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Promoting International Cooperation to Avoid Collisions Between Satellites

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Introduction

The deployment of large satellite constellations and periodic destructive anti-satellite weapons testing have elevated the chances of collisions between objects in orbit. Collisions involving satellites create debris that subsequently threaten the safety and security of other satellites. Satellite owners and operators, both commercial actors and governments alike, have growing stakes in reducing the likelihood of such collisions. It is impossible to sustain a thriving space sector, both now and for future generations, without systematically addressing these risks. Surprisingly, given the stakes involved, no comprehensive approaches to reduce the risks of collisions between satellites appear on the near- or even medium-term horizon.

Potential collisions—called conjunctions—come in three distinct types: between operational satellites, between a satellite and a piece of debris, and between pieces of debris. Reducing the risks of each type poses distinct technical, operational, and political challenges. For instance, little can be done to mitigate an impending collision between two pieces of debris; the logical approach to reduce the associated risks is to proactively remove derelict objects and limit the creation of debris in the first place. This strategy is obviously inappropriate for preventing collisions between operational satellites. Instead, satellite operators must maneuver satellites out of the way of impending collisions to avoid a crash. A more nuanced, collaborative collision avoidance regime is urgently needed to mitigate the risks stemming from dangerous interactions (see table 1).

Table 1. Three Types of SSA-Related Failures

Satellite operators contend with several types of risk, not least of which is the risk of collisions with other space objects. Mitigating this risk is dependent on an up-to-date operating picture for the space environment, adequate information about close calls between satellites, and efficient communication with other operators who may be affected. The cases illustrate not only the hazards themselves but also the gaps in the risk-avoidance methods available to the global spacefaring community today.

Unforeseen Incidents	Incompatible Analyses	Incongruent Risk Tolerances
NASA has catalogued over 250 satellite fragmentation events caused by several factors such as battery explosions and propulsion issues. This list continues to grow as experts look back in time to determine the causes of satellite breakups. Accidental collisions are one culprit that forensic analysts evaluate when explaining why a satellite may have broken into many pieces. The 18 SCS identified one such instance in 2021. Analyses of the incident concluded that a Chinese satellite, YunHai 1-02, collided with a small piece of mission-related debris from a prior Russian satellite launch. The reason for the YunHai 1-02 fragmentation had, to that point, been unknown. This accidental fragmentation is the fifth confirmed collision between catalogued objects. It is unclear whether the YunHai 1-02 satellite could have maneuvered to avoid this collision, but this example illustrates the risks of incomplete data and analyses. Without knowing satellites are on a collision course, there is nothing operators can do to avoid conjunctions.	In April 2021, observers from the EU's SST predicted a collision between a defunct meteorological satellite and a spent rocket body. The EU's analysis predicted a one-in-five chance of a collision. However, other analyses of the same objects determined there was a one-in-fifty chance of conjunction. While dramatic, this tenfold decrease in probability is still an alarmingly high chance. In general, operators will conduct evasive maneuvers if the risk of collision exceeds a one-in-ten-thousand chance. In this instance, neither object was maneuverable, so there was little for observers to do but hold their breath. However, it is not difficult to extrapolate this experience to a situation involving operational satellites with the potential to maneuver. While both satellites eventually passed each other without incident, this situation illustrates that even though two analysts may both identify a conjunction risk, that does not mean they will necessarily agree about the magnitude. Severe gaps between analyses may hinder mitigation strategies in the future.	In late 2021, China addressed the UN secretary-general about two instances involving Starlink satellites and the Chinese Space Station. China maneuvered its space station in July and October 2021, precisely to avoid collisions with Starlink satellites. The United States, in its own note to the secretary-general, refuted that any Starlink satellite had come close enough to endanger the Chinese Space Station. The difference between the two perspectives is unclear: China may be more risk averse than the United States and may thus have lower thresholds for maneuvering its space assets. The instruments used to determine the location of the involved satellites may provide different levels of accuracy and precision, or the analytical tools employed by each country may result in different conclusions. The root of the divergence may be a combination of all three or another factor entirely. While it may not be surprising that China and the United States viewed the same situation differently, the encounter indicates that states do not always agree on what is and what is not safe.

To be effective, a collision avoidance regime must identify potential collisions, harmonize the wide range of risk tolerances among operators, and support efficient communication among satellite operators. Well-designed policies and practices must account for these issues to enable operators to identify satellite conjunctions, socialize reasonable risk thresholds, and provide pathways to coordinate satellite maneuvers. Furthermore, the foundation for any systematic approach to collision avoidance requires robust space situational awareness (SSA) and conjunction analysis capabilities, as well as a reliable means for sharing conjunction assessments. Satellite operators rely on such analyses—probabilistic estimates of whether two objects will be in the same place at the same time—to inform and schedule potential evasive maneuvers.

Progress toward a mutually beneficial solution to prevent catastrophic collisions between satellites remains comparatively stagnant, even as the market for space-enabled or -derived data and services balloons. Even incremental improvements in data sharing and coordination have been slow to take hold, while a broader, cooperative system among international actors is far from view. The following sections synthesize views from global experts, including policymakers, operators, economists, members of civil society, and business leaders. These views help identify underlying causes for the lack of progress on avoiding collisions and validate ways to accelerate progress. The paper concludes by recommending a variety of cross-sectoral efforts and cooperative measures to reduce the risks of collisions in space.

Methods

The Carnegie Space Project conducted semistructured interviews with government officials, commercial actors, and industry leaders to better understand the array of perspectives on the state of cooperative conjunction avoidance practices. The interviews were anonymized and aggregated, to facilitate more open and frank conversations. Respondents were roughly evenly split between technical and political competencies. Because several categories of respondents both use and produce data and analysis, perspectives were instead grouped into those from industry (including commercial SSA providers and satellite owners and operators), government (including advanced, emerging, and nascent spacefaring states), and third-party actors (including professionals from international organizations, academics, and members of civil society). This paper also benefits from ongoing Carnegie efforts to engage with European and Chinese colleagues on space issues. These discussions aided the paper's scoping and informed the findings.

In aggregate, these conversations revealed several primary and secondary challenges as well as policy options for legislators and regulators interested in improving safety, sustainability, and security in space. The resultant recommendations focus on how states can be more productive partners in collecting and analyzing SSA data over the long term. For instance, states should redouble their efforts to align views on conjunction avoidance practices at regional forums, which are generally free from major power politics. These engagements can help states grow their technical capacities, gain access to other sources of data, and create room for regional actors to develop and execute cohesive policies. At the state level, governments around the world should review their licensing processes with an eye toward requiring granular information that would support a communication and coordination network among satellite operators involved in dangerous conjunctions.

Systemic Challenges

Avoiding collisions between space objects has been a priority for satellite operators for decades. Until recently, policy-focused work has been a small fraction of the total volume of work on SSA. Nevertheless, technical work reveals persistent themes within the SSA field that have significant policy implications. These issues can be broadly categorized as challenges with collection, analytics, and operations.

Collection. Satellite location data is the foundation of any activity supporting safety in space. To comprehensively assess conjunction risks, satellite operators must know the precise orbit of their satellite and have an accurate understanding of the orbits of other satellites that may pose collision threats. In any calculation, these orbital parameters carry some level of uncertainty. Although an operator may have precise data on their satellites, their estimates of other satellites' orbits are likely less accurate. The uncertainty inherent to conjunction assessments can be reduced by using data collected closer to the expected time of a predicted conjunction. Thus, access to more frequent observations of satellites can increase the precision of conjunction assessments.

Analytics. Analysts use predictive models to compensate for the inherent gaps in observations. It is necessary to use models to understand and forecast satellites' locations and trajectories because no organization currently has a sufficient network of telescopes, radars, or other sensing equipment to maintain a perpetual track of any given satellite. While constant observation of a satellite would be ideal, it is unlikely that any provider will be able to build the infrastructure needed to accomplish this soon. Using predictive models allows SSA analysts to provide value without making significant capital investments in more hardware, but these analytical practices present other systemic challenges. Notably, the analytical process is not always transparent. Thus, end users may be unable to reconcile contradictory findings produced by different analysts who employ different prediction algorithms. This added layer of uncertainty erodes the impact of good analysis and reduces the efficiency of the entire system. The systemic lack of transparency has been reinforced over decades of analytical practice.

At a basic level, analysts input observational data into models to predict the future location of a satellite in orbit. Operators and observers must make assumptions about the effects of external stimuli to predict where a satellite is at any given moment that it is not under observation. The forces that might affect a satellite's movement through space include, for example, the effect of solar radiation pressure. Orbital position models systematically account for these forces, but specific models may use different values or constants when estimating the effects of certain forces. These models have changed over time as calculations and observations have offered more precise inputs, but these changes have not always improved the transparency of the overall SSA ecosystem.

Operations. Even the best analysis cannot alone reduce the risks of collisions in space. The data and analysis must be distributed to affected satellite operators in a timely fashion, promptly enough so these operators can plan and execute evasive maneuvers. First and foremost, this process relies on trust between operators and those producing analyses. Second, the satellite must have the capability to maneuver. Third, the satellite operators planning the maneuver must be sure not to unintentionally move into another high-risk orbit. This is especially important in cases involving two maneuverable satellites: the risks of collision remain if both affected operators take the same evasive maneuver but move into each other's paths again. Thus, there must be an effective and prompt communication network.

The history of space sensing and analysis is instructive for thinking about how to develop effective policies to guide future efforts to mitigate the risks of collisions between space objects. The U.S. government developed the standard practice for modeling satellites' trajectories in low Earth orbit in the 1960s, periodically revising the source code throughout the 1980s. This code was designed to work solely with U.S.-derived orbital data, limiting the ability of others to use the code with their independent or proprietary data. The scientific community and interested observers have amended the equations over time to suit their or their clients' needs, resulting in a variety of new codes. Many of these became proprietary intellectual property, and some new models produced irreconcilable predictions about satellites' future positions. These new models did not always clearly communicate why and how the code produced different findings, all but eliminating the possibility for the community to check each other's work. Efforts to forensically recreate and synthesize a master source code have aimed to standardize analyses and restore trust in the network of space observers and data providers.

These collection and analytical issues inform operational concerns. Satellite operators make decisions about maneuvering assets based on opaque analyses that often apply proprietary algorithms. Furthermore, resolving to initiate an evasive maneuver often happens in a black box. Risk tolerances are influenced by a variety of factors such as a satellite's purposes, capabilities, and operator culture. For instance, operators' risk tolerance in cases involving human-inhabited spacecraft is likely to be lower than in similar cases involving relatively inexpensive, academic CubeSats. Since there are neither globally accepted standards nor widespread formalized communication channels among satellite operators, affected operators may either be left questioning why their neighbor performed a maneuver or, worse, attempt to evade a collision only to exacerbate the risk by moving closer to the other at-risk object.

Furthermore, not all satellites are maneuverable, and not all maneuverable satellites are equally agile. These operational differences impede harmonization of responses to risk. For instance, the schedule for mitigating collision risks between two maneuverable satellites differ based on the methods each satellite uses to maneuver. Satellites that need multiple orbits to move away from an impending collision do not have the luxury of waiting for more precise measurements, reducing operators' decision timelines. Satellite operators who are responsible for relatively agile satellites may choose to wait for more precise analyses when deciding if or how to evade a predicted conjunction. This difference in how and when satellites maneuver can impact global perceptions of orbital behavior among operators, observers, and state actors. Operators may initiate an evasive maneuver before others in their orbital neighborhood recognize the risk-informed reason for such behavior, potentially spurring misinterpretation and reducing trust. Risks stemming from operators' perceptions of others' behavior are heightened by a dearth of avenues for diffusing misinterpretation, such as a platform for announcing maneuvers or other approaches to sharing critical information.

State of Play

The SSA landscape is rapidly evolving alongside broader advancements in space systems. Perhaps most notably, a new market for commercial SSA and conjunction analysis is emerging as satellite owners and operators seek data and analysis to supplement information traditionally provided by governmental agencies. Commercial actors have stepped in to satisfy this demand, diversifying both the community of SSA providers as well as the methods of SSA collection and analysis. Simultaneously, and in part as a response to changes in the commercial sector, governments are also restructuring relevant bureaucracies to better serve the rapidly expanding space community. The confluence of changes across the private and public sectors has created a chaotic information environment that reduces clarity for satellite operators on safe space behaviors.

Conjunction avoidance practices are neither systematic nor standardized across the broad community of satellite operators. So too are the incentive structures. The mosaic of government and commercial entities that own and operate space objects presents diverse imperatives that can be difficult to reconcile, especially in situations that require prompt responses. For instance, geopolitical interests incite competition between governments as they contribute to data aggregation and conjunction analyses, while financial interests and market forces drive competition between commercial entities. Such competition creates barriers to trust and cooperation between key actors. Different visions for who can legitimately collect SSA data, produce conjunction analyses, and compel operators to avoid collisions compound this lack of trust. Some states are also driven by domestic industry interests to protect a commercial market for SSA services. These competitive dynamics sustain, if not deepen, fractures among current global leaders in SSA.

Generally, states with existing or emerging SSA capabilities recognize that good sensing systems and robust analysis are the foundation of safe orbital operations. Nevertheless, each state has taken a nuanced approach in establishing its SSA capabilities and effecting the end goal of improving space safety by enabling conjunction avoidance. Around the globe, states have developed and demonstrated unique SSA collection practices that are tailored to their broader space strategies. For instance, states with broad aspirations for space preeminence are leading multinational efforts to strengthen their leadership, while others are innovating to facilitate collaboration and communication between operators. Those with comparatively less lofty aims have adopted proven technologies and engaged in limited partnerships to support their domestic space projects. Others are pushing the boundaries by demonstrating new technological paradigms for SSA data collection, potentially as a way toward self-sufficiency. Some states have recently marshaled their domestic industry to develop SSA services and capture a larger portion of the global space market. This variety of strategies provides a dynamic landscape in which states learn from each other's successes and shortcomings.

Global Approaches to SSA Data Collection

The U.S. government is currently the leading service provider for collecting and disseminating SSA data. The U.S. Department of Defense traditionally executed this mission. Currently, the 18th Space Defense Squadron (18 SDS), a component of the U.S. Space Force, uses noncooperative methods, such as the U.S. Space Surveillance Network, to track objects orbiting Earth. The 18 SDS shares some of this data with stakeholders outside the U.S. Department of Defense, including with other governments, commercial entities, and academic partners, through a public website. The 18 SDS also screens the predicted trajectories of tracked satellites against others in its catalogue to determine future conjunctions. Conjunction warning messages are distributed to the owners or operators of the involved satellites, who then may conduct internal risk assessments and execute an avoidance plan if they deem it necessary.

Others around the world are building robust SSA capabilities to preserve safe and sustainable uses of space. The European Space Agency established a federated approach to build on the European Union's (EU's) 2014 Space Surveillance and Tracking (SST) Support Framework. The SST function has transitioned into a core competency of the EU's Space Programme. European perspectives now reflect the role SSA data play in supporting European freedom of action, autonomy, and continental security. To this end, the EU sponsored a draft code of conduct that would preserve access to and use of space for future generations. While it never evolved beyond a draft, this code suggested that adhering states should provide information about the space environment collected through national SSA capabilities to other affected parties. Notably, the SST framework offers a communication portal to enable collaborative decisionmaking and coordination among affected or potentially affected users. This allows over 190 civil, security, and commercial satellite operators to deconflict their actions and preempt misinterpretation.

Informed by European success, China's major contribution to global SSA comes through its leadership within the Asia-Pacific Space Cooperation Organization (APSCO). APSCO's flagship SSA capability, the Asia-Pacific Ground-Based Space Object Observation System (APOSOS), was rolled out in an initial capacity in 2012 at sites in Iran, Pakistan, and Peru. Optical telescopes in these states collect data on objects in low Earth orbit primarily to serve the needs of APSCO members' satellites. APOSOS focuses on optical sensors primarily due to the low cost of construction and maintenance. This network has grown over the last decade to include more optical observation sites in Indonesia and Thailand, increasing the network's coverage of Earth's orbits and diversifying the group's political interests.

APSCO has also enlarged its technical scope. Recently, APSCO approved the design of a new SSA network scoped to focus on space debris. The Asia-Pacific Space Sciences Observatories is a planned system of optical telescopes to be installed in all APSCO member states by 2025. While this project might focus its technical attention on debris, the political aspects remain consistent: China's National Space Administration is the project lead.

Multinational SSA collection systems remain popular in Asia even without the formality of an international organization. South Korea's Optical Wide-field patroL Network (OWL-Net) collects SSA data using telescopes at sites in Israel, Mongolia, Morocco, and the United States. OWL-Net sites abroad are vital to the system's success, as optical telescopes can only capture satellites when they are within frame. Achieving full coverage of Earth's orbits with optical sensors necessitates a broad network of collection systems. The Korea Astronomy and Space Science Institute chose to use relatively low-cost and proven optical observation technologies, a logic akin to the APOSOS network. Additionally, the South Korean Defense Ministry and the U.S. Department of Defense share SSA data.

Other Asian states are exploring new political and technical paradigms for SSA. Japan, for instance, operates eleven dedicated terrestrial SSA facilities and has committed to developing new sensing capabilities. In addition to these ground stations, Japan has partnered with the United States to host in-situ space sensing capabilities on the Quasi-Zenith Satellite System, the Japanese-operated satellite positioning system. This push to upgrade and expand Japan's SSA collection capabilities is occurring in parallel with an effort to streamline domestic organizational responsibilities for SSA collection and conjunction avoidance. This political and organizational refresh has illuminated an expansive policy perspective. While most states' policies reflect the relationship between SSA and space safety, Japan has also recognized that improving national SSA systems encourages broader industrial growth. This linkage is most clear in the Japanese government's intent to stimulate private sector growth by collaborating with industry on removing space debris.

India is developing an SSA capacity and expanding conjunction avoidance services by advancing its domestic SSA capabilities through both public and private initiatives. New Delhi has established a Directorate of Space Situational Awareness and Management within the

Indian Space Research Organisation (ISRO) to centralize the government's work on space safety, including conjunction avoidance. ISRO also issued a national space policy in 2023 that explicitly directs nongovernmental entities to "develop space situational awareness capabilities for enhancing observation, modelling and analysis." India is pushing the commercial space sector to develop these capabilities and services to fill gaps in government-provided services with commercial offerings. Indian companies are capitalizing on ISRO's push and have begun to fundraise for future SSA systems.

Next Steps in SSA Development

The SSA community is clearly growing in multiple directions. Emerging space actors are developing SSA competencies and building proven capabilities. States appear to recognize that adopting these traditional observation capabilities in the context of broad partnerships is an easy way to participate in cooperative, collaborative conjunction avoidance networks. While more conventional observation technologies, such as optical sensors, remain the most common and likely easiest pathway for states to begin indigenous SSA collection and analysis, some states and private entities are experimenting with new data collection paradigms.

It is too soon to say that the traditional methods of SSA data collection are outmoded, and low-cost options will likely always play a part in a comprehensive SSA network, but states' efforts around the world indicate that there is a desire to take risks, explore advanced concepts, and bring innovative solutions to bear. These different methodologies are poised to support states and satellite operators in developing a better operational picture of Earth's orbits. How quickly these new collection techniques can be deployed, validated, and integrated is yet to be determined, however.

The Future Forecast

The traditional SSA architecture satisfied the needs of early space activities, in which a few states owned and operated most satellites and used these capabilities as both operational and symbolic instruments of national power. The rapid increase of objects and diversification of actors in space has dramatically changed global perceptions of safety in space. These perspectives have prompted new actors to create innovative paradigms for SSA data collection and services that fulfill modern requirements for effective and actionable conjunction avoidance services. The near-term future for SSA data collection and services may scarcely resemble the traditional approach. The pace of progress over the next decade is likely to be determined by state-led approaches to space and SSA systems. Some states are in the midst of political and regulatory changes to improve SSA service provision and lower barriers to technical progress.

One illustration of this evolution and the associated bureaucratic, operational, and cultural tensions is occurring today in the United States, where the government is in the process of transitioning SSA functions from the Department of Defense to the Department of Commerce. The civil and public space safety mission does not fit neatly within the Department of Defense's mission to protect and defend national security interests. The civil nature of the SSA service is also misaligned with the combat-relevant work performed by the 18 SDS. These organizational conflicts have prompted the U.S. government to reconsider which federal organ should be responsible for conducting civil SSA activities. This decision was simultaneously escalated and accelerated by significant changes in the field, including the expanding diversity of actors generating and using SSA data along with the rapid increase of commercial reliance on conjunction warning services.

Changes in U.S. SSA Architecture

With this new landscape in mind, the Department of Commerce is preparing the Office of Space Commerce (OSC) to absorb the responsibility for analyzing and distributing SSA data for civil and commercial use. Yet, OSC does not have an active SSA service. The office is working to operationalize the Traffic Coordination System for Space (TraCSS) and is currently scoping requirements for this system to better serve the satellite community. This effort is in accordance with Space Policy Directive–3 and subsequent executive branch activities that prioritize nurturing a civil, free, and U.S.-led SSA system. OSC is also responsible for encouraging a market for U.S. commercial SSA services and other nongovernmental actors. Fulfilling this obligation may, at times, stand in contrast with OSC's duty to provide no-fee SSA and conjunction warning services for public safety. OSC's plans to balance these two accountabilities, and what types of justifications the office will use to make related decisions, are still unknown.

The Department of Commerce has yet to communicate an overarching evaluation of core issues, such as whether SSA data is a public good. Core governmental competencies beyond the reach of market forces, like assessing the strength of public interest in space safety, remain unbroached. In interviews, industry observers emphasized that it is difficult to provide comprehensive guidance on the future of the U.S. space safety network without clarity on such keystone assumptions. To date, the department has solicited input from the public, but it has yet to evaluate or publicly incorporate these findings into its SSA operations. Some analogues, like drawing lessons from U.S. utility regulations or the taxation process, could be readily applied if the Department of Commerce clarifies its perspective.

Interviews with commercial and industry experts revealed competing evaluations of the nature of SSA services, which may forecast the Department of Commerce's conclusions. The divergence hinged primarily on the valuation of SSA data and services, including conjunction analyses. Several industry leaders supported a future paradigm in which a government or governments purchase SSA data or services from the market and redistribute that product as a free-of-charge package to their constituents. Views on what should be the specific components of such a service varied broadly, but leaders within the SSA service industry agreed that a free service could ensure a baseline level of safety, yet not compete with advanced commercial services. The Department of Commerce's commitment to developing a free SSA service is likely to produce quasiregulatory effects by providing a baseline offering that for-profit SSA service providers must surpass.

Subject Matter Expert Views on Role of SSA

From a different angle, however, several analysts, observers, and end users of SSA services (whether provided by government or commercial entities) argued that SSA data should be considered a public good. Nuances among responses illustrated how this overarching perspective can be informed by many different considerations. Motivated first and foremost by safety, some satellite operators noted that monetizing conjunction avoidance services would exclude participation and fail to achieve deep reductions in risks. While the most successful satellite operators can afford exquisite analyses, smaller or less profitable operators might be restricted to less expensive options that may be either lower quality or less responsive to acute risk. Operators of large satellite systems recognized inherent concerns of such an inequitable system. Less awareness of urgent conjunction issues would stunt improvements to space safety, even for those who are paying for robust SSA services.

From the perspective of economic experts, treating SSA data and conjunction warnings as a public good would likely spur innovation and growth by lowering barriers to market entry. Currently, firms interested in entering the market must either buy data from existing SSA data collection services, limiting their ability to differentiate from the existing market, or start enormous capital infrastructure projects to build observation platforms. It is unclear whether several firms should all be making these same investments, especially while the expected market dynamic strongly favors consolidation and centralization.

The commercial market for SSA services has recently emerged as an alternative to government-provided data and conjunction warnings and, in the process, changed expectations about the delivery of SSA services. The burgeoning private sector has emerged directly because of the shortcomings of government-provided, free-of-fee services. Private sector SSA providers offer proprietary infrastructure, analytical tools, and procedures to differentiate their services from the rest of the market. Broadly, these practices follow a similar blueprint to the existing U.S. SSA system. Many commercial SSA providers offer tailored services to customers that enable owners and operators to reduce risks of collision with limited operational disruption. Some satellite operators opt to purchase such services to inform their conjunction avoidance practices.

Recently, some states have engineered a third option by developing advanced in-space systems for collecting SSA data and are reducing the regulatory burden on commercial actors who might be interested in pursuing non-Earth imaging from orbit. These SSA collection systems could bypass the need for a global terrestrial network by collecting data from orbit and then transmitting the observations to Earth for analysis and subsequent action. States are experimenting with satellites that can use existing sensor technologies to inform maneuvers and evasive options. Beyond expanding the scope of observations without requiring additional terrestrial sensing sites, in-space observation platforms can also detect hazards that are otherwise too small for ground-based sensors. Even with new paradigms on the horizon for space sensing, there are still several looming roadblocks that may hamper progress toward improved SSA analyses and conjunction avoidance practices.

Perspectives

Interviews with global experts from industry, government, and academia revealed several key themes about conjunction avoidance. The concerns and sentiments address both the existing practice of reducing the risks of collisions between space objects and global expectations or requirements for future systems. The common themes can be categorized into technical gaps and political hurdles. Combined, these two aspects delay progress toward a risk-reducing collision avoidance system.

Technical Challenges

Several distinct technical issues hinder progress on comprehensive collision avoidance mechanisms. These include the entanglement of civil and military missions, the precision and accuracy of analyses, and operator behavior. These issues echo and, in some cases, are entangled with challenges related to recent advances in other space technologies. While fields such as space launch and satellite engineering have evolved rapidly over the past fifty years, SSA technologies have not followed an equivalent trajectory. This is particularly striking when considering the shared roots of space technologies, specifically the military origin of rocketry, satellite missions, and SSA capabilities.

Civil and security entanglement. Several space-related products and services, such as rockets, satellites, and tracking systems, are rooted in defense applications. The technologies that enable conjunction avoidance and collision risk abatement practices are no different. However, this suite of technologies has not experienced the revolutions and paradigm shifts that are apparent in human spaceflight and satellite constellation design. The sensing and analytic tools that inform conjunction assessments still leverage legacy platforms that are often repurposed from military and security applications. For instance, many radars used for SSA were originally built for tracking ballistic missiles and were assigned to this new mission with few upgrades.

The use of military assets to produce conjunction analyses for civil and commercial operators contributes to political friction. Military and security interests often take precedence in determining how to task sensors that can be used for both civil and military space tracking operations. This imposes a zero-sum regime on sensor accessibility and tasking availability. Thus, either SSA services may not always be available to support civil space applications or the data used for assessments of conjunctions involving civil or commercial assets may not always be as precise as possible.

Government officials and industry leaders from around the world recognize issues inherent to the military origins of SSA systems. Nearly universally, interviews conducted during this research suggested that conjunction analysis networks will continue to be stunted without built-for-purpose sensing systems. These concerns also highlight the age of existing systems. Widespread adoption of newer technologies and methods could, in some experts' opinions, improve the data collection process and seed improvements to the overall data collection and analysis process. Several companies promote their proprietary technologies or novel applications as ways to overcome these data collection gaps.

A separate but related concern given civil-military space entanglement is that operators must assume that SSA services provided by governments are not comprehensive. State security services and other national space agencies often either classify or do not share information about their satellites, including orbital parameters, size, and maneuverability. However, these organizations are also incentivized to reduce their risks of collision. Thus, it is possible that some operators may face a conjunction with a military satellite without ever knowing it. These types of interactions, between classified and nonclassified space assets, reduce operators' trust in government-provided data, especially if the data are provided by security services.

Many experts from various backgrounds noted that arrangements in which SSA data are collected, analyzed, and distributed by state military entities exacerbate these issues, but they held different perspectives on how impactful military association is on the credibility of SSA data and analysis. End users accept some level of apprehension due to the absence of guarantees about the comprehensiveness and clarity of government-provided conjunction analyses and SSA services. This sentiment is based on the perception that any security-related organization capable of collecting and processing SSA data would avoid exposing its own classified military space capabilities, leading to a lack of transparency, skewed data, or influence on the conjunction assessment process.

Industry experts from commercial firms active in both satellite operations and SSA services identified several ways to improve the current paradigm of avoiding collisions. These proposals inform potential incremental steps to advance the status quo in space. Reducing the uncertainty in predictions of satellites' future positions is paramount. Operators identified several ways to achieve this goal. Most policy and technical experts agreed that simply being transparent about the assumptions inherent in calculating spacecrafts' predicted locations would improve end users' abilities to accurately interpret analyses and act on the findings. From a technical perspective, international commercial SSA analysts outlined the benefits of their efforts to expand their proprietary sensor networks. Increases in sensor availability affect global collision avoidance in two ways. First, private sector entities are working to optimize the geographic spread of their proprietary sensor networks to reduce the temporal gaps between observations. Moving toward a full-coverage sensor network reduces uncertainty of future predictions by increasing the amount of time satellites are under observation. Second, some analysts pointed out in their interviews that additional commercial SSA facilities not only improve the global footprint of space observation platforms but also diversify the ownership of data sources. This alleviates some concerns related to states controlling access to SSA data, especially concerns related to state security bureaucracies being involved in decisions about the availability of SSA data.

During interviews, satellite owners and operators recognized the inherent risks of relying on military services for vital operational data. Some voiced clear concerns about the completeness of data provided by military entities. Specifically, some remained skeptical that governments are well-prepared to handle risky encounters between commercial satellites and classified assets belonging to the military or intelligence community. One industry leader remained concerned that instructions from their government about impending conjunctions involving classified satellites would be both urgent and imprecise, inhibiting effective risk mitigation.

Government officials and observers alike reflected on the impact that broad political relationships have on the amount of trust between an SSA service provider and an end user. While data from military and security entities may affect end users' trust in the information, these experts considered the overall relationship between states to be the more impactful driver of mistrust in SSA sharing or exchange, holding technical challenges equal. Experts often defaulted to considering these instances in the U.S.-China context, often lamenting that the United States transmits SSA data to Chinese counterparts but receives neither confirmation that the messages reach the right parties nor invitations to collaboratively address risks. Nevertheless, industry experts supported SSA data exchange even in these low-trust instances.

Other experts from rising space powers had severe concerns about the potential for mistrust among states based on the dual-purpose use of SSA data. Many of these apprehensions were rooted in a concern that data used for conjunction analyses could, and likely would, be repurposed to inform military targeting, planning, and use of anti-satellite systems. Foreign anti-satellite systems could be, in these experts' opinions, tools used to limit their state's ascent. This pervasive belief applies to commercially collected data as well, indicating a concern that commercial SSA providers are in some way connected with state security organizations. Specifically, some observers from major spacefaring powers firmly believed that even if space sensing entities were reasonably separated from military functions, the data itself could be misappropriated and used to inform targeting decisions. On the other end of the spectrum, Western experts rebutted these concerns, suggesting that states capable of harming satellites likely use military sensors that far surpass commercially available systems to produce targeting information.

Second, both operators and SSA analysts indicated a need for satellite owners and operators (O/Os) to participate more meaningfully in the SSA process. Generally, respondents advocated for deeper cooperation with SSA services but offered a variety of opinions about the purpose and objective of cooperation. Some promoted ingesting satellite vector data sourced from O/Os to improve SSA accuracy. Others disagreed, arguing that the lack of quality standards for data collection and calculation could further complicate conjunction avoidance efforts. Some respondents suggested that a comprehensive system would include more detailed information about satellites themselves. These elements included potentially sensitive information such as the status of a satellite's onboard propulsion mechanism.

Other types of cooperation are likely to be more fruitful, or at least less contentious. Nearly all respondents recognized the need for better communication channels to facilitate operations. Current collision avoidance communication practices are unstandardized and rudimentary at best, often involving emails, phone calls, and fax machines with no guarantee that messages reach the right people in time, if they are seen at all. Many business and technical leaders rely on personal networks, often facilitated by industry organizations, to determine the most appropriate point of contact when an SSA service predicts a risky conjunction. Some commercial entities have arranged memoranda of understanding with other satellite operators to reduce the potential for future flash points. However, it is unreasonable to expect that a global network of memoranda could adequately address all potential risks and crises. Practitioners anticipated the negative impacts of this practice to worsen as more entities emerge as satellite operators, expanding the number of potential emergency contacts.

Satellite operators also characterized formal communication between O/Os that are coordinating a conjunction avoidance as an active process. While in theory conjunction avoidance planning could be done passively through indirect communications, experts who were familiar with facilitating the current process suggested that an active system would be far more effective and efficient. Active communication between affected satellite operators would both allow for faster resolution and avoid situations in which operators attempt to mitigate the conjunction but move both satellites into another collision course.

Many experts across all sectors recognized that satellite operators could provide valuable information about planned maneuvers. These notifications of maneuver would not only aid other operators in preparing for unexpected conjunctions but also assist SSA. Announcing planned maneuvers allows satellite operators and SSA analysts, both commercial and governmental, to prepare for and recover from what would otherwise be unanticipated changes in the orbital environment. Analogues for this type of announcement include notices to air missions (NOTAMs), which circulate essential safety information relevant for air traffic. The International Civil Aviation Organization maintains a repository for global notices and initiated a campaign in 2021 to improve efficiency by reducing the volume of spurious notices and streamlining the arcane format. Lessons from this effort could inform changes to how the satellite and SSA communities communicate about hazardous instances like forecasted conjunctions (see box 1).

Box 1. Recommendations for Improving Formal Communication Between O/Os

States should arrange a forum to facilitate the exchange of maneuver notices among operators.

Emergency points of contact should be made official.

- States should require regularly updated emergency points of contact as a part of the satellite licensing process.
- SSA system operators should require regularly updated emergency points of contact as a part of the basic user agreement for participation.
- States should distribute emergency contacts to relevant individuals and facilitate crisis management processes in the event of hazardous conjunction warnings.
- States should initiate a multilateral mechanism at the UN Committee on the Peaceful Uses of Outer Space to consolidate points of contact from both government and industry.

Process, precision, accuracy, and error. Relying on legacy military technologies such as missile defense radars presents both hardware and data issues. These limitations are generally interwoven, but expert observers and operators averred that modernizing sensors and expanding the SSA collection network are necessary but insufficient technical solutions to a multifaceted problem. Most glaring among the myriad technical issues are the lack of standards and limited capacities for interpreting SSA and conjunction data. These challenges limit interoperability between systems and hinder cooperation or collaboration.

Technical limitations of current data collection and analysis networks hamper efficiency and effectiveness of collision avoidance. Two major analytical results inform conjunction avoidance deliberations: probability of conjunction and miss distance. Without a standard approach to incorporating these parameters in decisionmaking, different operators privilege one or the other indicator in considering if and how to avoid predicted conjunctions. This difference compounds the variations that arise from analysts' use of different orbital models and calculations about the location of satellites. In practical terms, one satellite operator may receive information about a very probable conjunction and decide to maneuver to avoid it, while the other satellite's operator may perceive it as less dire based on a predicted wide miss distance and decide not to maneuver. Observers and analysts alike expect that the impact of these differences will continue to grow as more objects are launched into space.

Other issues that stymie effective collision avoidance center on data format and the amount of error in analyses. Specifically, these limitations reduce the actionability of conjunction analyses. The most common data format used to describe satellites' orbital parameters, two-line elements (TLEs), fails to provide necessary context for conjunction analyses and avoidance. TLEs do not provide orbital covariance, essentially the uncertainty about a satellites' orbital states. Failure to accurately represent orbital covariance leads to incorrect assessments of satellites' probabilities of collision, which in turn impedes decisionmaking as it relates to mitigating conjunction risks.

Furthermore, TLEs do not include high-fidelity information, such as the materials, dimensions, or orientation of a satellite. Thus, analysts must make assumptions about the size and shape of satellites of interest. This degrades the precision of conjunction analyses, which in turn limits potential options for collision avoidance.

TLEs are the basis of the public catalogue maintained by the 18 SDS. However, this catalogue generally does not publish the covariance, forcing analysts to either process TLEs to extract meaningful information or use other independent data sources to determine covariance. Compounding this issue, the error present in current conjunction assessments provided by the 18 SDS reduces the utility of the system. The immense volume of warnings for satellite operators is artificially inflated by spurious instances in which the system labels a conjunction as risky but the uncertainty is too large to reasonably spur action. Some entities receive thousands of conjunction data messages (CDMs) annually. Industry experts who have experienced this deluge of information pointed out that not all CDMs contain actionable data. Interviews revealed that relatively few practices related to triaging CDMs are shared among operators. What was clear based on these responses was that the lack of precision in conjunction alerts reduced some commercial operators' trust in the current federally funded U.S. system.

Political Considerations

Consistent with most other challenges related to international cooperation, establishing comprehensive global conjunction avoidance practices can take bottom-up or top-down forms. These efforts need not be mutually exclusive, but certain tools are more effective for creating a fruitful political environment depending on the form factor of interest. Bilateral diplomacy, regional or bloc-based work, and large multilateral organizations all have a role to play in producing a streamlined and effective conjunction avoidance regime. Over the course of interviews conducted for this paper, experts and practitioners from all backgrounds reflected on their engagements at all levels. While the inherently global nature of space lends itself to broad multilateralism, a rigidly top-down approach may not be feasible for various political and functional reasons. Thus, flexible multilateralism or coordinating bottom-up collaboration and fluid interchange among states, regions, and blocs may be the most productive and efficient path forward.

Bilateral engagements. SSA is an inherently global endeavor. The mechanics of satellite orbits prevent any state from having independent sensing systems based entirely on its own territory. Thus, states must either negotiate with each other to lease sites for sensors or share data from national systems to develop a comprehensive understanding of what is happening in Earth's orbits to accurately predict the future. Traditionally, this was accomplished by engaging at the bilateral, or sometimes minilateral, level to negotiate terms for sharing data and SSA services.

Bilateral SSA arrangements have created an interwoven hub-and-spoke network of partners that both produce and receive a mix of data and services, creating opportunities to share expertise. Some experts from academia divided SSA sharing agreements into two categories: partnerships between relatively evenly matched space actors and unequal relationships in which there was a clear technical leader. Cooperation and collaboration between relatively balanced states is chiefly incentivized by the potential to distribute costs among partners, while incentives for imbalanced partnerships varied. Relatively junior states might, for example, gain access to talent exchanges and other capacity development activities in exchange for hosting another state's sensing equipment. Scholars and practitioners underscored opportunities for advanced states to consolidate general soft power by leading SSA data-sharing arrangements.

Technical experts and scholars agreed that SSA data-sharing arrangements institutionalize pathways that support partners in developing a shared understanding of the space domain. At a state level, these networks open communication channels between government experts, which facilitate reciprocal political understanding of space behavior and can contribute to mutually developed interpretations of events in orbit. This type of engagement often deepens trust among partners. This virtuous cycle can result in subsequent arrangements, such as technology co-development, that further reinforce the relationship. However, the practice of engaging in and managing many unique bilateral agreements is onerous. Furthermore, absent a concrete vision for these types of partnerships, states risk muddling their policies and failing to achieve strategic outcomes. A brief case study of U.S. efforts illustrates systemic challenges as well as hurdles erected by attempts to refresh outdated practices.

The United States has a widespread bilateral SSA data-sharing network with both government and nongovernment entities. Historically, U.S. Strategic Command negotiated these agreements, underscoring the primacy of U.S. military control of SSA services. U.S. Space Command assumed responsibility for negotiating these agreements in 2019. Study participants who were familiar with these agreements reflected on the intense military representation at these negotiations, which they perceived to have reinforced concerns outside the United States related to the entanglement of military data with civil or commercial end uses. Some interviewees reflected on instances in which this strong military presence overshadowed the engagement and implied that the data-sharing agreement was a specifically Department of Defense priority instead of a U.S. government initiative to improve space safety. This was especially pertinent in situations where the United States was negotiating an agreement with a significantly less-experienced partner.

U.S. approaches to SSA data sharing are shifting away from this paradigm for several reasons. First, while early SSA data-sharing negotiations were strongly affiliated with national defense, this scope has expanded to include civil, commercial, and academic concerns. Negotiating agreements that address this newly broadened scope is not a core competency of the Department of Defense. Second, there is no clear policy or strategy guiding these engagements, although U.S. officials noted that some proponents of the traditional approach hoped that a critical mass of bilateral agreements could form the basis of a bottom-up process toward a future multilateral agreement. Third, it is difficult to measure if or how these agreements attenuated crises sparked by conjunction warnings. Finally, negotiations at the regional and minilateral levels have become more standard practice. For instance, the marquee U.S. space initiative, the Artemis Accords, encourages states to make a voluntary unilateral declaration of principles instead of committing to a specific bilateral or multilateral agreement.

Other recent U.S. initiatives begin to address some of these issues. The Department of State released the first Strategic Framework for Space Diplomacy in 2023 to clarify the strategic goals of space diplomacy. Relevant for conjunction avoidance, the framework emphasizes how the United States plans to use diplomatic levers to develop and attract participants in a transparent and open SSA system to coordinate space traffic. While the framework indicates incremental progress by codifying and streamlining existing U.S. efforts, there are still outstanding concerns. It remains difficult to isolate and measure the effects of international agreements on augmenting safe space operations. Further, divisions of responsibilities among U.S. government departments are still indistinct. The Department of Defense historically developed, operated, and negotiated with others for access to SSA. These practices are now diffused across the government: the Department of State leads negotiations with other states on space safety issues, the Department of Commerce is developing the civil SSA system, and the National Aeronautics and Space Administration (NASA) is forging ahead on other diplomatic efforts to promote the Artemis Accords. Independent from other government agencies or departments, NASA also engages in memoranda of understanding with private entities that guide their conjunction avoidance practices. It is unclear where the authorities and responsibilities start, stop, and overlap, and how these will cohere into a broader cooperative SSA system.

The complex relationships between relevant U.S. government organizations are not exactly mirrored in other states, but the responsibility for space issues, including SSA and conjunction avoidance, is often complicated. States would benefit from clarifying which organization should focus on ensuring safe space behaviors and which organization(s) should be empowered to lead on engaging with others on conjunction avoidance issues. There is plenty of room for collaboration in the diplomatic process, but effecting this framework and these principles across the spectrum of bilateral, minilateral, and multilateral engagements requires strong internal coordination (see box 2).

Box 2. Recommendation for Resolving Space Challenges in International Engagements

Governments should define organizational responsibilities for conjunction avoidance and refine government roles for bilateral and multilateral engagements.

Minilateral approaches. Beyond the United States, other countries, namely in Europe and Asia, participate in regional SSA networks. These networks tend to crystallize around other geopolitical initiatives. This dynamic is most obvious in Europe, where the EU and European Space Agency offer ready-made policy frameworks to facilitate these arrangements. Other narrowly scoped projects, such as the International Scientific Optical Network (ISON), began with foundational, technical SSA competencies and expanded to support state-to-state partnerships and investments. APSCO illustrates yet another pathway, including SSA as a facet of broader burden-sharing among space-minded regional partners in Asia.

In interviews, government officials from around the world outlined that states have various incentives for creating a leading SSA system. Beyond the operational imperatives discussed earlier, states are incentivized to develop a national SSA system to legitimize domestic space programs and enhance international prestige. If creating a robust national SSA capability is out of reach, participating in an influential, multinational SSA collective is another, less burdensome way to cultivate competence and respect.

Beyond prestige, incentives for establishing multinational cooperative SSA networks differ from organization to organization. For instance, European organizations are broadly motivated by the pursuit of strategic autonomy. This incentive unsurprisingly trickles down into European space endeavors. Experts on the evolution of European space policy, along with European-based practitioners, noted that Europe has aimed to achieve strategic autonomy in space through EU and European Space Agency endeavors. European experts expected this trend to continue in the case of SSA systems as well. Europe seeks to preserve the continent's ability to conduct robust SSA analyses as a hedge in case third-party SSA services and conjunction warnings suddenly become unavailable.

Scholarly work highlights other challenges of disaggregation in regional approaches, leaving some states relatively isolated from others that engage in more robust partnerships. This is seen most prominently within ISON, which is led by Russia. State participants in ISON have relatively limited access to SSA data compared to other states that produce SSA data or participate in multiple partnerships that provide access to diverse data sources. This relative isolation poses distinct problems for states within the network, offering lessons for the future of SSA data-sharing practices.

At a basic level, access to geographically diverse data sources improves SSA products. Without this diversity of sources, states face an artificial ceiling for data quality and precision. States that have developed few relationships with SSA service providers also assume a risk of overreliance. These associated risks are especially acute if a state relies entirely on a single SSA data source or provider. States in these types of relationships may struggle to cultivate an accurate understanding of the space landscape, especially if their SSA provider has a conflict of interest or severs service entirely. In contrast to states' concerns, industry representatives downplayed the risks that satellite operators would lose access to conjunction avoidance services, recognizing that the commercial market for SSA services could rapidly reconstitute what may have been lost.

In interviews, industry experts illuminated the risks of entrenching splintered SSA networks, highlighting states' struggles to improve conjunction avoidance practices by attracting truly global participation in an SSA data-sharing regime. Some experts likened the current state of efforts to build more global SSA connectivity to the historical experience of various states and supranational organizations building indigenous global navigation satellite systems (GNSS). These systems, like the U.S. Global Positioning Service, the EU's Galileo, and China's BeiDou Navigation Satellite System, were all developed to empower the operator and avoid overreliance on another state. This is especially salient in the case of Galileo, which was originally intended to escape civil entanglement with U.S. security systems that may be targeted during conflict. However, unlike SSA services, inconsistent or contradictory outputs from multiple navigation systems rarely expose end users to grave risks.

Nearly universally, experts raised concerns related to international interoperability given the tense relationship between China and the United States. Their concerns were particularly acute regarding the apparent reticence of Chinese operators to interact with U.S. entities on space safety matters. The two countries are responsible for a large portion of the satellites in orbit today, and many practitioners expect China and the United States, along with their constituent commercial industrial bases, to remain the key drivers of satellite population growth. Based on this forecast, some industry executives expect that attempts to ameliorate the status quo without mitigating this contentious relationship will ultimately fail, as they would not address the most important sources of risk (see box 3). Some experts who noted similarities between SSA services and GNSS also pointed out that, despite having disparate systems, China and the United States have cooperated in the past on issues related to compatibility and interoperability between GPS and BeiDou.

Box 3. Recommendations for Establishing Multinational Cooperative Efforts

Industry and academic partners should further study the underlying reasons that competing states have been able to collaborate on multiple GNSS systems.

The United States should collaborate with partners, allies, and like-minded states to set an expectation for information sharing and standards for data collection and analysis.

The United States and like-minded partners should investigate how to attract potentially isolated states in partnerships that support cooperation on conjunction avoidance. Candidate states could include Egypt, Mexico, and Pakistan.

Asia illustrates a different challenge. Several regional organizations address space issues, all taking slightly different approaches in both method and scope. APSCO is the formal result of Beijing's efforts over several decades to support regional development by promoting others' use of Chinese space technologies. APSCO is modeled in part after the European Space Agency in that it is a juridical organization with an emphasis on legal affairs and external relations, with the intent to present a unified regional perspective during international discussions of space governance. Other organizations, notably the Asia-Pacific Regional Space Agency Forum (APRSAF) and, to a more limited extent, the Association of Southeast Asian Nations (ASEAN) provide alternative models and methods for promoting space as part of Asia-Pacific states' development.

APRSAF and ASEAN present an alternative to the Beijing-led APSCO, despite some overlapping functions. APRSAF operates primarily as a convening organization. In the context of satellite conjunctions, relatively new working groups and initiatives host experts and government officials to examine legal structures of participating states and identify gaps. These processes provide a vector for capacity building and support states' legal and political maturity as related to the long-term sustainability of space activities. ASEAN hosts similar efforts through its Subcommittee on Space Technology and Applications, founded in 1999. This forum facilitates regional cooperation, such as technology transfers, to support foundational space activities and contributes to broader efforts toward developing best practices. However, these efforts are only loosely oriented within the organization's broad strategic aims of integrating Southeast Asian states' economic and security interests.

The variety of efforts in Asia illustrates both the value and challenges of regional and minilateral engagement. Some experts from the region noted that several states do not have the institutional frameworks to engage more established space actors, limiting their potential for bilateral ties. Thus, these regional efforts are essential for raising the baseline of space expertise. The current structures and missions of these organizations indicate a range of perspectives on how best to achieve goals related to space safety, with some organizations initiating a rules- or standards-based effort for conjunction avoidance and others gravitating toward a consensus-based norm building process (see box 4).

In their interviews, participants in these efforts recognized that regional venues are especially useful for emerging or aspirational spacefaring states. Experts from emerging spacefaring states championed regional capacity-building processes as a successful avenue for growth. Specifically, diplomats from emerging spacefaring nations viewed regional pathways as a primary way to facilitate a sense of ownership on space safety issues and develop their diplomatic capacity. Regional associations reportedly helped states develop and refine perspectives on common issues, which then informed other space-related engagements. Experts who facilitated side sessions at these regional gatherings noted that this growth improved the inclusivity of outcomes.

Box 4. Recommendations for Shaping Content of Multilateral Forums

Multinational and regional organizations should facilitate technical-policy interfaces to enable states to align both technical competencies and legal or political frameworks for SSA data collection, data sharing, analyses, and conjunction avoidance coordination.

Regional organizations should begin to expand their scope and focus on galvanizing political support for preferred guardrails or other governance mechanisms for conjunction avoidance.

Regional organizations and formal blocs should work to identify acceptable principles of responsible and safe uses of space and promote these perspectives at debates on future governance tools or normative expectations related to conjunction avoidance.

Multilateral processes. The very framing of conjunction avoidance is politically charged at the international level. Discussions of how to best ensure the safety of existing space objects are generally led by advanced spacefaring states that have the most objects in orbit and thus face more material risk. On the other end of the spectrum, aspiring spacefaring states instead face competing priorities and have limited resources and expertise to apply toward space security issues. Furthermore, aspiring and emerging spacefaring states are not always strongly incentivized to negotiate on issues like conjunction avoidance, as these topics are significantly downstream from their interests. These states are more often incentivized to focus on space issues that have longer time horizons, such as preserving access to space for future missions. Many policy experts noted that these views can coexist in a diplomatic resolution: tackling acute issues is not mutually exclusive with taking actions to preserve space sustainability over longer time frames.

Expert observers also noted that variance in interstate cooperation is tied to the specific international forum in which discussions occur, and certain topics face stronger political headwinds in some forums compared to others. For instance, issues related to the creation of and collisions with debris are increasingly politicized within United Nations (UN) bodies broadly, but technical conversations occurring within the UN Office of Outer Space Affairs' Committee on the Peaceful Uses of Outer Space tend to be less affected relative to other UN organs. These challenges can be relatively attenuated by initiating discussions in less politically charged forums, although doing so may lower the likelihood of politically or legally binding outcomes.

Multilateral discussions outside the UN have allowed states to advance safety-promoting agendas that include conjunction avoidance, while avoiding highly politicized or noninclusive forums such as the Conference on Disarmament. Bodies such as the International Organization for Standardization provide room for technical engagement. However, many technical organizations still privilege states as the primary actors and some exclude industrial actors, who are unable to share their perspectives unless their concerns are carried by government officials participating in the discussion. States also bring politically charged views to technical organizations, embedding political challenges in the foundation of debate.

Political hurdles extend beyond arranging agenda items at appropriate forums. The division between advanced and emerging spacefaring states also impacts debates on how to address conjunction avoidance rules. States with advanced capabilities sometimes offer to provide SSA products, but project participants with experience in facilitating international dialogues pointed out that would-be-recipient states are often wary of implied quid pro quo arrangements or other expectations. These would-be recipients generally reject proposals that would see advanced states deliver analyses conducted in black boxes but restrict holistic capacity building or technical exchanges on topics like SSA modeling capabilities. This is in part due to the perception among emerging space powers that export controls are intended to entrench national advantages of technology holders instead of addressing legitimate security concerns.

Experts who facilitate international dialogue found that emerging space powers' reticence to accept limitations on technical exchange and capacity building is born out of past experiences in which networked export controls created barriers to growth. These experts agreed that, in the case of SSA data collection and analysis techniques, technology transfer restrictions do impede the viability of a future global cooperative SSA system. Few states have the hardware, software, or expert personnel to meaningfully contribute to an SSA and conjunction avoidance network, yet these tools, techniques, and procedures are invaluable for aspiring space states because they enable the types of safe operations expected of responsible space actors. Without the requisite workforce to perform comprehensive SSA and conjunction avoidance, emerging spacefaring states are hamstrung from the beginning of their space activities. This is especially pertinent to the current situation due to the large number of states that would not be able to meaningfully participate in a space data-sharing arrangement. The time-intensive processes associated with indigenous technology development, coupled with the lack of concrete incentives, indicate that this condition is unlikely to improve over the next decade.

Not all states can fully and adequately participate in international data-sharing agreements. Some states are unable to provide precise data, while others do not have the competencies to process raw data they may receive. Many states can accomplish neither task. This creates imbalances in which the value of data varies widely among states that might negotiate an agreement, erecting political and functional barriers to effective communication about conjunction risks. These barriers in turn limit the possibility of mitigating dangerous occurrences. Some states have used bilateral and regional arrangements to manufacture pathways to overcome these technical limitations, but the global baseline for SSA competencies remains severely lacking (see box 5).

Box 5. Recommendation for Overcoming Technical Limitations

States should implement capacity-building efforts to raise the global baseline for SSA analyses and conjunction avoidance.

Experts with deep experience in international organizations recognized that the political climate is unlikely to facilitate improvements to current data-sharing processes, especially at the international level. The UN Register of Objects Launched into Outer Space, established in its current form in 1976, currently serves as a global clearinghouse for certain space data elements, but the requirements are too generic to serve modern needs. Satellite operators and commercial SSA analysts voiced concerns about the quality of the data collected by the UN. The 1974 Convention on Registration of Objects Launched into Outer Space charges launching states to provide basic information about a satellite's orbit "as soon as practicable," with no clear deadlines or consequences. Furthermore, the convention does not require states to update information about satellites if an object maneuvers into a different orbit.

Even though state-provided data is not always timely and precise, personnel from international organizations underscored the UN's proven ability to serve as a central node in a data-sharing network. In these experts' estimation, member states were responsible for improving their submissions' data quality and could expand reporting practices without stumbling on political pitfalls. These improvements, such as including more precise data, would potentially increase trust among states and spur future improvements (see box 6).

Box 6. Recommendation for Refining Data Quality

States should cooperatively expand the existing data collection system to allow for voluntary inclusion of data, such as emergency points of contact.

However, continuing to solely rely on the UN as a central data-sharing facilitator or expanding the process would likely exclude the private sector from direct participation, due to legal and practical challenges to private sector involvement. Experts from international organizations and industrial leaders alike recognized the need to incorporate the commercial space sector in discussions of future cooperative initiatives to improve space safety, since industry will continue to play a large role in providing conjunction analyses and warnings. The organizational structure and state-centric purpose of the UN remain the most significant barriers to incorporating commercial perspectives in a top-down approach.

Some states reject including private entities in multilateral discussions on the principle that only states can engage in multilateral decision making. Others recognize that expanding participation to include individual companies or other nonstate entities could overtax an already heavily burdened bureaucracy. Experts across sectors were also skeptical that a UN committee or other similar organizations could take on the bureaucratic aspects of delivering acute conjunction warnings to affected parties at requisite speeds (see box 7). Executing SSA analyses and informing participants of predicted conjunctions places a strong premium on promptness, and large multilateral organizations are not generally known for rapid operational pace.

Box 7. Recommendation for Strengthening Diplomatic Processes

States should initiate a separate diplomatic pathway in the shape of, for instance, a recurring summit to include both states and private entities in conversations about cooperative practices on pressing SSA sharing and conjunction analysis issues.

Recommendations

Considering the technical and political hurdles surveyed above, effective collision avoidance practices and governance frameworks could take several forms, with each prospective option uniquely balancing efficacy, efficiency, and feasibility. While each type of space-relevant actor has independent motivations for addressing these issues, it is abundantly clear that the drivers of change are here to stay and are likely to intensify over the near term unless promptly addressed. Private and governmental satellite operators are incentivized to protect their investments. Established spacefaring states are further driven to shape the prevailing rules, norms, and behavioral expectations in support of their national interests. Other states that do not operate satellites but still benefit from space systems are motivated to preserve the provision of space-enabled services and forestall monopolistic trends from emerging in the SSA market.

With these stimuli in mind, states, operators, and industry actors can address several areas of concern to improve the status quo over the short, medium, and long terms. Some of these steps are incremental, while others require novel strategic decisions. These recommended state behaviors assume that the space industry (both satellite O/Os and SSA service providers) will continue to advance at the current rate and bring innovative products to market.

The most near-term political steps toward improving space safety and providing actionable conjunction analyses start at the state level, rather than at multinational debates. First and foremost, states should define their foundational perspectives and considerations of the nature of the products and services that are the foundation of an effective collision avoidance system. Such a process should include determining whether space safety data and services such as conjunction warnings are public goods. States that are prone to partisan shifts must be conscious of the potential political fragility of these findings and should take extra care to ensure the durability of the perspectives.

It is thus far unclear whether any state has completed or even initiated deliberations on these matters. As a result, the gap between governance structures, capacities, and requirements continues to grow. Promptly reviewing the government's role in facilitating conjunction avoidance maneuvering would help the state address gaps and build the necessary competencies for the future. After a thorough government-wide understanding of how to regulate SSA data services and satellite conjunction issues, the state should review the organization of governmental competencies that relate to conjunction avoidance. Some states spread this responsibility across several policy and regulatory bodies, but progress often stagnates without a clear focal point.

Because individual states will come to different conclusions about the inherent values, principles, interests, and responsibilities of government, industry, and satellite owners, there will likely be nuanced and different organizational practices around the world. Nevertheless, some organizational principles may serve as best practices. Governments should streamline conjunction avoidance processes by reallocating or consolidating authorities to enable faster crisis responses. A further step would be to associate the government organization responsible for administering the national conjunction warning system with the state's satellite licensing authority. This association would both facilitate SSA data collection and enable states to address noncompliance.

In such a paradigm, future licenses for satellite operations could be made contingent on providing detailed SSA data to the licensing authority and continued good standing in updating critical information, such as points of contact. Instead of major reorganization, states may instead prefer to implement a simple pipeline between the licensing agency and the governmental SSA provider to ensure O/O-provided information remains current, while still subjecting satellite operators to the risk of losing licenses if they are found to be out of compliance.

Over the medium term, states should use regional forums that are less hampered by major powers' political roadblocks to pursue meaningful cooperation. These regional organizations can also help states organize multicountry initiatives and public-private partnerships that facilitate technical and policy exchanges. States should avail themselves of cross-functional engagements to build trust among technical and political communities as well as to grow SSA capacities.

Regional organizations such as APRSAF, ASEAN, the EU, and others with the agency to sponsor discussions should prioritize collaboration on SSA collection and analysis, with the intent to improve conjunction analyses. Currently, only a few regional organizations have formalized discussions on preferred guardrails or other governance mechanisms to revise the conjunction warning process. The secretariates and other organizers should work to close this agenda gap. The confluence of political and technical competencies in regional organizations can help states arrive at a united perspective on core issues, which can then be presented at large multilateral organizations such as the UN Committee on the Peaceful Uses of Outer Space and the UN General Assembly's First and Fourth Committees. This is an especially important tactic for aspiring space actors, to ensure inclusion in the debates that are otherwise broadly dominated by the interests and motivations of advanced spacefaring states. This dynamic, in which more advanced states dwarf the interests of emerging and aspiring states, is apparent in most multilateral space-related forums. This compounds other challenges of multilateralism in SSA and conjunction warnings.

Other methods of diplomacy can help states bypass these challenges. For instance, states should consider sponsoring summits or other broadly attended forums on SSA and collision avoidance. These engagements would complement ongoing work at multilateral institutions by more adequately involving the commercial sector and industrial actors, who are vital partners in any viable conjunction avoidance system. Such a series of forums, conferences, or state-sponsored summits could be hosted in emerging spacefaring nations to further reinforce the necessity of global SSA cooperation.

Taking a long-term view, it is important to engage emerging and aspiring spacefaring states on issues of space safety at the genesis of their space activities so that novice space actors can operate safely and practice sustainable behaviors. Ensuring aspiring spacefaring states' perspectives are included in negotiations is not only valuable to those states but also can aid the current cadre of advanced spacefaring states by facilitating buy-in for a complex norm-setting process. Leading states can reach out to relatively isolated states to support basic practices through partnerships that promote SSA principles and develop conjunction assessment competencies within government and civil society. Because broad participation is a key element of space safety agreements, the nonparticipation of a competent spacefaring actor may jeopardize an entire conjunction avoidance regime. Other long-term recommendations include raising the technical baseline for SSA and conjunction analyses.

At a high level, the prevailing perspectives of policymakers from a range of states, industry representatives, and space experts interviewed for this project considered that the efficacy of any future conjunction avoidance system is predicated on a high baseline level of technical inputs sourced from a diverse network of participants and observation systems. Experts strongly indicated the importance of transparency and broad membership, but there were several different recommendations on how to best facilitate participation. For instance, respondents noted that exquisite observation platforms and subsequent analyses can identify close conjunctions, but these analyses are useless if the information cannot be effectively communicated to affected parties in time for them to act. Effective communication, in this case, is a product of both the utility of the information itself and the process of delivering information to an end user. Thus, it is necessary that end users maintain a high baseline of analytical competencies and provide up-to-date emergency contact information.

Meaningful participation in a conjunction avoidance network additionally includes preemptive communication about satellites themselves, not just about imminent hazardous interactions between satellites. Valuable information includes dimensions and onboard propulsion capabilities, inter alia. This suite of data is generally sensitive, and leaders in the commercial sector believe that sharing it publicly would degrade their competitive advantages or generate security issues. Thus, nearly all interviewees supported building a system that could serve as a trusted broker of information and enable O/Os to voluntarily submit this type of information and flag instances in which information is unknown or missing. While private companies and industrial partners are well-positioned to collect and use this type of information in advanced analyses, many practitioners and government representatives noted that states are inherently well suited to disseminate conjunction warnings and serve as a coordination clearinghouse. The role of government in facilitating conjunction avoidance was especially salient in cases that might incorporate sensitive information. A government-led system would also be able to consolidate and broker information related to operational information like planned maneuvers or changes to satellites brought about by in-space servicing or manufacturing.

All these potential activities interact and can make a more lasting impact on space safety and security when taken in concert. The challenge is to promptly effect these changes. Some of the necessary activities will, in any reasonable estimation, take time. Learning to conduct complex SSA analyses, for instance, is not a rapid process. Constructing new sensors around the world is another lengthy process. Nevertheless, the pace of change must accelerate to address the extant and emerging threats to satellites, not least of which is collisions with each other. Without guardrails, guidelines, or normative expectations for safe and responsible behaviors, the impending boom in satellites orbiting Earth could easily tip the scales toward a chaotic and unsustainable future.

About the Author

Benjamin Silverstein was a research analyst for the Space Project at the Carnegie Endowment for International Peace. His research investigates prospects for multilateral cooperation on issues like space situational awareness and orbital debris remediation. His other interests include arms racing dynamics, space capability management in alliances, and the evolution of national space policies. Before joining Carnegie, Silverstein worked on space policy issues at Lawrence Livermore National Laboratory and at the United Nations Institute for Disarmament Research.

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Satellites in Earth orbits—such as remote sensing capabilities that support environmental monitoring or position, navigation, and timing networks that map our daily commutes—constitute critical civil and military infrastructure. Yet despite the inextricable importance of space-based services to everyday life, pervasive debris and disagreement about acceptable behaviors in space threaten the long-term security and sustainability of human activities in Earth orbits.

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