SPACE TRAFFIC MANAGEMENT: THE CHALLENGE OF LARGE CONSTELLATIONS, ORBITAL DEBRIS, AND THE RAPID CHANGES IN SPACE OPERATIONS

Marlon E. Sorge, William H. Ailor, and Ted J. Muelhaupt

Big increases in space activity and new approaches to space operations necessitate organizational and technical changes to the way the United States and the world manage space traffic. Several key actions need to be taken to position the United States to lead these changes, ensuring a safe operating environment in space and enabling future growth.

Introduction

Activities in space are rapidly changing. Order-of-magnitude or more increases in satellites, numerous new players from satellite operators to tracking data providers, and entirely new missions like satellite servicing are seriously stretching conventional approaches to safe space operations. The United States needs to lead in the development and implementation of good space traffic management to ensure that safe space operations practices are followed by all operators in a domain that is intrinsically international. To do this, the United States must:

- Clearly establish organizational authorities and required resources for a national approach to space safety, addressing the technical and organizational challenges this requires.
- Establish mechanisms for international coordination and cooperation with government and commercial entities.
- Develop clear definitions of nationally "acceptable" levels of safety and risk to enable development of thorough and justifiable norms of behavior and performance-based rules to encourage innovation while ensuring safe space operations.

The rapid advances in space operations offer many new opportunities and a number of challenges. The United States needs to be a leader in meeting these challenges to maximize the opportunities.

This paper highlights key actions wfor implementing effective space traffic management and safe space operations. These actions will assist the space community in establishing the organizational and technical capabilities needed to develop safe space practices.

Space Traffic Management. The term *space traffic management* (STM) has a range of definitions. Space Policy Directive-3, National Space Traffic Management Policy (SPD-3) signed by the President on June 28, 2018,[1] focused on laying out U.S. policy directions and defined STM as "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment." STM focuses on activities that facilitate safe operations in space both now and in the future. Considerations of safe space operations are growing in importance as the level of space activity increases and as new actors arrive in an increasingly democratized Earth orbit.

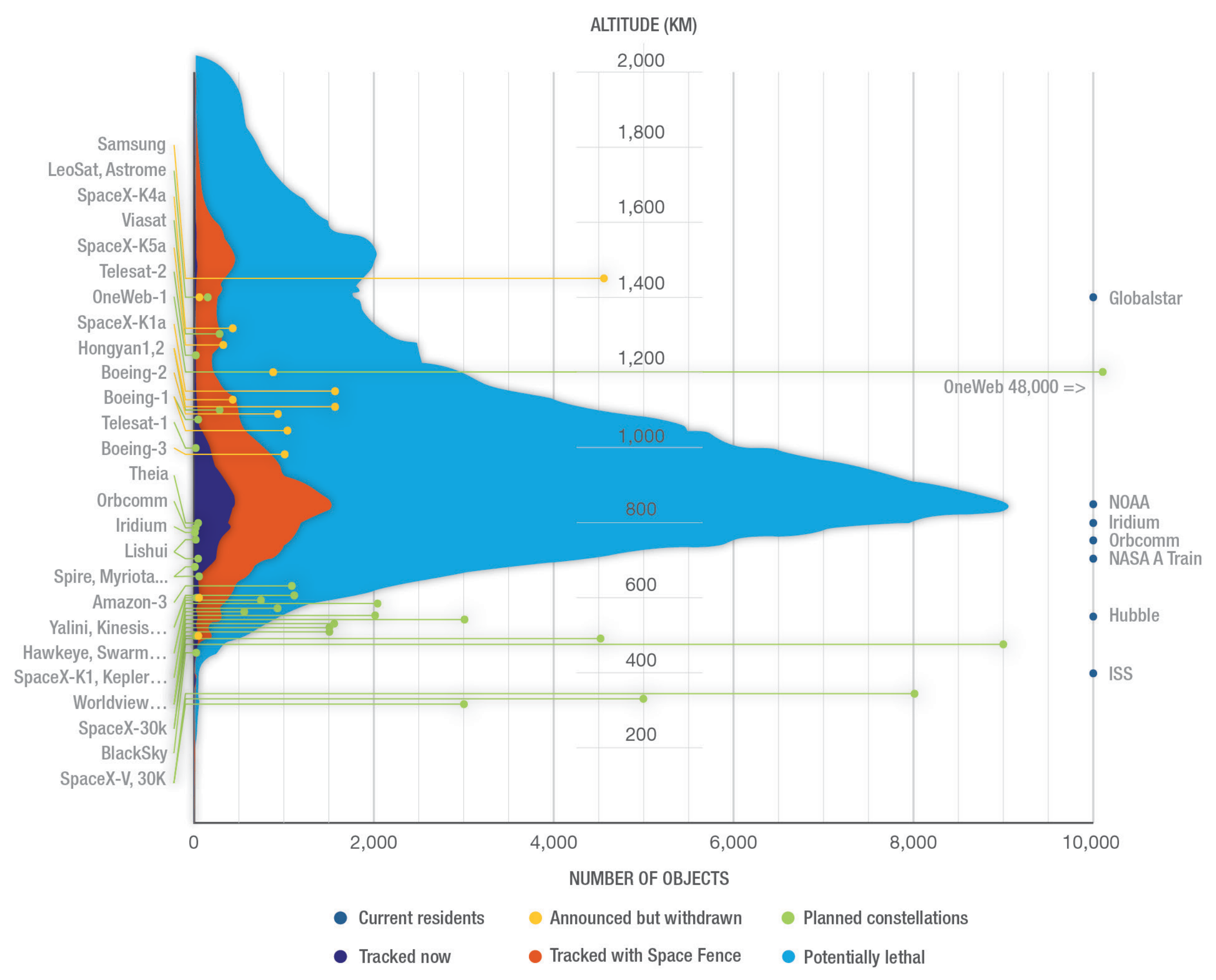
Space was originally thought of as a "big sky" where interactions between satellites were very unlikely. There were only a few satellite operators, and they could operate "Wild West" style with few rules and fewer consequences. The challenge now is that space is becoming more crowded with order-of-magnitude increases in commercial activity, greatly expanded numbers of satellite operators, both organizationally and internationally, and numerous organizations having launching capabilities. With that increased and diversified activity, having structure and norms of behavior for operating in space becomes critical to ensure safe operations for everyone.

In the United States and internationally, safe operations in space are governed by few regulations. The Outer Space Treaty of 1967 and associated treaties provide some basic international structure for operating in space, including definitions of ownership and responsibility but little in the way of practical operations structure. On June 21, 2019 United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) adopted a preamble and 21 guidelines for the long-term sustainability of space.[2] These voluntary guidelines represent practices that would improve the safety of space operations. The guidelines cover a wide range of topics, including the importance of national regulations and what to include in those regulations, the promotion of information sharing, encouragement of operations safety practices like collision avoidance, and promotion of safety-related research.

Orbital debris mitigation is one of the subsets of STM where there has been more success at generating guidelines, best practices, and standards both within the U.S. and in the international community. Within the United States, the Orbital Debris Mitigation Standard Practices (ODMSP) were recently updated[3] and contain rules followed by U.S. government organizations. Organizational standards such as NASA's Standard 8719.14[4] and Air Force Instruction 91-202[5] describe debris mitigation requirements in more detail. For U.S. commercial space systems, the Federal Communications Commission (FCC), Federal Aviation Administration (FAA), and National Oceanic and Atmospheric Agency (NOAA) all include debris mitigation requirements as part of their licensing processes. Internationally, the Inter-Agency Space Debris Coordination Committee (IADC) has developed and revised consensus guidelines.[6] The International Organization for Standardization (ISO) includes international standards for debris mitigation.[7] Other nations have their own debris mitigation rules or, as in France, legal requirements for debris mitigation.

Currently, the Combined Space Operations Center (CSpOC) under the U.S. Space Force's Space Operations Command (formerly the 14th Air Force) has the responsibility to track objects on orbit for the nation. Because of its capabilities in this role, as well as the risk of collision as highlighted by the debris-generating 2009 collision between the active Iridium 33 and inactive Cosmos 2251 satellites, CSpOC also has taken on the task of providing conjunction warnings for operational satellites from around the world. Other organizations also contribute to space safety: e.g., the NASA Goddard Spaceflight Center Conjunction Assessment Risk Analysis (CARA) team provides collision warnings predominantly to NASA satellites using data provided by the CSpOC, and space agencies in other countries actively follow risks to their own satellites.

Space activity and space operations are undergoing one of the largest changes since the beginning of the space age.[8,9,10] The substantial increase in commercial space activity, including participation from around the world, is both crowding and democratizing space—pushing the quantity and nature of space operations well beyond the traditionally government-dominated activity of the past, and challenging existing processes. With the advent of large constellations of hundreds or thousands of satellites, the number of operational satellites may increase by an order of magnitude or more over the next decade. The development of small satellites, including CubeSats, has opened up space to a whole range of organizations that previously would have been unable to afford satellites. These include universities and even high schools. The democratization of space means that there will be significantly more operators than in the past and many will have relatively little experience in space. This diversity of space operators also includes an expansion of international operators outside of the traditional spacefaring counties adding to the complexity of coordinating space activities, requiring a broader-than-traditional U.S.-centered approach to ensure safe space operations practices are followed.



Significantly increased launch traffic and expanded space tracking capabilities will increase both the number of objects in space and the number of objects that can be tracked and need to be avoided. The plot above illustrates both changes.

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 System. This includes both active satellites and debris. The orange region shows the distribution of objects with the improved tracking capabilities of the Air Force Space Fence. The blue region shows the distribution of potentially mission-ending objects down to 1 cm in size. Improved tracking capabilities beyond Space Fence will reveal more of this currently untracked region.

The dark blue dots on the right illustrate the altitude locations of some existing systems. The green and yellow dots show proposed commercial constellations and their possible operational sizes. Although not all of these proposed systems will be launched the scale of the increase in the number of active satellites these systems represent can be seen.

The large increases in the numbers of operational satellites and the number of tracked objects provide challenges for implementing an efficient system for safe space operations and space traffic management.

New classes of missions are being developed, including on-orbit servicing, mission life extension, and active disposal at end of life, which involve a servicing spacecraft rendezvousing with a customer satellite to provide the requested service. The range of orbits for operational use is also expanding to include elliptical and inclined geostationary orbits, medium Earth orbits, and cislunar space, which have seen only modest use in the past. New modes of operation are also being developed. Along with rendezvousing with other satellites, operators are employing extensive use of low-thrust propulsion and non-propulsive maneuvering techniques like changing satellite orientation to change the effects of atmospheric drag. These new capabilities allow frequent and autonomous station keeping and collision avoidance, but also complicate satellite tracking and maneuver coordination. All of these changes make tracking and maintaining awareness of the space environment more difficult and add to the challenges of safe space operations at a time when the United States' approach to STM is changing.

Space Surveillance in the Context of STM. The U.S. STM organizational structure is in transition. In 2018, SPD-3 stated that the U.S. Department of Commerce (DOC) would take over the public STM role from the Air Force to allow the Air Force to focus on its primary mission—and having a civil agency lead the nation's STM efforts might also facilitate international and commercial cooperation. This transition required action from Congress to define and allocate the responsibilities between organizations and provide the associated funding to the DOC.

Although two or more bills have been introduced in Congress to transition STM responsibilities to a civil agency, to date none has been enacted into law. There is still discussion at the congressional level about whether the DOC or another civil agency should take on the U.S. STM responsibilities (in late August, a congressionally mandated independent report from the National Academy of Public Administration endorsed the DOC taking on the STM role).[11] The DOC has assigned this role to its Office of Space Commerce but cannot fully execute the needed programs to complete the civil transition until Congress acts. The agency will need to create the required organizational and technical structure to take on the role. This leaves the United States in an extended transitional period which is occurring while space activities are rapidly changing. If the space operations changes occur before the nation has clear organizational, technical, and regulatory structures in place, implementing an effective STM strategy will be significantly more complex.

While there is a growing consensus on the need to transition STM to a civilian agency,[12] an inability to legislate the decision on which agency or to resource that agency to execute the mission keeps the mission in the Department of Defense. Moving forward on the assignment of responsibility of and funding for STM is recognized by many space operators as critical to enable the United States to progress in advancing STM capabilities and safe space operations, both within the nation and in coordination with international entities.

Key Action 1. **Establish the identity of the entity that will provide basic space situational awareness and STM services to all satellite operators and provide the resources and authorities to do so.** Critical changes in space operations are underway. The government needs to be in a good position to maintain safe space operations through the changes. There are differences between the various candidate organizations that are significant, but the pace of change in space operations means that the decision is needed soon. Much technical work is needed to establish a civil space traffic management capability. Operating in space is an intrinsically global endeavor as the location and operation of satellites literally spans the globe. As such, one of the primary needs of a U.S. STM agency is to facilitate information gathering and sharing. It must also facilitate the associated coordination of activities, such as collision avoidance, that the collected data enables and are required for effective STM. Once a civil agency is chosen, one of its major tasks will be determining how to orchestrate the required data flow and coordination activities.

Key Action 2. **U.S. leaders should work with international counterparts to harmonize global STM practices and regulations.** Space is an intrinsically global environment, so bad actors affect all users of space.

The area of space surveillance, or keeping track of where things are and where they are going in space, is rapidly changing. Historically only a few government agencies around the world were capable of systematically tracking objects in orbit. For the United States, this was the Air Force. Recently the number of countries tracking space objects has been expanding. In addition, a number of countries have been increasing their capabilities either individually, such as Australia and Japan, or in cooperation as seen with the European Union Space Surveillance and Tracking (EUSST) consortium, which as of 2020 consists of eight member states.[13]

In parallel with government expansion of tracking capabilities, several commercial companies including LeoLabs, Numerica Corporation, and ExoAnalytics have developed their own space object tracking capabilities. These systems, both radar and optical, can collectively observe low and high-altitude orbits and represent an entirely new set of non-government players in space surveillance.

One of the big changes in space operations is the dramatic increase in the number of commercial satellites, surpassing those of government entities. Very often, satellite operators will have detailed knowledge of their satellites' orbits as well as foreknowledge of orbit maintenance and repositioning maneuvers. If shared, this information can add a whole new level of accuracy to the orbit knowledge for these satellites. The Space Data Association currently uses orbit data provided by its satellite operator members to perform collision avoidance assessments for its members' satellites.

It should be noted that more data is not necessarily better data. A civil agency responsible for STM will need to develop techniques to validate, calibrate and incorporate all of these data sources, and to integrate them with traditional U.S. Space Force-generated data. The integration of beneficial data sources is needed in order to have a full and accurate picture of what is going on in space; this is the first critical step to effective STM.

There are numerous challenges associated with effective data integration, the first being organizational. Even using data from within the U.S. government will present difficulties, especially when considering the differences between data management in a military vs. a civil organization as well as "ownership" issues. The civil agency will also need to develop data sharing relationships with allied space surveillance systems and work out the data sharing protocols that will be needed for routine exchange of information within constraints of operating internationally.

Commercial tracking data providers present a different set of challenges: they generate tracking information for profit, so a mechanism is needed to enable the civil agency to use the data for its purposes while still allowing the commercial companies to sell to other users. New mechanisms will also need to be developed to incorporate commercial satellite operator data into the civil agency's STM system. This is particularly important as commercial operators launch systems with large numbers of satellites and for those who are planning frequent orbit adjusts or station-keeping maneuvers. Without a process for rapidly incorporating and disseminating STM service data, it will not be possible to maintain safe space operations in the dynamic environment of the near future.

One of the primary STM-related tasks for which tracking information is used is to provide conjunction warnings. The paths of satellites are projected into the future, typically a few days to a week. Times are identified where there are particularly close approaches which might result in collisions. Future collisions cannot be absolutely determined because there are uncertainties in predicting where objects on orbit will be. Reducing these uncertainties limits the false alarm rate for potential collisions and makes for a more effective collision avoidance system.[14]

Although more tracking information can reduce the uncertainties, the utility of the tracking data and how much it adds to the overall knowledge of a satellite's orbit, is dependent on several factors beyond accuracy. The approaches for combining ground-based sensor data, space-based data, and data from satellite operators are different as are the combination of different sensor types like radar and telescope information. All of this adds to the difficulties that must be overcome by a civil STM agency to develop an efficient collision avoidance system.

Key Action 3. **Once authorized and funded, the STM organization's leadership should partner with commercial data and service providers, satellite operators, and international organizations to combine data and develop a set of services that meet the basic needs of space operators.** Many new data sources are being developed with the potential to greatly increase space safety. Data needs for safer space operations include:

- **Very accurate and timely data on all objects of sufficient size to seriously damage or destroy a satellite or damage a launching vehicle.** More complete data is required to provide basic space safety services in an increasingly crowded and dynamic space environment.

- **Warning messages to operators must be clear, consistent, and accurate.** Improved data quality would decrease false alarms and increase safety of flight.

Orbital Debris Mitigation and Management

One of the areas within the scope of STM that has received the most attention both nationally and internationally is orbital debris mitigation. The United States developed its Orbital Debris Mitigation Standard Practices (ODMSP) in 2001. The 2010 National Space Policy and subsequent directives[15] require U.S. government organizations to comply with the ODMSP. Exceptions to meeting the best practices require approval at the department or agency level, giving debris mitigation compliance high visibility. In November 2019, ODMSP was updated per guidance in SPD-3 and included many more quantitative requirements that had previously been included in the NASA Standard and Air Force Instructions.

Internationally, the Inter-Agency Space Debris Coordination Committee (IADC), a group of the 13 primary national and international space agencies, provides technical insight into the debris problem. The IADC developed a set of mutually agreed-upon debris mitigation guidelines in 2002, updated in 2007 and again in 2020. In 2010 the International Standards Organization (ISO), which includes both government and commercial participation, developed a debris mitigation standard (ISO 24113), which was updated in 2019. In the summer of 2019, the United Nations Committee on the Peaceful Uses of Outer Space agreed to 21 guidelines for improving safe space operations. Each of these organizations includes a different subset of the space operations community. In all of these cases the guidelines or rules are non-binding. Individual countries have decided to adopt aspects of IADC guidelines into their own national-level rules or laws or have required the application of ISO standards to contracts.

One of the major challenges with space is that poor debris mitigation practices can quickly affect all space operators. The Chinese anti-satellite test in 2007 generated more than 3,000 trackable objects and hundreds of thousands of untrackable but hazardous debris. That debris has resulted in numerous conjunctions and some collision avoidance maneuvers for other operators and may also be the source of some small debris that has impacted active satellites. It is in the best interest of the United States to disseminate its guidelines and best practices for debris mitigation to the other spacefaring nations if for no other reason than to protect U.S. assets.

There is no one international organization or document that controls the behavior of all nations with respect to debris mitigation, making distribution of norms a challenge. Effectively dissemination of debris mitigation best practices will require the United States to engage with international partner organizations to broadly influence thinking on debris mitigation issues. A similar situation exists for STM as more best practices are developed. Without a single international organization with broad responsibilities, a distributed approach will be required. Currently, U.S. influence is exerted through active participation in IADC working groups, via the Department of State at the United Nations and other organizations, and via interactions at international conferences and forums such as ISO.

Techniques have been developed to better understand the effects of space activities on the orbital debris environment and therefore on future space activities. These capabilities exist both in the United States and in other nations and make it possible to generally understand what types of actions need to be taken to move the evolution of the debris environment in a particular direction. The major component that is missing is *how much* of each of these actions needs to be taken.

There are currently no clear limits defining what is and is not acceptable with respect to the effects of the orbital debris environment on space operations. Current rules are typically based on individual organizational decisions rather than broader purposeful choices as to what is an acceptable consequence or risk. Without this specificity, it is possible to point in a preferred direction (e.g., limit the growth of debris) but not provide more specific instructions on what needs to be done to direct actions toward the specific goals and effectively balance cost and benefit. Without a more definite decision on what is "acceptable" it would be easy to either do too much, which will create excess costs now, or too little and create significant costs in the future when space systems are forced to operate in an unacceptable debris environment. This issue will become a problem in other STM-related areas as development of best practices advances. Purposefully choosing what is "acceptable" will enable the United States to clearly define the required levels of and types of activities needed to keep the debris environment within "acceptable" limits. It will also provide concrete and justifiable targets for which the nation can advocate with the rest of the spacefaring nations.

Key Action 4. **Establish definitions of nationally "acceptable" thresholds for orbital debris and space safety consequences.** A clear understanding of where the lines need to be drawn for effects on operations, such as conjunction frequency, will enable consistent regulations.

Once the "acceptable" limits are defined, mechanisms need to be developed for monitoring, increasing, and perhaps eventually enforcing compliance. Producing new treaties with direct requirements for adherence will be very difficult, as illustrated by the long development time and incomplete success of the non-binding UN COPUOS Guidelines for the Long-Term Sustainability of Outer Space Activities. Other mechanisms exist including IADC, leading by example, use of international standards like ISO, encouraging voluntary rule adoption like the Space Safety Coalition (SSC), and encouragement techniques like the World Economic Forum Space Sustainability Rating.[16]

Within the United States, the commercial regulatory structure for debris mitigation, which is more developed than other facets of STM, is distributed among a number of organizations including the FCC, FAA, and the DOC. As the level of commercial activity increases, it will be important to streamline the U.S. debris mitigation regulatory processes.[17] As the U.S. civil STM capabilities develop, coordinating the debris mitigation regulatory structure with the STM organization will also be necessary, since there is significant overlap between debris mitigation and safe space operations. An inefficient system will hamper U.S. companies when competing with the rest of the world.

Key Action 5. **Organize and streamline the U.S. regulatory structure for debris mitigation.** A more efficient regulatory system coordinated with other STM-related efforts will ensure the United States remains a location of choice for commercial space operators.

Space Safety Regulations for Future Space Operations

The rapid pace of change in the space industry necessitates both the rethinking of organizational and regulatory approaches to space operations. Focusing on what needs to be done for safe space operations—performance, rather than specifically on *how* to do it—will provide greater flexibility and encourage new approaches to operating safely. The use of performance-based regulations versus prescriptive rules will enable innovation especially from commercial endeavors. It will also place emphasis on the need for sound technical justification for rules and more technically complex capabilities to assess compliance. In order to support effective performance-based regulations, supporting technical justification and substantiating data are critical. Essentially, the justification explains why specific performance goals are set and what they accomplish. More sophisticated assessment capabilities are also needed to evaluate new approaches and determine if a proposed solution meets requirements.

The regulations will need to be applicable both to individual satellites as has been done historically, and to large constellations of satellites. Aggregated risks from individual constellations can far exceed individual satellite requirements.[18] An illustration of this approach is in the 2019 ODMSP with reference to limiting reentry risk from a whole constellation. Flexible, well-substantiated debris mitigation practices will be far easier to propagate into the international community, which is essential for any successful efforts to mitigate the risk from the orbital debris environment.

Key Action 6. **Establish performance-based, technically justifiable rules based on the "acceptable" consequences and then disseminate globally**. It is essential that best practices be followed by all space operators, and rules need to be flexible enough to accommodate the rapid pace of technology change while still resulting in the desired outcomes.

Key Action 7. **Establish technical expertise to provide the knowledge to develop effective rules and to evaluate the diverse implementations of those rules by space operators.** This capability is necessary to develop and enforce performance-based rules.

Conclusion

Space operations are changing rapidly and will have profound effects on how and by whom space is used. The implementation of norms of behavior for safe space operations is critical for ensuring effective use of space in the future. The United States needs to be a leader in the effort to guarantee that space operations remain unimpeded by risks to operations. Seven Key Actions have been discussed to establish the organizational and technical capabilities needed to develop safe space practices and effectively disseminate them to the space community. Establishing these capabilities will allow the United States to guide the development of global space traffic management in this rapidly changing environment.

References

[1] Space Policy Directive-3 National Space Traffic Management Policy (https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/).

[2] Guidelines for the Long-term Sustainability of Outer Space Activities (https://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf).

[3] U.S. Government Orbital Debris Mitigation Standard Practices, November 2019 (https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf).

[4] NASA Standard 8719.14 (https://standards.nasa.gov/standard/nasa/nasa-std-871914).

[5] AFI 91-202 (https://static.e-publishing.af.mil/production/1/af_se/publication/afi91-202/afi91-202.pdf).

[6] Inter-Agency Space Debris Coordination Committee Space Debris Mitigation Guidelines (https://www.iadc-home.org/documents_public/file_down/id/4204).

[7] ISO 24113: Stokes, H., Y. Akahoshi, C. Bonnal, R. Destefanis, Y. Gu, A. Kato, A. Kutomanov, A. LaCroix, S. Lemmens, A. Lohvynenko, D. Oltrogge, P. Omaly, J. Opiela, H. Quan, K. Sato, M. Sorge, and M. Tang, "Evolution of ISO's Space Debris Mitigation Standards," 1st International Orbital Debris Conference, Sugar Land, TX, December 2019.

[8] Space Traffic Management in the New Space Age, Muelhaupt, Sorge, Moring, Wilson, Journal of Space Safety Engineering (2019) 80-87.

[9] Glenn E. Peterson, Marlon E. Sorge, William H. Ailor, Space Traffic Management in the Age of New Space (https://aerospace.org/paper/space-traffic-management-age-new-space).

[10] Jamie Morin, "Four steps to global management of space traffic," *Nature*, March 5, 2019 (https://www.nature.com/articles/d41586-019-00732-7).

[11] National Academy of Public Administration, "United States Department of Commerce: Space Traffic Management," (https://www.napawash.org/studies/academy-studies/united-states-department-of-commerce-office-of-space-commerce), August 19, 2020.

[12] "Space Traffic Management," A Report by a Panel of the NATIONAL ACADEMY OF PUBLIC ADMINISTRATION for the United States Department of Commerce (https://www.napawash.org/studies/academy-studies/united-states-department-of-commerce-office-of-space-commerce).

[13] European Union Space Surveillance and Tracking (https://www.eusst.eu/).

[14] Peterson, Sorge, McVey, "Tracking Requirements for Space Traffic Management in the presence of Proposed Small Satellite Constellations," 69th International Astronautical Congress, Bremen Germany, October 2018.

[15] Barack Obama, "National Space Policy of the United States of America," PPD-4, June 28, 2010 (https://aerospace.org/sites/default/files/policy_archives/National%20Space%20Policy%2028Jun10.pdf).

[16] Rebecca Reesman, Michael P. Gleason, Slash the Trash: https://aerospace.org/paper/slash-trash-incentivizing-deorbit

[17] Marlon E. Sorge, Commercial Space Activity and Debris Regulation (https://aerospace.org/paper/commercial-space-activity-and-debris-regulation).

[18] William H. Ailor, "Large Constellation Disposal Hazards," Center for Space Policy and Strategy, The Aerospace Corporation, 2019.

About the Authors

Marlon E. Sorge is a principal engineer for the Space Innovation Directorate of The Aerospace Corporation. He supports a wide variety of space debris and space situational awareness-related projects as well as strategic planning, conceptual design, technology development programs, and astrodynamics analysis. For more than 30 years, Sorge has conducted space debris research and analysis in a broad range of fields including debris risk assessment, fragmentation analysis, operations support, debris mitigation technique implementation, debris event reconstruction, satellite design for debris survivability, orbital and suborbital range and space safety, ballistic debris management, debris environment projection, collision avoidance, orbital reentry prediction, and national and international mitigation guideline and standards development. He developed the Aerospace fragmentation model and conducted some of the first work in realtime fragmentation event risk assessment. He organizes Aerospace's debris research program, is a DOD representative on the NASA delegation to the IADC, and is the U.S. lead for the ISO Orbital Debris Working Group. Sorge holds a bachelor's degree in physics and a master's degree in aeronautical and astronautical engineering from Purdue University.

Dr. William H. Ailor is a Technical Fellow with the Center for Orbital and Reentry Debris Studies at The Aerospace Corporation in El Segundo, California. He has chaired 12 international conferences, including 8 on protecting Earth from asteroids, and served on the United Nations subcommittee that developed protocols for international cooperation in the event a threatening asteroid or comet is discovered. He testified to Congress and was featured on *NBC Nightly News*, *CBS Evening News, ABC News,* and CNN as an expert on the Leonid meteor storm's possible effects on satellites during the period of the storm. Ailor is also known for his expertise in space debris and reentry breakup and has appeared on CNN, the Discovery Channel, and the Learning Channel discussing these topics. He testified to the Columbia Accident Investigation Board on what might be learned from debris recovered after that event. He provided expert commentary during the reentry of the Upper Atmosphere Research Satellite (UARS) in 2011. He holds bachelor's and master's degrees from North Carolina State University and a Ph.D. in aerospace engineering from Purdue University.

Ted J. Muelhaupt is the principal director of Aerospace's Center for Orbital and Reentry Debris Studies (CORDS). Applying more than 40 years of experience in analysis and operation of space systems, Muelhaupt provides corporate oversight for space debris analysis for Aerospace. In CORDS, Aerospace has one of the largest concentrations of space debris and collision avoidance experts in the world. Muelhaupt is also the principal director of the Southwest Regional Office at Aerospace, and is the deputy operations lead for National ETG. His technical specialties include orbit analysis, modeling and simulation, performance analysis, and software development. Muelhaupt has been a leading proponent of system visualization techniques and a leader or sponsor of major software tool developments. Throughout his career, he has also been a corporate leader in information technology issues, especially as they are applied to users. Muelhaupt holds a bachelor's degree in aerospace engineering and a master's degree in mechanics from the University of Minnesota. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

About the Center for Space Policy and Strategy

The Center for Space Policy and Strategy is dedicated to shaping the future by providing nonpartisan research and strategic analysis to decisionmakers. The Center is part of The Aerospace Corporation, a nonprofit organization that advises the government on complex space enterprise and systems engineering problems.

The views expressed in this publication are solely those of the author(s), and do not necessarily reflect those of The Aerospace Corporation, its management, or its customers.

For more information, go to www.aerospace.org/policy or email policy@aero.org.