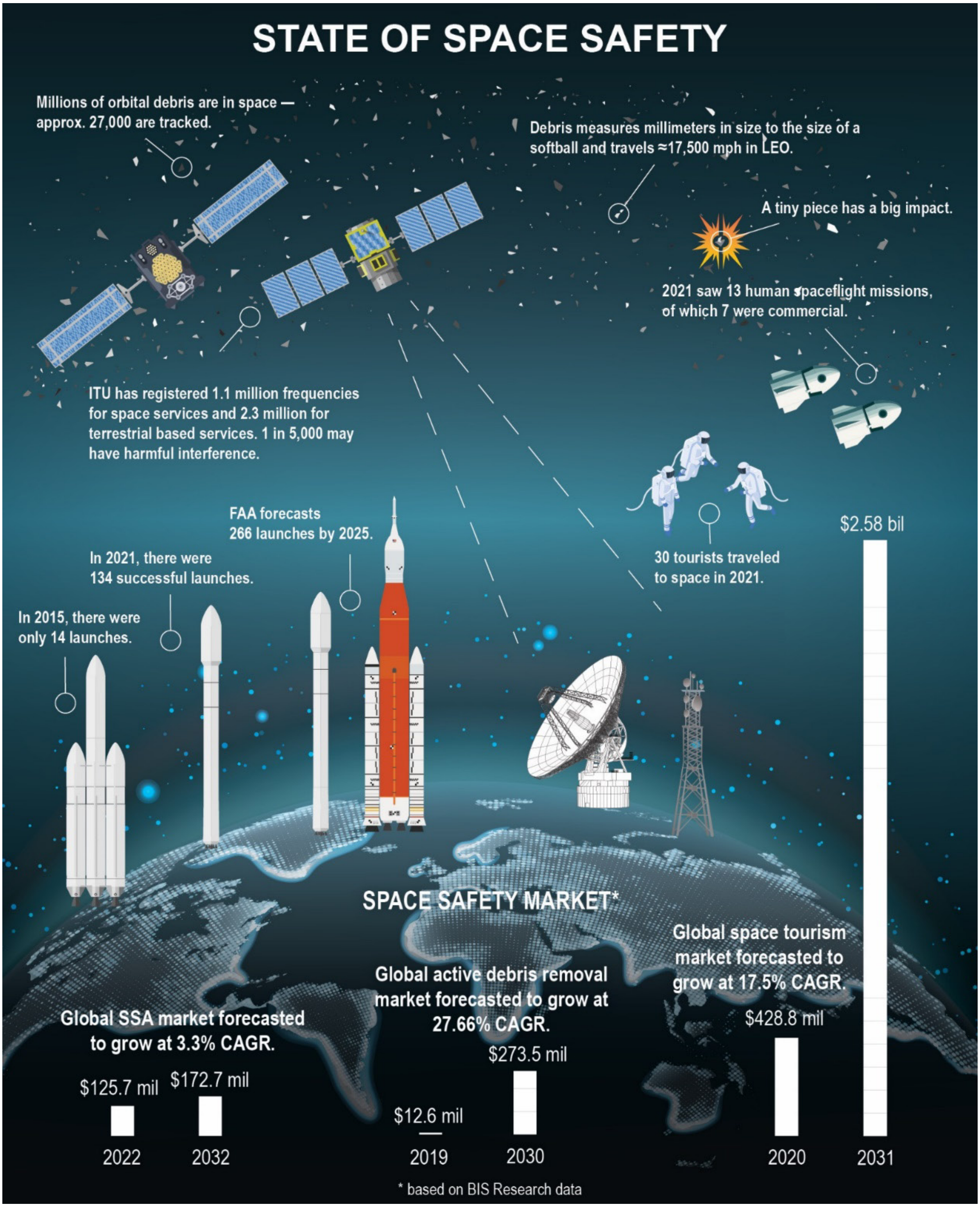
**Recommendation 6.4**: Match norm characteristics to development approaches.

**Recommendation 6.5:** Consider the whole lifecycle of norm development.

**Recommendation 6.6**: Implement model development strategies.

**Recommendation 6.7:** Develop strategies and processes to maximize data sharing.

# STATE OF SPACE SAFETY



# CONTENTS

# 1. SPACE SITUATIONAL AWARENESS (SSA)

In just the last few years, commercial companies have proposed, funded, and, in a few cases, begun deployment of very large constellations of small-to-medium-sized satellites. These constellations will add much more complexity to space operations. Two dozen companies, when taken together, are planning to place over 85,000 satellites in orbit in the next 10 years, another 66,000 have been withdrawn, and one announced system would add another 100,000. For perspective, in the history of the Space Age, fewer than 8,100 payloads have been placed in Earth orbit. Of those 8,100 payloads, only about 4,800 remain in orbit of which approximately 1,950 are still active.[1] 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 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 or "New Space" represents a fundamental change.

Although many of these large constellations may never be launched as proposed, the traffic created if just half are successful would be more than quintuple the number of payloads launched in the last 60 years and more than 20 times the number of currently active satellites. Most current space safety processes, such as space surveillance, collision avoidance (COLA), and debris mitigation, were designed for the previous population profile, launch rates, and density of low Earth orbit (LEO) space. These processes should be reconsidered based on a greater understanding of the changing space environment.

Space situational awareness (SSA) plays a foundational role in understanding the New 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. Orbit propagation models are used to predict the motion of objects in space and can predict future conjunctions between objects for collision avoidance and 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 management (STM), identifying operational threats and enabling collision avoidance maneuvers. It is also critical to space domain awareness, which is understanding the intent of other actors in current and predicted operating environments. Decisionmakers in the U.S. government and space sector use SSA 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 keys 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

The changes in the space environment can be seen on this chart of LEO, which extends to 2,000 km above Earth's surface. Figure 1 shows the LEO environment as a function of altitude.[2] Soon the problem of space congestion will become more pronounced since new constellations will continue to be launched and potentially tracked by the Space Fence[1] tracking system, which became operational in 2020. 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 current tracked (purple field), these new systems will drastically alter the density of their local neighborhood. As a result, the number of collisions and collision alerts that both the constellation owners and other LEO operators will have to address will increase. Fortunately, the operators of these new large constellations generally recognize the challenges and are implementing procedures to cope with the new environment.

Figure 1 reveals how much of the potentially lethal region is currently untracked. Therefore, efforts to model and simulate the space environment are critical given the predicted population growth in LEO satellite constellations and to further increase the safe operations of spacecraft.

***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—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 the operational Space Fence to enable improvement in SSA metrics.
- Develop improved algorithms for orbit determination, orbit propagation, conjunction prediction, and collision probability estimation used by the U.S. space community's operations.

[1]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 will track an order of magnitude more objects than the first-generation space surveillance system.

- Support sharing of SSA data, including owner-operator data, via mechanisms such as space-track.org, the Unified Data Library (UDL), and the Office of Space Commerce's proposed Open Architecture Data Repository (OADR).
- 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 encourage or even require broad information sharing.

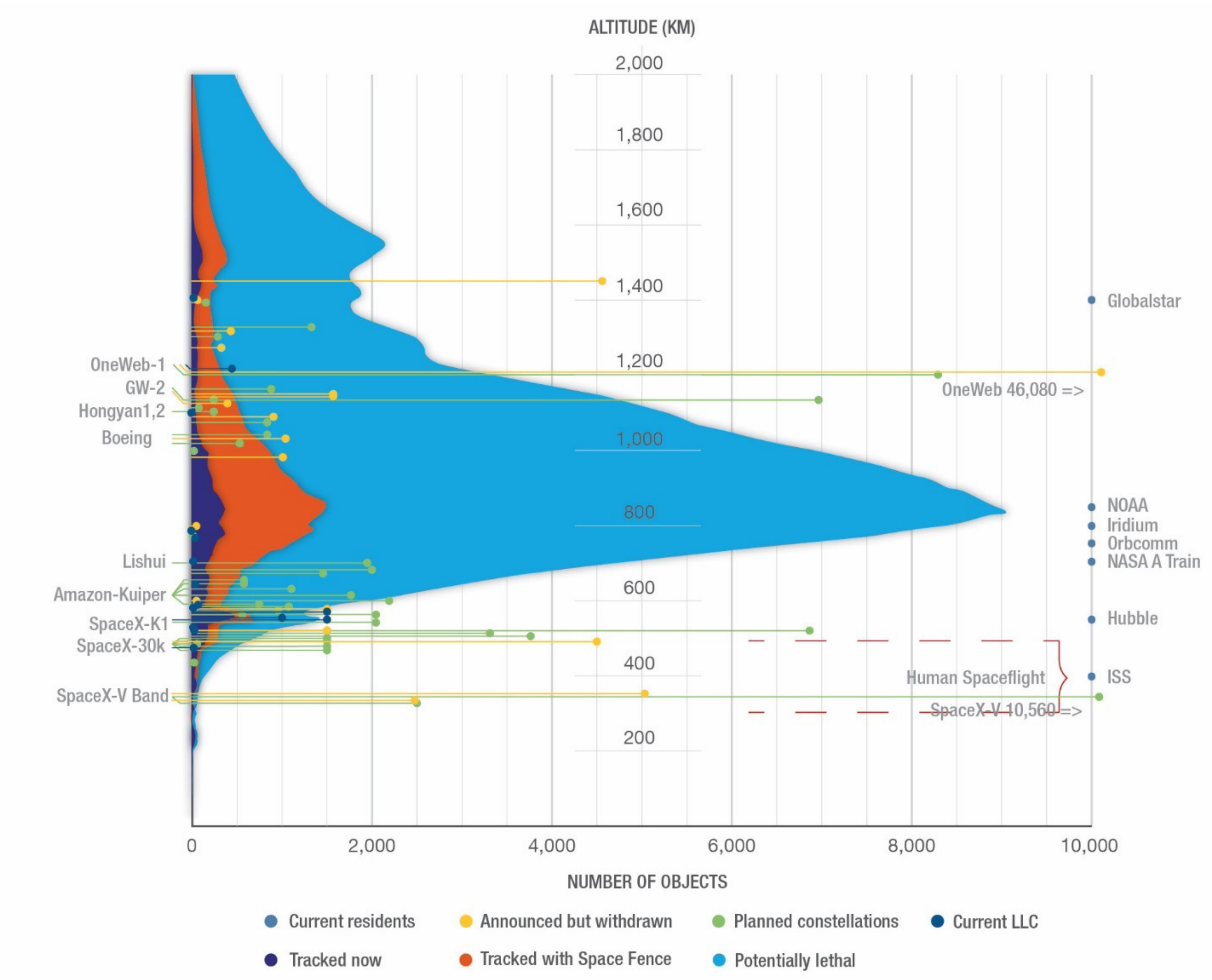



**Figure 1.** The plot shows the number of objects by altitude. The purple region on the left shows what is currently tracked by the Air Force Space Surveillance Network. This includes both active satellites and debris. The orange region shows the distribution of objects with the potentially improved tracking capabilities of the Air Force Space Fence, which is designed to detect objects as small as 2 cm to 5 cm in size and up to geosynchronous orbit. 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.

***Recommendation 1.2:*** **Enhance SSA data analysis, services, and tools.** A critical factor for safe space operations is fully understanding the SSA data that we obtain and using it to improve decisionmaking. For example, the visualization in Figure 2 provides decisionmakers with enhanced information about the situation immediately following an on-orbit breakup. 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).

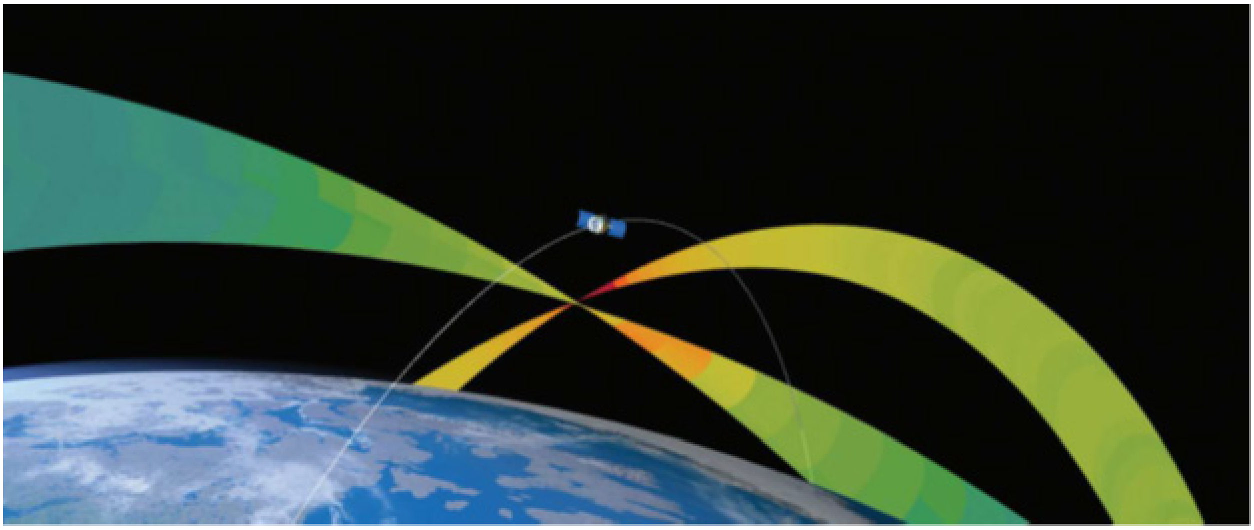


**Figure 2.** Visualization of the debris risk of a newly created debris field from a collision. The passage of a spacecraft near the "pinch point" (highest density) can be seen as safe since boundaries of the risk are also shown.

Aerospace's Center for Orbital and Reentry Debris Studies (CORDS) has led the development of 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
- 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

Furthermore, the addition of the Space Fence and commercial SSA sensors for tracking space objects may also improve collision analysis to better locate currently untracked objects and improve tracking for other objects currently in space. These tools and practices enhance our understanding of space situational awareness, space traffic management and space debris impacts.

## 1.2 Accurate Satellite Tracking in the Era of Large Constellations

A common feature of new large constellations is their concentration in LEO orbit, where they can pose a risk to other satellites residing nearby or passing through such altitudes. 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 collisions and collision alerts that both constellation owners and other LEO operators will have to deal with has increased and will continue to increase.[3,4]

One major concern for the space community is the large number of collision alerts that are expected to be generated by SSA tracking systems as these satellites are being operated and disposed of.[5] Studies estimate thousands of collision alerts per day depending on the threshold violation criteria that is selected. The goal of any SSA system is to correctly identify impending collisions without generating an undue number of unnecessary alerts. Crucial to this goal of accurate identification is determining the tracking accuracy required to eliminate as many unnecessary alerts as possible.

It should be noted that the volume of alerts is primarily an issue for small operators and legacy operations. New and larger systems usually incorporate automation to deal with the volume of conjunction alerts and may even welcome additional, but less critical, alerts.

Aerospace has examined the tradeoff between the level of tracking and the number of unnecessary alerts for an actively managed STM system. Results indicate that it is not sufficient to reduce the uncertainty on the primary large LEO constellation (LLC) satellites only, but, rather, that 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 Space Policy Directive-3 issued in 2018.[6]

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 warnings may be ignored since almost all alerts are low probability in an absolute sense. In the past, lack of automation was 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 an unacceptably close approach distance. Planned stationkeeping maneuvers might have been altered or skipped. However, at the time, the then-common two-line element (TLE) data for satellites was all that was shared. Since covariances and maneuver plans were not shared between the operators and the Joint Space Operations Center (JSpOC), the danger of the conjunction was not identified using the practices of the day. Using the tools of the time, the probability of collisions did not stand out from many other conjunctions faced by Iridium that day (Figure 3). Subsequent analysis[7] showed that had today's practices been followed, the conjunction would have been flagged and acted upon. This illustrates the importance of sharing high-quality information in a timely fashion and incorporating operator maneuver plans.

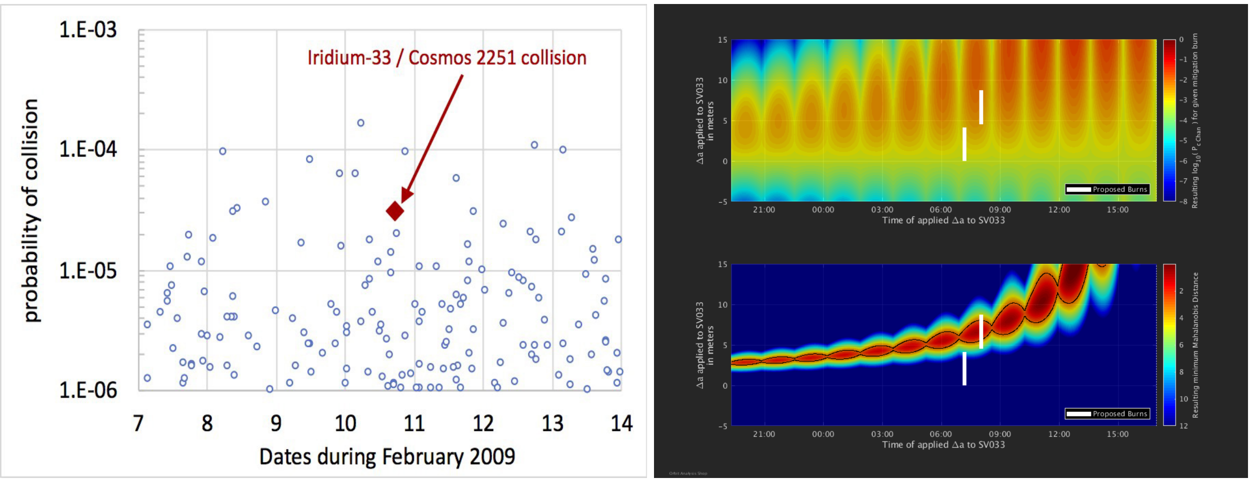



**Figure 3.** On the left, the Iridium constellation conjunction probabilities during the week of February 7, 2009. Under then-current information sharing, the actual collision between Iridium-33 and Cosmos 2251 did not stand out from other conjunctions that week as being noticeably dangerous. On the right, the conjunction and maneuvers using current Iridium software and special perturbation tracking data. Current practices using full information sharing would have flagged the event.

The number of alerts is exacerbated when a collision between two objects occurs, and debris clouds are created. For example, the November 2021 Russian ASAT test created a large cloud of debris that still is actively threatening the Starlink constellation, neither of which existed in 2009. Fortunately, Starlink automation was able to handle the load, but could still only avoid objects that are actively tracked. These clouds can pose a risk to other satellites flying in the vicinity. Assessing the risk can provide satellite operators the information needed to decide whether to maneuver their satellite. While today's operators can expect a sharp increase in the number of warnings and alerts because of the increase in the cataloged population, almost all the increase will come from newly detected debris. SpaceX reported that, in the first months since the November 2021 Russian ASAT test, their Starlink satellites had to maneuver 1,700[8] 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.[9] Automation helped Starlink deal with the load, but less-prepared operators could be overwhelmed.

***Recommendation 1.3:*** **Reduce tracking uncertainties to make more informed STM decisions.** The data that SSA systems produce on satellite locations, debris, and potential collisions is integral to space traffic management 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 4 shows how using a standard external tracking tool on the left would result in a conjunction warning and possible COLA action, while smaller uncertainties using onboard data would not.

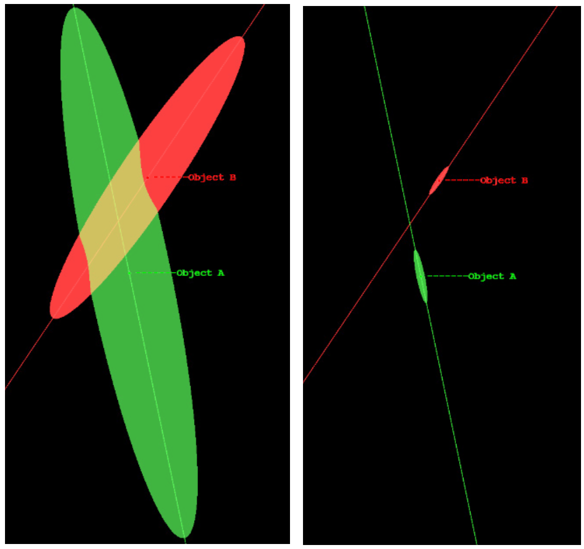



**Figure 4.** The covariances for a conjunction using external noncooperative tracking are compared to those from an onboard GPS receiver. The situation on the left would result in a conjunction warning and possible COLA maneuver, but the situation on the right would not trigger an alert.

Aerospace examined which kind of tracking uncertainties would have to be reduced to produce an effective STM service.[2] 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 uncertainty down to the 0.01 scale factor 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.[10]

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 above, the effects of maneuvers must be included to identify dangerous conjunctions. Moving one of the objects a distance equivalent to its own body width (meters) is sufficient to change a collision to a very near miss, or vice versa.

***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,

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[2]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.

including “dead” satellites and cataloged debris of all tracked sizes may need to be in 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 dominate the population.

Space operators should establish and implement tracking accuracy goals in the orders of meters (Figure 4) to accommodate LLCs. 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, collision avoidance to date has relied on the assumption that we can accurately predict the position of objects long in advance. This assumption is not valid when the objects actively maneuver. The most effective way to address this is by owner-operators actively sharing planned maneuvers 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 space traffic management systems actively make use of the data. The community should develop standards and processes for sharing maneuver plans, improving SSA accuracy, 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, which can reduce the need to make overly conservative assumptions.

# 2. SPACE OPERATIONS ASSURANCE

Operations in space are currently experiencing a revolution that will continue to accelerate 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 CubeSat 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 including on-orbit servicing, satellite life extension, and active debris removals are expanding the possibilities in space and how satellites interact with each other. These activities substantially shift the dominance in space operations from government systems to commercial, changing the priorities and operating parameters.

These changes bring many new opportunities but also different types of safety challenges on different scales than those with which the space community has dealt previously. 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 implementation of norms of behavior becomes onerous on already existing systems.

This chapter examines issues related to the challenges of New Space activities in space operations, such as space traffic management (STM), active debris removal (ADR), and rendezvous and proximity operations (RPO), and proposes practical solutions.

## *2.1 Space Traffic Management: Challenges of Large Constellations and Debris*

New Space activity is stretching conventional approaches to safe space operations. In the previous chapter, we highlighted the need to improve SSA tracking 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 is intrinsically international in nature.[11]

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

*Recommendation 2.1:* **Fund and authorize the Office of Space Commerce (OSC) to perform STM coordination and support its rapid and effective implementation.** The president's fiscal year (FY) 2023 budget proposes a significant investment of $87.7 million for the OSC to stand up a civil office with an operational SSA and STM capability to meet the industry's needs.[12] It includes funding for several SSA activities, such as building an operational open architecture data repository, continuing the work to transition from the current prototype to initial operating capability by FY 2024. While OSC has named a new director, Richard DalBello, who will help support this implementation, Congress should also authorize this funding so that OSC can ramp up its capabilities to facilitate STM coordination. How active OSC is regarding the management of space traffic will in large part depend on the resources available to the office.

***Recommendation 2.2:*** **Establish mechanisms for international coordination and cooperation between stakeholders.** U.S. leaders should work with international counterparts to harmonize global STM practices and regulations. Bad actors affect all users of space. Currently, no international, legally binding agreements exist that constrain a country's freedom of action in space[‡] except for prohibitions on nuclear weapons tests in space and prohibition on the placement of nuclear weapons (or other weapons of mass destruction) in space. 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.[13]

## *2.2 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 often requires satellites to maneuver to avoid 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, mitigation, and removal[§] to control the debris environment.[14] 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 removed annually to flatten the curve in the space debris population.[15] Since many of these studies were done, the pace of on-orbit activity has substantially grown the LEO population and increased the need for active removal. Going further than five objects per year would decrease the overall amount of debris even more, moving toward a more sustainable model for space.

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[‡]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.
[§]This includes post-mission disposal.

Yet viable options for ADR remain 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 1). 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.[16] U.S. national law, policy, and regulations from the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC), and the National Oceanic and Atmospheric Administration (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 2.3:*** **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.

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 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 ITAR control issues, if any
- Intellectual property transfers, if any
- Messaging and public communication responsibilities

**Table 1.** 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:<br>• No specific applicable laws to ADR</td><td>Legal:<br>• MOU or bilateral agreement recommended</td></tr>
<tr><td>Regulatory:<br>• Not applicable, any issues would be addressed in interagency deliberations on policy</td><td>Regulatory:<br>• Debris: follow existing regulations; update any licenses<br>• Service provider: no specific regulations applicable</td><td>Regulatory:<br>• U.S.: Not applicable and would be handled through interagency deliberations<br>• Follow any applicable foreign laws and regulations</td></tr>
<tr><td colspan="3">U.S. Policy:<br>• U.S. space policy<br>• U.S. orbital debris mitigation standard practices (ODMSP)<br>• NTIA/FCC Frequency Assignment<br>• Export issues unlikely</td></tr>
<tr><td colspan="3">International:<br>• IADC guidelines<br>• OST and Registration Convention<br>• Solid messaging campaign recommended</td></tr>
<tr><td rowspan="4">U.S. Commercial Service Provider</td><td colspan="2">Legal:<br>• Remote Sensing Policy Act<br>• Space Launch Act</td><td>Legal:<br>• MOU or bilateral agreement recommended</td></tr>
<tr><td colspan="2">Regulatory:<br>• NOAA (to license camera)<br>• NTIA/FCC spectrum deconfliction<br>• FAA payload review if applicable</td><td>Regulatory:<br>• NOAA<br>• FCC<br>• FAA payload review if applicable<br>• Follow any applicable foreign law and regulations<br>• Export issues unlikely</td></tr>
<tr><td colspan="3">U.S. Policy:<br>• U.S. ODMSP<br>• SPD-3</td></tr>
<tr><td colspan="3">International:<br>• IADC guidelines<br>• OST and Registration Convention<br>• Solid messaging campaign recommended</td></tr>
<tr><td rowspan="4">International Service Provider</td><td colspan="2">Legal:<br>• No specific applicable laws 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:<br>• Not applicable</td><td>Regulatory:<br>• Debris: follow existing regulations; update any licenses; export control if applicable<br>• Service provider: no specific regulations applicable</td></tr>
<tr><td colspan="2">U.S. Policy:<br>• Export issues possible<br>• U.S. space policy<br>• U.S. ODMSP<br>• SPD-3</td></tr>
<tr><td colspan="3">International:<br>• IADC guidelines<br>• OST and Registration Convention<br>• Solid messaging campaign recommended</td></tr>
</table>

Legal | Regulatory | U.S. Policy | International

If multiple nations are involved, a second agreement in the form of a bilateral memorandum of understanding (MOU) may also be useful to incorporate and address any cross-national issues, such as export control and differences in national regulations.

Using the principles of consent and permission, Table 1 shows a matrixed overview of what legal, policy, and regulatory issues might need to be addressed. 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 mission based on permission and consent would also greatly facilitate transparency, confidence building measures, best practices, and make active debris removal a common practice.

***Recommendation 2.4:*** **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 a myriad of hurdles concerning the technical feasibility of rendezvous, grappling and 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. For example, Aerospace has been working with the XPRIZE Foundation to pursue ADR demonstration missions.

***Recommendation 2.5:*** **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 possibly noncooperative but consenting[††] target, and modifying the orbit of the target. Government and industry are encouraged to pursue and enable on-orbit servicing technologies as a first step toward ADR. This includes adding rendezvous aids such as radar and optical reflectors, and grapple fixtures to facilitate possible future retrieval.

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[**]TRL measures 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.

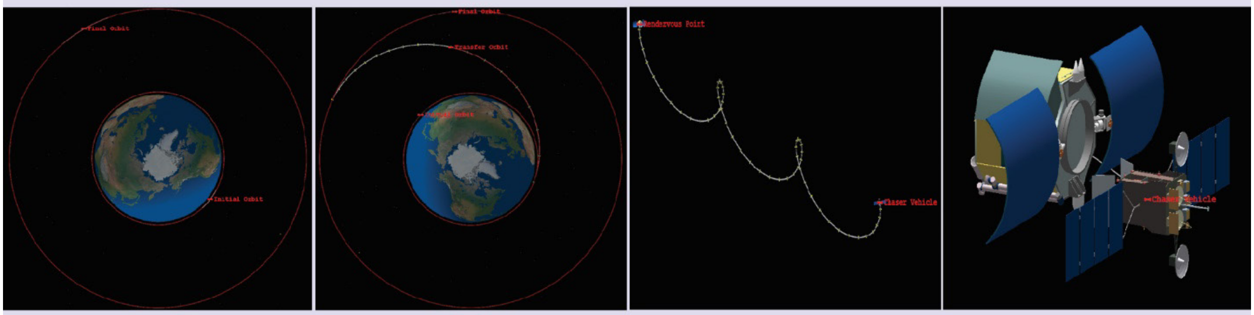
[††]"Noncooperative but consenting" refers to when information transfer between the chaser spacecraft (vehicle performing the rendezvous operation) and target object is one-way only. The target object will not actively provide information regarding its own state to the vehicle performing rendezvous. Efforts to service dead satellites or de-orbit orbital debris are examples of noncooperative but still consenting rendezvous and proximity operations (RPO). In contrast, cooperative RPO refers to missions where information transfer between the chaser vehicle and target is two-way; health, status, position, pointing, and other information are exchanged between the two spacecraft. (See Figure 5.)

## *2.3 Learning from Past Rendezvous and Proximity Operations*

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 rendezvous and proximity operations (RPO). RPO 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.[17]

**RENDEZVOUS AND PROXIMITY OPERATIONS**



Sequence of events that comprise RPO. Left to right: the initial configuration; the transfer orbit, which affects rendezvous; the relative maneuver that corresponds to proximity operation; and the final configuration just before docking.

**Definitions**

**Rendezvous:** Matching the plane, altitude, and phasing of two (or more) satellites.

**Proximity operations:** Two (or more) satellites are in roughly the same orbit and intentionally perform maneuvers to affect their relative states.

**Docking:** Subset of proximity operations where one satellite intentionally performs maneuvers to physically contact another satellite.

**Cooperative RPO:** Information (position, velocity, health/status, etc.) transfer is two-way via crosslinks, ground contact, etc. Example: docking with the ISS.

**Noncooperative RPO:** Information transfer between vehicles is one way only. Example: active debris removal.

**Figure 5**. 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 orbit. It is a cooperative effort among the United States, Russia, Canada, Japan, and the European Space Agency and has been continuously occupied for more than 17 years. Principally, a space station program document (SSP 50235) defines performance and interface requirements for the myriad of 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 and the Defense Advanced Research Projects Agency's (DARPA) 2007 Orbital Express missions provide important technology demonstrations with valuable lessons learned. NASA's demonstration was designed to autonomously rendezvous with and maneuver around a designated communications satellite, but, after eight hours within the demonstration, it started using more propellant than expected. A subsequent mishap report found a series of issues such as inadequate guidance, navigation, the control software development process, and poorly managed risk posture. Orbital Express sought to validate the technical feasibility of autonomous RPO pertaining to on-orbit servicing. However, there was a major failure in the sensor computer onboard ASTRO, nearly ending the demonstration prematurely. The key finding from a NASA postmortem technical report was the impact the navigation software had on the mission performance.

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 rarely, if ever, 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, the Demonstration of Autonomous Rendezvous Technology, and Orbital Express) highlighted the importance of ground operations, flight navigation software, collision avoidance 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 2.6:*** **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). The mission of CONFERS is to provide "a permanent, self-sustaining, and independent forum where industry could collaborate and engage with the U.S. Government in research about on-orbit servicing, as well as drive the creation of standards that servicing providers and clients would adopt."

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.

## *2.4 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 New Space activity is that spacecraft are now designed to be mass-produced and mass-launched 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 New Space LEO systems have relatively short lifetimes (e.g., five years) to enable rapid technology refresh, lower weight and cost, and permit 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, the SpaceX Starlink system has launched 2,975 vehicles and deorbited 240 as of August 11, 2022, (according to SpaceX) and is working on Generation 1.5 and Generation 2 updates.

Examining a *constellation of satellites*, or a system of systems, becomes much more important as the numbers increase.

***Recommendation 2.7:*** **Assess 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.

One advantage of considering the constellation as a "system" is that system-level risk mitigations can be considered. It is well known that "space is hard," and that some level of failures should be expected. 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" might be considered as a system-level backup plan to address failures.

***Recommendation 2.8:*** **Establish performance-based regulatory approvals for constellations**. As discussed above, many New Space 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 time spans under consideration at the system or constellation level, it would be prudent to make regulatory approval an on-going 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.

***Recommendation 2.9:*** **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 Inter-Agency Space Debris Coordination Committee (IADC) and is drawn from the 2002 IADC Space Debris Mitigation Guidelines.[18] 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), the White House has called for a reevaluation of the 25-year rule due to the growing risk to orbital operations by space debris.[19]

In fact, 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.[20] 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. In order to control debris growth, satellite operators will need to reliably ensure post-mission disposal of dead satellites at the constellation level.

All spacecraft and upper stages should be removed from orbit as soon as possible at the end of mission life. The preferred method for this is through controlled reentry as uncontrolled reentry requires the satellite to naturally decay, which may take more than 25 years if above 600 km altitude as recommended by the IADC and orbital debris mitigation standard practices (ODMSP). In late September 2022, the FCC announced a requirement for a 5-year deorbit, which lowers that ceiling by about a 135 km. However, for controlled reentry, spacecraft must remain under active control and perform active collision avoidance until located in a safe long-term disposal orbit or final reentry. Incentivizing deorbit may be necessary to encourage satellite operators to practice post-mission disposal in a timely manner.

# 3. LAUNCH AND REENTRY

For most of the space age, low Earth orbit (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 orbit, and when and how to decommission them.

To date, the most common method of disposal has been to simply let a satellite's orbit naturally degrade and finally 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, and, therefore, there would be no issues. This is not the case as debris from the satellite breakup at reentry can continue to fall and impact aircraft in the sky and people on the ground. With large LEO constellations (LLCs), the impacts from debris are amplified as the number of satellites being launched and disposed of dramatically increases.

## 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 six "spares" into orbit. The constellation provided voice and data communication services to users worldwide.

Within 14 months of being operational, possible bankruptcy forced Iridium to consider disposing all 74 satellites in the constellation—a possibility that raised the first concerns about hazards to people on the ground should a constellation be disposed of. 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 few months' time, 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, analysts 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 decisionmaking. Fortunately, while the bankruptcy did occur, the successor company did not deorbit the satellites but continued operations. In the last few years, as the constellation was refreshed, the first-generation satellites have reentered but no injuries have been reported.

Today, several commercial companies plan to launch constellations with thousands of satellites in LEO orbits. Satellites at the end of their operational life would be disposed of into the atmosphere, most with no control over where their surviving debris might land. If a constellation has 10,000 satellites, it may be disposing of 1,000 or more satellites on a yearly basis—several each day on the average. For reference, fewer than 120 objects of comparable size reentered in 2020.

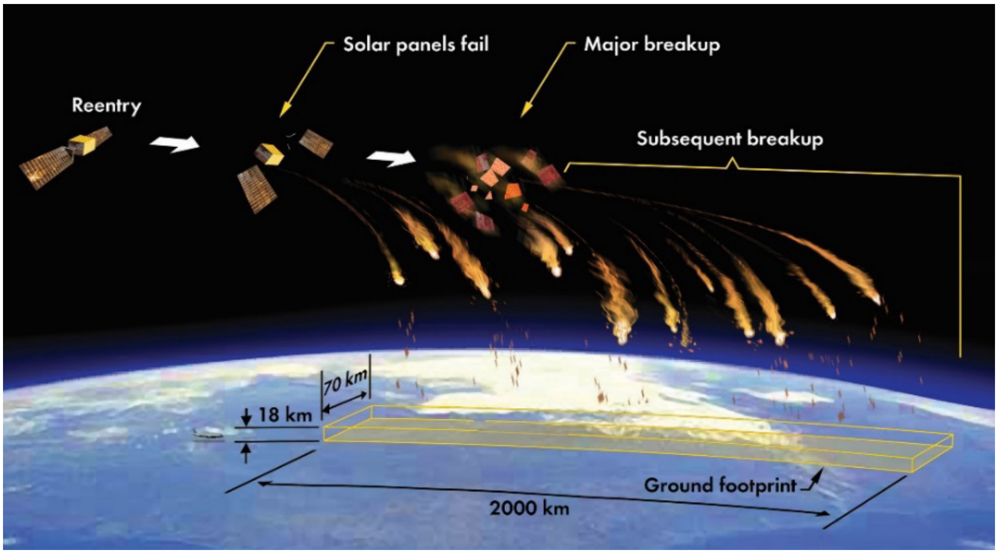



**Figure 6.** The final reentry breakup process, showing that debris surviving reentry would fall through airspace potentially occupied by aircraft (commercial airspace extends to 18 km above ground) and could spread over a long, narrow path as it impacts the ground, possibly causing human casualty.

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

## *3.2 Airspace Integration of Launch Operations*

Rockets launching into space only briefly intersect with flight levels of commercial aviation. Nonetheless, the launches can have noticeable impacts on air traffic and ground safety. Typically, launches require a significant amount of airspace to be cordoned off by defining regions that should be avoided due to possible risks from the 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. New Space activities, particularly of commercial operators, are significantly increasing launch, adding new ranges from which rockets may be launched and adding entirely new operations like flyback of launch vehicle first stages. All of 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*.[21] 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; 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/explosion). These hazard areas can cover the airspace over many hundreds of square miles and last for substantial periods of time (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 effects can be out of proportion to the actual risk.

This kind of accommodation is burdensome, but, at launch rates of approximately 20 per year (from Cape Canaveral Air Force Station, for example), it is manageable. In addition, most space launches have historically been for government customers, so acceptance of this process by other users of the NAS has had an aspect of “for the greater good.” With the anticipation of increased launch rates from commercial customers (see Figure 7), there is a need for better integration of space launch activities in the NAS.

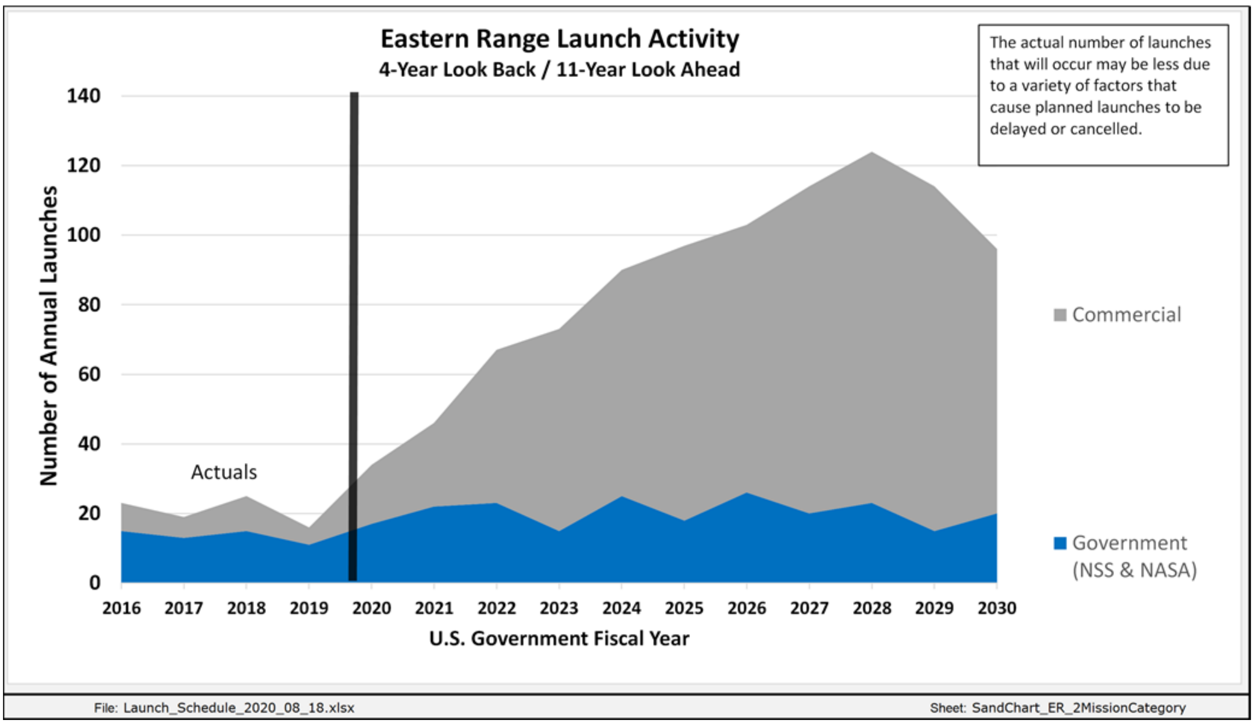



**Figure 7.** Eastern Range Launch Activity. Derived from several data sources as of August 18, 2020; in particular, the Federal Communications Commission (FCC) filings for planned satellites, which telegraph a large potential increase in future launch rates.[22]

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.** 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. This includes:

- 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 on-orbit satellites, what is less considered is the role of launch and satellite de-orbit (disposal) in collision assessments. These are critical because the large uncertainties associated with launch vehicles are far greater than for uncertainties related to orbiting objects on a particular trajectory. So improved tracking of on-orbit assets alone will not noticeably improve launch collision avoidance.

Decay, failures, and/or disposal of these satellites could also pose a threat to satellites operating at altitudes other than the constellations' 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 have shown that, over the long term, a wide range of

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

collision rates for LLCs with lethal debris can be expected. This, however, depends on the LLC traffic and success rate of debris mitigation practices.[23] These collisions can occur both during operations and during the 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 the launch risk. The growing population of on-orbit satellites can result in some launch windows being entirely closed due to launch collision avoidance (LCOLA) concerns using current practices.

The goal of any LCOLA system is to identify high probability conjunctions between the 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 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, which increased the amount of tracked debris by over 50 percent, plays a greater role in LCOLA than adding new large constellations to the space environment. Since the Space Fence will see more objects than just the large constellations that are expected to deploy, the Space Fence objects will be more likely to influence LCOLA systems. Compounding this effect is that the newly tracked objects less than 10 cm are only observed by Space Fence 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 altitude. However, it must be noted that much of the "new" risk comes from the debris newly tracked by the Space Fence. 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 can provide additional risk reduction.

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

In order 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 also include other high-value space assets?

## *3.4 Large Constellation Disposal Hazards*

While, historically, satellite disposal has involved a deorbit when it "burns up" in the Earth's atmosphere, Figure 8 shows that some hazardous fragments do actually survive. In fact, the objects in the figure are large enough to cause human casualty or catastrophic damage to an aircraft.[24]

This section discusses a first-order assessment by Aerospace of potential risks to people and aircraft associated with random reentries of large numbers of satellites from large constellations in LEO. The assessment, based on constellations totaling approximately 16,000 new satellites, concludes that risks to aircraft posed by small debris surviving a reentry might also pose a problem to large constellations. Worldwide risk of an aircraft striking a reentering debris fragment is estimated to occur once every 200 years. Hazards to people on the ground from larger debris objects will be a more pronounced problem, with expectations as high as 1 casualty somewhere on Earth every 10 years for uncontrolled reentries.

**Figure 8.** Recovered composite overwrapped pressure vessels, or COPVs. The left photo shows debris from Centaur stage of Atlas V booster, and the SpaceX Falcon 9 Stage can be seen in the right photo.

Since the assessment was completed, proposed LEO constellations have increased to approximately 85,000 satellites in orbit, intensifying the risk to people and aircraft as a result.

***Recommendation 3.3:*** **Design spacecraft and disposal plans to limit disposal hazard risks.** Design spacecraft components and features so that fewer hazardous fragments survive. 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. Space weather also plays a role as it changes satellite drag during reentry.

It should be noted that many, or even most, operators rely on government-provided models to assess the hazards of reentering debris from their spacecraft. It is critical to provide the community with accurate models of reentry risk to both accurately assess compliance with standards and regulations, and to not overly constrain 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 the satellite is deemed fully demisable, then the reentry point could be uncontrolled and take place anywhere. Currently, there is limited hard data on actual debris survival, and, in fact, collecting radar observations of actual reentries would provide more information. More refined hazard estimates are needed to improve constellation satellite designs, lifetimes, and disposal strategies.

# 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.

There are three key aspects of cybersecurity: confidentiality, integrity, and availability (CIA). The Committee on National Security Systems Instruction (CNSSI) Glossary (no. 4009) defines CIA 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 and includes ensuring information nonrepudiation and authenticity.
3. **Availability:** Timely, reliable access to data and information services for authorized users.

The following three sections and associated recommendations address one or more of the CIA key aspects of cybersecurity. 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.[25]

In response, the U.S. government has given significant prominence to cybersecurity concerns. Space Policy Directive-5 (SPD-5) 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 in order 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, have to be made cyber resilient and secure. It is critical to define robust cybersecurity principles and cyber requirements for space systems and engineer them into initial designs. Using threat-informed, risk-based systems engineering and applying defense-in-depth principles throughout space systems, particularly on the spacecraft themselves, is imperative.

***Recommendation 4.1:*** **Properly fund 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 the directive (SPD-5), "Space System" means 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, 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*

Space systems, often considered part of the critical national infrastructure, comprise many government and commercial components where cybersecurity and space operations are inextricably linked.[26] Current policies do not address the meshing of space and cyberspace, especially for spacecraft. Some examples of cyber threats to a typical space system are shown in Figure 9. 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.

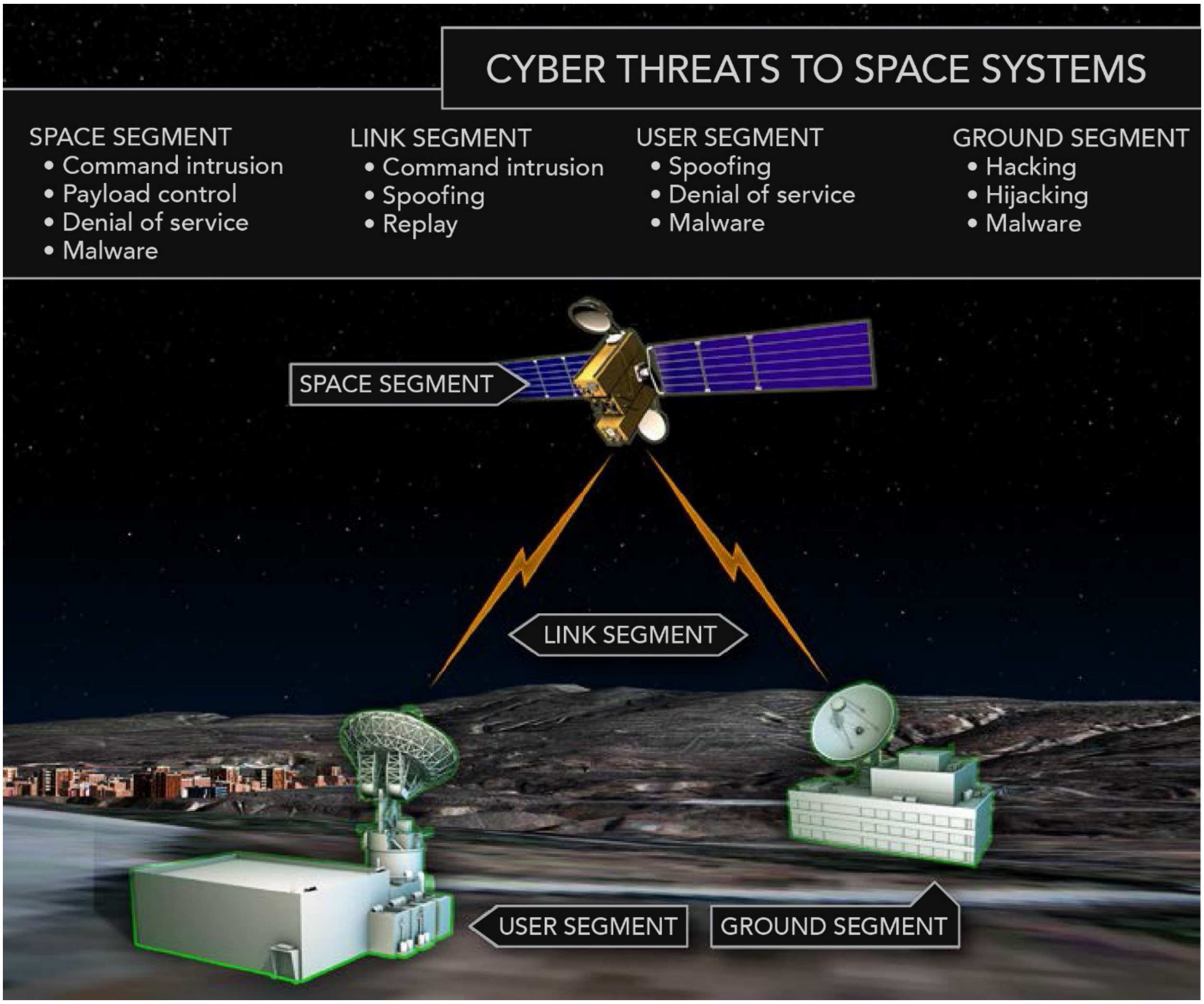



**Figure 9.** Cyber threats across the full integrated space system. This includes the space segment, user segment, link segment, and ground segment.

Space systems operators should also implement additional spacecraft defenses in order to address emerging threats. Historically, spacecraft have been considered relatively safe from cyber intrusions. However, recent 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 techniques for spacecraft protection will help ensure the spacecraft is resilient to a cyber intrusion. This includes the U.S. government, industry, and international partners working together to address the increasingly complex cybersecurity needs. Potential solutions will need increased cooperation across all sectors and will require a blend of policy and technical solutions.

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.

***Recommendation 4.3:*** **Develop and employ defense-in-depth (DiD) principles to cybersecurity**. In the absence of formal policy and regulations, industry and government alike can implement DiD[§§] and recoverability principles and cybersecurity plans throughout the ground and space vehicle architecture. The implementation 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.

To mitigate risks, decisionmakers need to ultimately determine what kinds of DiD principles to apply. While not all risks can be eliminated, budget and personnel should be prioritized appropriately.

***Recommendation 4.4:*** **Integrate onboard cyber intrusion detection and prevention applications.** Operators can identify and block cyber intrusions by leveraging signature-based detection, which assigns a unique identifier to known threats to detect them quicker in the future and 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 in cybersecurity planning.** Proper cybersecurity planning must include a supply chain risk management program to protect against malware inserted in parts 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 supply chain risk management, 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 incur mission failure.[27]

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 have to be flexible and responsive. Emerging threats and dynamic cyber and supply chain landscapes, due to pandemics like COVID-19, natural disasters, Huawei, and more, require a framework that can be applied to a variety of circumstances. Getting ahead of a 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 supply chain risk management (SCRM) governance. This will allow organizations to proactively leverage and exchange peer knowledge, processes, and best practices. It also

[§§]Defense-in-depth (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.

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.[28] 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, weather, and water monitoring systems at risk.

The increasing demand for spectrum and its finite supply will continue to present tough choices for regulators, the space community, and commercial communications companies. A series of Aerospace papers illustrate the context of this ongoing debate and examine various policies for managing spectrum-sharing.[29,30]

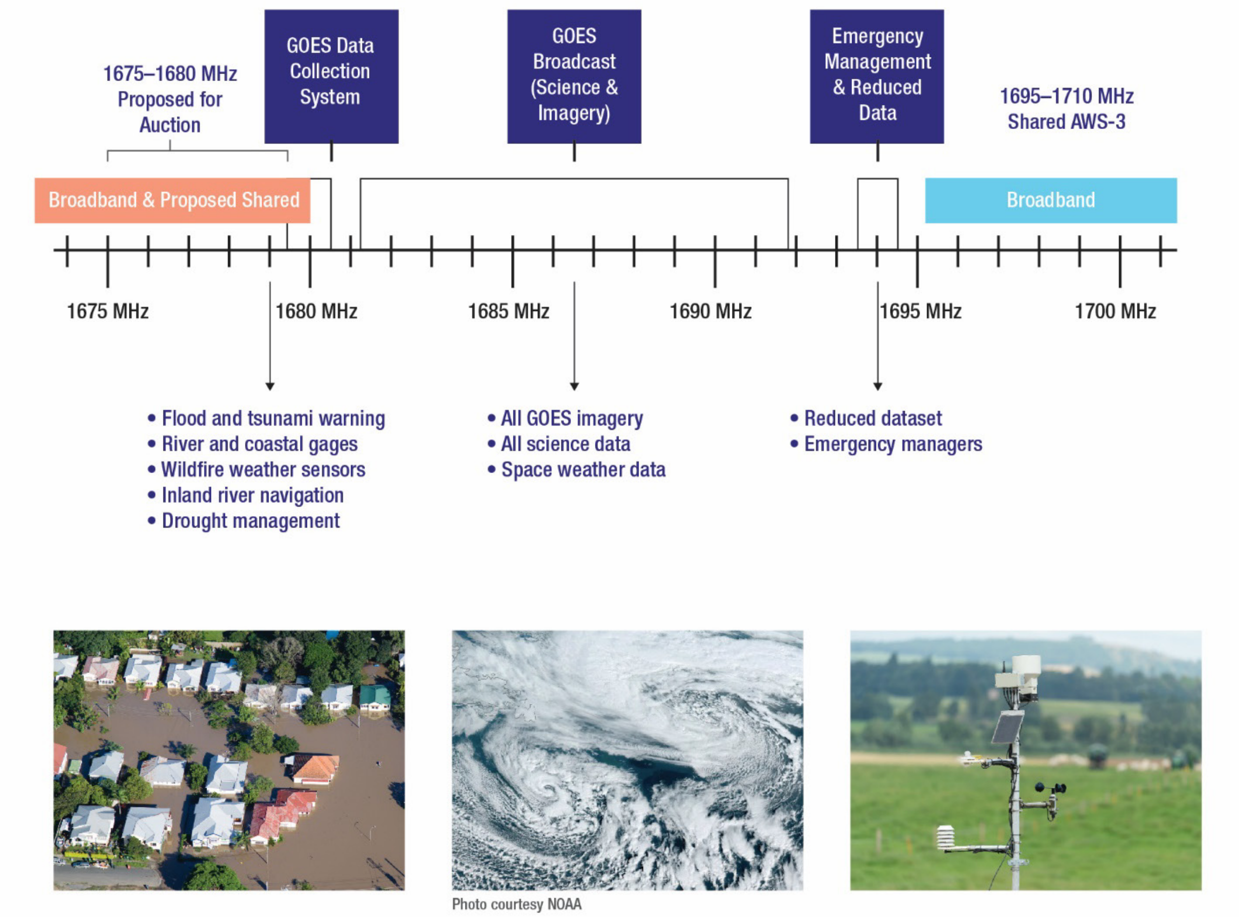



**Figure 10.** An example of the potential interference of geostationary operational environmental satellites (GOES) communications/transmissions.

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 Federal Communications Commission (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 the positioning, navigation, and timing (PNT); aviation; and weather satellite 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 nearby space allocations. These space allocations have historically been relatively quiet, and growth of new and adjacent terrestrial service spectrum allocations are causing interference to long-standing, space-based spectrum allocations.

# 5. HUMAN SPACEFLIGHT SAFETY

The United States is in the midst of a major transformation in how it operates in space. Over the next decade, there are plans for five new and different kinds of human spaceflight missions, four of which will be courtesy of private industry rather than the government:

- NASA missions to the moon in support of the Artemis program
- Suborbital commercial spaceflights that take off from and land at the same location, either for research purposes or for space tourism
- Commercial missions to LEO
- Commercial missions to the moon
- 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 based on the safety case methodology. This methodology would provide a flexible approach for operators to ultimately prove to the Federal Aviation Administration (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.

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

## 5.1 Human Spaceflight Safety Regulatory Moratorium and Mitigating Concepts

The FAA is currently 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. The limitation is scheduled to expire in October 2023. The moratorium, or learning period, was originally put in place in 2004 for eight years in order to help ensure that government regulations did not stifle the industry, and adequate experience had been gained 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.[†††] With the delay in commercial flights, Congress extended the moratorium—first until 2015 and, then, later until 2023.

As the current licensing authority for commercial space transportation, the FAA may be directed to assume regulatory responsibility for commercial human spaceflight should an accident occur before the moratorium expires. While the FAA has encouraged the development of voluntary industry consensus standards, the agency would not be fully prepared to assume this regulatory responsibility today. The following recommendations may help better prepare the FAA and the human spaceflight industry writ large for keeping human spaceflight safe 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 ensuring problems in spacecraft design and manufacture of commercial systems are discovered and resolved. 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 a number of interagency agreements that govern the investigation process. However, despite the involvement of these various agencies, 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 a U.S. space vehicle owned or contracted by the federal government or passenger on that vehicle. This provision may have been appropriate for the space shuttle era but has outlived its usefulness for the current commercial environment. A presidential commission is unlikely to apply to commercial space vehicles and passengers and, in fact, has not been established under this statute to this 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 United States and (2) promote commercial space launches in the private sector, including those that involve spaceflight participants. The dual mandate arguably limits the independence of the agency conducting the investigation.

[†††]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.

In contrast, the NTSB is an independent investigatory agency that is charged with determining the facts, circumstances, and causes of all transportation accidents and incidents. However, unlike the FAA, NTSB has no regulatory authority and can only provide an independent assessment of the accident with recommendations to the FAA.

Finally, the current interagency agreements in place are limited in scope likely because they were developed before commercial human spaceflight was a major concern. [‡‡‡]

Due to these various gaps in mishap investigation, several issues must 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 concerns with public safety.
- Independence and transparency of this process will be critical in developing a successful human spaceflight industry that holds 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 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 the contractor may not understand exactly what the government is looking for and how to demonstrate that its system satisfies 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 United Kingdom. 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."[31] 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

[‡‡‡]On September 9,2022, the FAA and NTSB signed an MOU on Commercial Space Mishap Investigations. It replaces "Appendix H to the 1975 Reimbursable Agreement between the NTSB and FAA as well as all prior memoranda of agreement (MOAs), memoranda of understanding (MOUs) and agreements between the NTSB and FAA for commercial space mishap investigations."

process would require applicants to fully implement a performance-based regulatory philosophy, along with the requirement for the launch operator to accept the responsibility for operating safely and the necessity to advocate 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, 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 (horizontal launch, vertical launch, balloon launch) and destinations (point-to-point, suborbital, orbital, 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.

## *5.2 The In-Space Rescue Capability Gap*

Due to the FAA moratorium prohibiting spaceflight regulations, current FAA policy, in accordance with the Commercial Space Launch Amendments Act, does not regulate the safety of the space traveler. The policy simply mandates that the traveler be informed of associated risks. Therefore, without rescue plans and dedicated resources, today's space travelers journey at their own risk.

One of the risks that space travelers 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 from a distressed spacecraft in low Earth orbit or anywhere else in space.[32]

The lessons of Apollo, Skylab, and the space shuttle with respect to the rescue of astronauts in space seem to have been forgotten as this new era of space flight includes commercially provided spacecraft, space tourism, and the return of U.S. astronauts to the moon. Apollo 13 demonstrated the lifesaving properties of two spacecraft capable of sustaining the crew during the journey to the moon. In similar fashion, great 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. However, there are currently no rescue plans in place for the SpaceX-crewed Dragon launch or other crewed missions.

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 enablers of in-space rescue include ensuring that all crewed spacecraft have common docking mechanisms, timely availability of a rescue spacecraft or a safe haven to escape to, and organizational entities—government, commercial, or international—chartered and sufficiently resourced 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. Article V of The Outer Space Treaty (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 Agreement of 1968, which focuses on the rescue and return of astronauts that have made emergency landings somewhere on Earth.

***Recommendation 5.5:*** **Ensure that operators utilize common docking systems for spacecraft**. This can support and improve in-space rescue efforts. In October 2010, NASA, the European Space Agency, the Canadian Space Agency, the Japanese Space Agency, 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, “This International Docking System Standard (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.

***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. Since orbital launches are occurring with increasing frequency worldwide, there is, on average, a rocket within approximately three days of launch at any given time of the year. If rescue plans were integrated into launch plans, rockets sitting on the launch pad could be utilized for in-space rescue as well. This requires prelaunch determination of the various vehicles’ orbit compatibility so that there are no crashes. Another factor that should be considered is whether there is enough propulsive capability onboard the rescue spacecraft to dock in the necessary orbit and accomplish a successful rendezvous.

# 6. CROSS-CUTTING ISSUES

The compendium's previous chapters on key space safety issues are already intended to cut across a wide range of technologies and policies. However, there are also a number of issues that cut across even these broad categories.

In particular, these include how to strengthen the space workforce to be adaptive and enduring. People problems are space safety problems, and many challenges facing space safety today cannot be resolved without finding solutions to some key cross-cutting issues of personnel. The people who create the technologies and make decisions that are key to space safety in the mission areas discussed in previous chapters will be integral to the future of the enterprise. This chapter will have key workforce development recommendations.

Another key cross-cutting issue is the relationship between space safety and international politics and diplomacy. The physics behind orbital debris and the electromagnetic spectrum mean that, in some situations, the actions of any one country, company, or even individual in space can affect everyone. Even if the majority of space actors agree to improve measures for space safety and sustainability, failure to establish broader international consensus could ultimately lead to failure if someone behaves recklessly. This chapter will also share options for how to develop international norms of behavior for space, including for space safety, through the lens of a strategic decisionmaking framework.

While this chapter highlights just a few examples of cross-cutting issues, there are many other dynamics that will affect all areas of space safety. This includes the health and competitiveness of the space industry and its relationship to government regulators; the growing pattern of partnerships between different countries; and the rate of growth and development for new technologies with space safety applications, such as active debris removal or blockchain technology for information-sharing. This assortment indicates the importance of not treating space safety issues in a vacuum: Many of these issues are highly interconnected and interdependent and should be treated as such.

## 6.1 Developing a Strong Space Workforce

The U.S. space industrial base provides hundreds of thousands of jobs, spurs innovation, and is a catalyst for high-technology economic growth.[33] In order to keep this workforce pipeline strong, there needs to be a strong space industrial base with consistent public and private investment in quality education, especially education in science, technology, engineering, and mathematics (STEM), which benefits society writ large.

While industry and government leaders in the space sector regularly talk about the importance of education and workforce development, the space sector must enable consistent investment at scale. Indeed, the "STEM crisis" in the United States has been discussed as a national security concern within the defense, cybersecurity, and research and development (R&D) sectors, broadly speaking. Creative new approaches that bring together government, industry, and the education sectors are key to the health of the space workforce in the long term.

Additionally, the clear relationship between innovation and diversity of thought could be a valuable asset to the space sector. The sector is limiting its potential by not bringing in more diversity of gender, ethnicity, nationality, etc. Expanding the candidate pool will be integral to maintaining a robust space industry. As Table 2 shows, the space sector needs to make significant improvements for greater diversity and inclusion in the aerospace workforce.

**Table 2.** Aerospace/Defense Workforce Diversity, 2018*

| Demographic | Percent of Employees |
|---|---|
| Female | 24 |
| Black | 6.8 |
| Hispanic | 7.6 |
| Asian-American | 10 |

**Source: Q1—The Space Report 2019, The Authoritative Guide to Global Space Activity*[34]

In order to better understand diversity and inclusion challenges, Aerospace hosts an annual Space Workforce Inclusion Summit. This event brings together higher education students from across the nation to have an open conversation about diversity, equity, and inclusion in the space workforce.

Leaders have to think now about tomorrow's U.S. space workforce. Strategic investments in STEM education and diversity, equity, and inclusion will lead to a stronger space workforce 25 years from now.

***Recommendation 6.1:*** **Invest in STEM education and continuous training.** Decisionmakers interested in the health of the U.S. space industrial base should cultivate a robust, diverse, and multifaceted space industrial base workforce, from early education to higher education to continuous training. Decisionmakers in the space sector can support improvements in space workforce development by:

- Providing continued public-private partnerships and investment in space-related STEM education.
- Fostering leadership champions for STEM education who expand and diversify opportunities.
- Emphasizing the role of nondegree, non-STEM training in the space sector.
- Developing a national strategy that includes a centralized index of space-specific STEM education initiatives and measures for success.

***Recommendation 6.2:*** **Improve the narrative of a space career.** Decisionmakers interested in the health of the broader U.S. economy should also view an investment in the space workforce as a key opportunity to create energy and enthusiasm for education in fields of general applicability to U.S. economic prosperity and competitiveness.

Space jobs are often seen through the lens of hard science and inaccessible to many, including underrepresented populations. The space sector should consider how to update the view of a "successful space employee" to be more inclusive and span across the vast array of space jobs, not just STEM. Industry changes, as well as how space is represented in the media and popular culture, could make a significant difference in the numbers and types of people seeking space jobs.

***Recommendation 6.3:*** **Expand the school-to-space pipeline.** The inaugural Space Workforce Inclusion Summit in July 2021 revealed that to ensure a strong space workforce in the future, there needs to be a better understanding of the school-to-space pipeline and the barriers that exist for underrepresented populations. The space sector can improve the school-to-space pipeline by improving strategies for outreach and recruitment and workplace culture with better allyship and mentorship. Additionally, it involves highlighting to employers the value of greater diversity of thought in the workplace, which also encompasses accessibility and neurodiversity differences.

## *6.2 Building Normentum: A Framework for Space Norm Development*

There appears to be a rising consensus among U.S. policymakers and space experts that norms of some kind are necessary to protect the safety, stability, security, and sustainability of the space domain.[35] It is a U.S. national policy aim to lead the development of international space norms, so what would a strategy to achieve that aim look like? This section proposes a framework for the development of international norms of behavior for space. It emphasizes four strategic decision points involved in developing norms:

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.

Aerospace has developed a strategic framework supplemented by analysis of three case studies of space norm development. These include the 1963 development of a treaty banning the testing of nuclear weapons in space, the 2007 adoption of the UN Space Debris Mitigation Guidelines, and the responses to China's 2007 anti-satellite (ASAT) weapon test. This framework and analysis show that 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 11 can help analyze and compare these tradeoffs while demonstrating how different decisions in norm development will interact with each other.

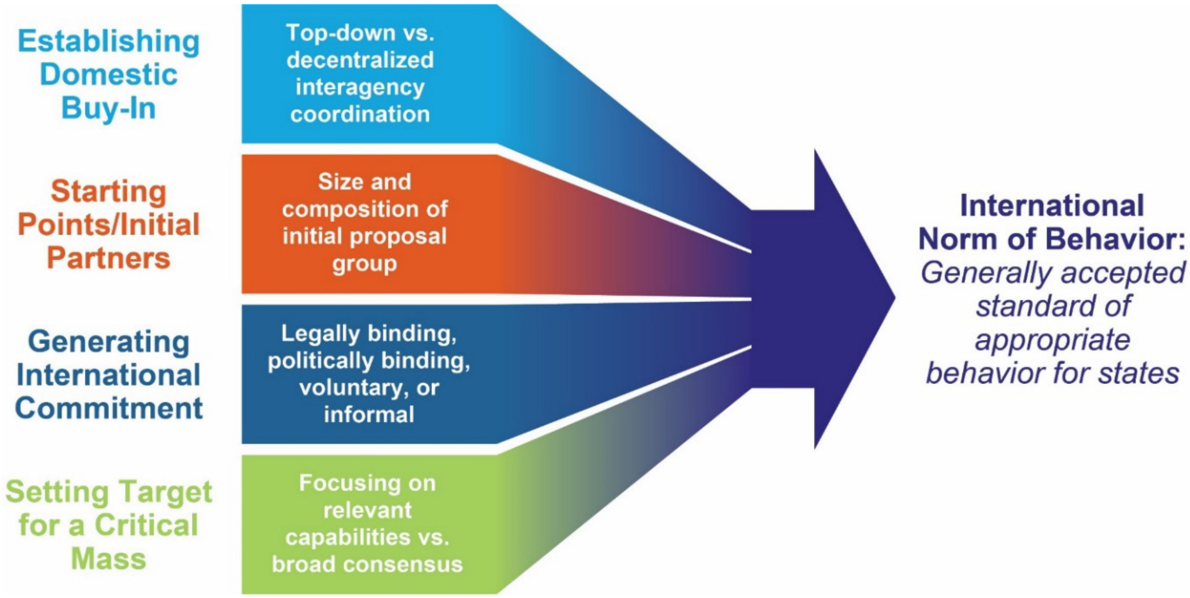



**Figure 11.** The norm development decision point framework. The analysis for this framework uses a definition for international norms of behavior with several elements common to norms discussions: "generally accepted standards of appropriate behavior for states."

*Recommendation 6.4:* **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.[36] 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.

*Recommendation 6.5:* **Consider the whole lifecycle of norm development.** Strategic decisionmaking for norm development should look beyond questions of the 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.

# 7. 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 non-stop flight across the Atlantic. Perhaps someday, the 2020s will be referred to as the “Golden Age of Commercial Space.” This time, rather than a definition based on the feats of daredevil pilots and wing-walkers, perhaps that distinction will be earned based on partnerships and collaboration, and a renewed focus on improving space safety.

This compendium highlights many of the challenges the space sector faces in this era of enhanced commercial space activity. It covers policy implications of issues within five core mission areas: space operations assurance, space situational awareness, satellite launch and reentry, cyber and spectrum security, and human space flight safety, as well as two cross-cutting areas. Finally, it offers some key actions and recommendations for decision- and policymakers to tackle these challenges. These recommendations are based on a collection of Aerospace 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 Space Safety Institute 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.

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