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Executive Summary

By the end of 2017, there were over 1,700 active satellites—some of them the size of a breadbox—in orbit around Earth, approximately twice as many as there were 15 years ago. Between 2018 and 2026, at least another 3,000 satellites are expected to be launched: two-thirds for various commercial organizations, and the remaining third for civilian and military agencies in over 60 countries. The world's dependence on space is growing, in particular for critical national security uses, as well as economic and societal services and infrastructure. The resulting vulnerabilities to any disruptions caused if the space assets do not perform as planned is leading to mounting interest in and need for capabilities to track and monitor objects in space—not just the satellites themselves but the total number of objects including space debris. There is also concern that tracking and surveillance capabilities have not kept pace with the need for these services. Maintaining accurate and precise awareness of the locations of satellites and debris and the environment around them, in addition to ensuring operation free from radiofrequency interference, is increasingly being seen as critical for safe and sustainable operations in space.

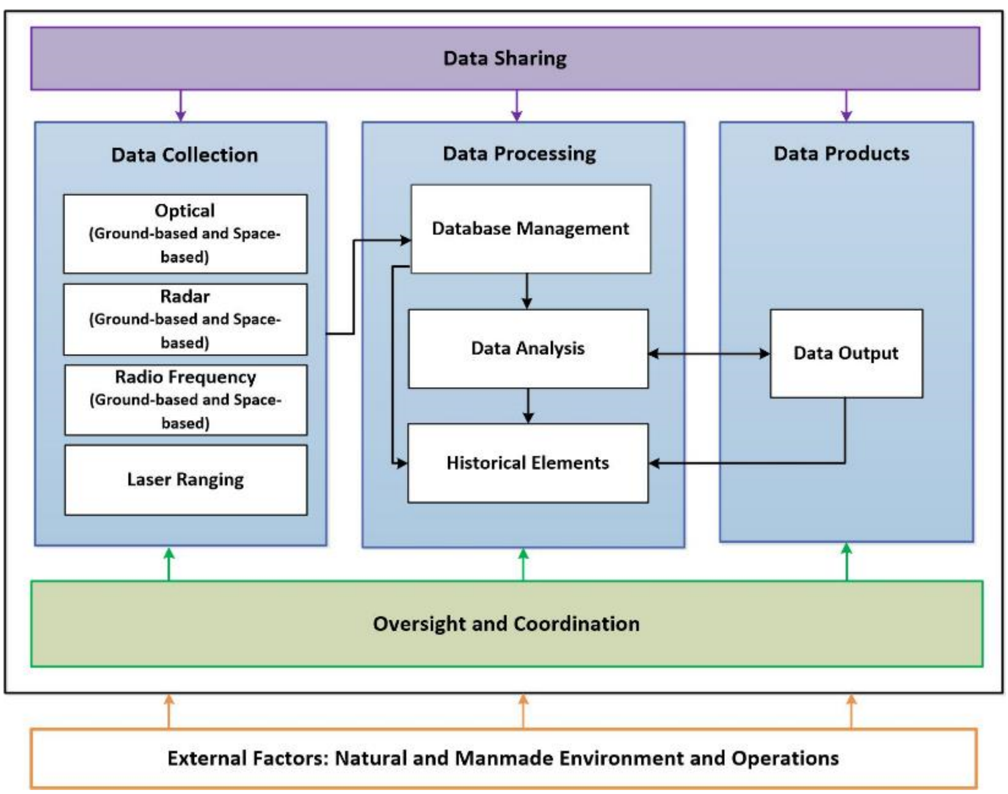
Until recently, the United States Department of Defense (DoD) was the only organization in the world—outside, perhaps, of Russia—to develop high-fidelity space situational awareness (SSA) information. Today, DoD shares varying levels of this information freely with satellite operators across sectors globally. The DoD system is based on a legacy architecture that originated as part of a missile warning system in an era where there were relatively few objects in space, typically operating in predictable orbits and engaging in predictable activities. Emerging trends in the space environment—where there is growth in the number of objects in space, growth in the number and diversity of operators, increasing diversity of the types of activities in space, and changing satellite technology—would increasingly strain DoD's ability to provide actionable SSA services not only for its own needs but also for those of its global partners. As a result, operators increasingly view today's DoD SSA system and service as inadequate to achieve safe operations in space. Activity to supplement DoD information—with some efforts to establish independent capabilities—is increasing, both within governments around the world and the private sector.

Given concern about the rapid pace of activity that can affect SSA and Space Traffic Management (STM), the IDA Science and Technology Policy Institute (STPI) identified current and emerging global trends in SSA and STM.

Methodology

In accordance with sponsor interests, our focus in this project was on developments *outside* the United States, and U.S. Government efforts such as those related to the upcoming Air Force radar system Space Fence were out of scope. However, since U.S. private companies work internationally, an examination of commercial U.S. entities was within our purview. Also, while we view radiofrequency interference as an important component of SSA and STM, to constrain the scope of the study, our focus was on *physical* interference. Lastly, our emphasis was to identify trends, rather than next steps or best practices in the domain.

Since there are no commonly accepted definitions of SSA or STM, to minimize confusion in interactions with stakeholders, we first developed a framework that operationalizes the space traffic system, and used this as a means to communicate with the stakeholders. The proposed framework divides the space traffic system into roughly six components (Figure below). The first is *data collection*, which refers to civil, military and commercial sensors, whether ground- or space-based. The second is *data processing*, which refers to managing the observations to create a database of resident space objects, analyzing the data to create products such as conjunction warnings, and maintaining a data archive. The third is creating *data products* such as conjunction or collision warnings that lead to actions such as those taken by operators to avoid collisions. The fourth is a set of activities that provides *oversight and coordination* of the environment, and includes regulations, policies, guidelines, standards, and best practices. The fifth is *data sharing* which, as with oversight and coordination, spans the entire continuum of the space traffic system. Last but not least are *external factors*—the combination of environmental and operational realities that are driving changes both on the technical and coordination sides.



Analytic Framework for a Space Traffic System

Once an analytic framework was ready and tested (and iteratively improved), we conducted case studies of the space traffic systems in 18 countries to identify trends in a structured, systematic, and bottom-up manner. Our questions covered topics including: definition of SSA; motivations for doing SSA; investments and roles in SSA; technical capabilities in data collection, processing, and products; domestic and international space policies; and regional and international cooperation on SSA, as well as oversight and coordination. The case studies were conducted via more than 70 interviews and a review of the open source literature. Interviews were conducted over the phone, in one-on-one discussions, and at venues such as the Advanced Maui Optical and Space Surveillance Technologies (AMOS) conference, the International Astronautics Congress (IAC), and the meetings of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

Lastly, to promote constructive dialogue with stakeholders and examine their assumptions, we developed four archetypical SSA scenarios for the next decade. We presented the scenarios to stakeholders and sought feedback on which scenario they viewed as the most likely and the most desirable. The scenarios were also explored at a roundtable organized by the Secure World Foundation at the 2017 AMOS conference; the scenarios and the roundtable are discussed in the Appendices.

Findings

External Factors. Our case studies showed that increasingly there is an expectation on the part of operators—including foreign governments as well as private operators—that the SSA information they receive be more precise and transparent than it is today. Given their own growing dependence on and vulnerabilities in space, governments of other countries would also like to be more self-reliant with respect to SSA capabilities, especially if SSA services provided by the United States become unexpectedly unavailable or are no longer available for free. There is also a desire among some countries to be a more equal partner with the United States and make more substantive contributions to the global SSA enterprise. As a result, there is growing demand for SSA sensors, software, products and services; country-level funding for SSA is increasing, dramatically in some countries such as Australia and Japan, and gradually in others such as Poland and Thailand.

Concurrent with this growing demand, technological developments have enabled the SSA "system" (comprising data collection, processing, and creation of products) to be segmented such that different organizations can service each part. Unlike the integrated DoD SSA system, organizations providing sensor data need not process it, organizations processing the data into a "catalog" need not collect it, and organizations developing value-added SSA products need neither collect data nor develop a catalog. Each segment in this "functionally modularized" system is also less expensive, which means that the private sector can step in and operate in each independently. This trend is visible already, with private sector firms especially in the United States and Europe focusing on one or more elements of the system. Experience in other industries that grew out of government investment (e.g., computing) has also shown that entrance of the private sector is a precursor not only to falling cost and greater innovation, but also to growing democratization. Our case studies indicate that globally SSA activities will likely remain dominated by national security-oriented organizations, even as they collaborate with their civil and commercial space counterparts, domestically and internationally; as a result, the field will likely be slower to democratize than others have.

Data Collection, Processing and SSA Products. Breaking up of the system has enabled each segment to evolve somewhat independently. On the data collection front, there is already an explosion of new sensors through the development of new sites. Countries and companies are also looking for "signals of opportunity" to repurpose existing sensors such as those used for astronomy and atmospheric science research and, for a small investment, utilize them for SSA. Newly added sensors include all types—optical, radar, and radiofrequency (RF). Expecting a growing market for SSA, many private companies have plans to add more radar, RF, and space-based sensors. The fact that the cost of these sensors and their operation is falling, primarily for optical but also potentially for radar, is beneficial for the private sector, which has to raise funds in private markets. However, the trade-off between cost and performance of radar may continue. When properly located, more sensors, even if they are not necessarily exquisite, allow for more persistence—ability to see assets more of the time. Over time, the expansion of sensors would allow data to become more of a commodity (the need for exquisite data for certain applications will always remain) with the value remaining in software systems.

On the processing front, there is growth in the number of systems for creating catalogs and producing more actionable SSA products. Some of the software is open source with the potential to enable faster rates of innovation, although most appears to be proprietary and owned by governments and individual private companies. While most of the development is in the United States, there are pockets of activity in France and Spain, among other countries.

Innovation is not limited just to the counts of sensors or software: there are qualitative changes under way that are likely to improve SSA capabilities. For example, on the sensor front, there are efforts to examine whether optical sensors, which are cheaper, easier to install, and more abundant, can be used to track objects in low Earth orbit (LEO), where most of the growth of space traffic is expected. On the processing front, machine learning and other techniques in the mainstream IT community are increasingly being applied to process data expected to come from the growing number and diverse phenomenologies of sensors (e.g., combining data from optical and radar sensors to create new insights not feasible with just one type of sensor). There is also effort to use large amounts of data to compensate for physics-based models in algorithms (e.g., effect of solar weather), and predict orbits at similar levels of accuracy as with more sophisticated models. As a result, both countries and companies are increasing capabilities.

In the coming years, this innovation—both on the quantity and quality front—would allow for increasingly more (e.g., including covariance information) and better (e.g., smaller error ellipses) SSA information. Given growing capabilities in the private sector, it is also likely that the cost of SSA products could substantially decrease. This innovation could allow other countries to follow different pathways (for example, by leveraging the private sector or developing international partnerships), and leap-frog closer to the expertise level of the United States without the same investment of time and funding. This in turn would allow them to become more equal partners as well as acquire capabilities that are closer to being on par with the United States, with the end result that while the U.S. Government may have the best SSA information in the world, it will not be the only source of SSA information in the world.

Since space shares many features of a free resource with its concomitant tragedy-of-the-commons implication, there is widespread agreement among stakeholders interviewed for this report, including those in the United States, that to ensure safe operations in space, there is greater need to share SSA information. As a result, in addition to the data sharing agreements many countries have with the United States, there is increasing collaboration between other countries as well, both bi- and multilateral. In some cases, the partnerships, such as the European Union-Space Surveillance and Tracking project (EU-SST) or Chinese Asia-Pacific Ground-based Optical Space Objects Observation System (APOSOS), do not involve the United States. Many countries are also placing sensors in other parts of the world, particularly in southern hemisphere countries, in exchange for capacity-building in the broader space sector.

Oversight and Coordination. There is growing agreement in the SSA community that data sharing alone across countries and organizations is not enough and that there is a need to collaborate to ensure the safety and sustainability of space activities (for example, ensuring that there is no radiofrequency interference across satellites, or that objects move out of each other's way if there is risk of collision) that is both domestically and internationally coordinated. As a result, efforts to oversee, manage, and coordinate space traffic have been increasing. There is growing interest across spacefaring countries to contribute to the development of approaches to address the challenge of growing space activity. At the same time, participants in international forums recognize that with increasing numbers of players, technologies and activities in space, this will be complex. Issues related to lack of trust and transparency pose challenges to efforts to develop more binding and formal institutions for STM. For these and other reasons, unless some "wildcards" (an example being a significant collision event in space) come into play, or unless significant political will is exerted, there is likely to be no international agreement on an international STM regime in the next decade.

Our overall finding is that in the next decade, while U.S. Government capabilities in SSA would continue to be seen as the gold standard, many other countries would likely develop capabilities that would allow them to become increasingly more self-sufficient and less reliant on the United States. The world is on a path-of-no-return for the proliferation of SSA capabilities, a trend that has significant implications for transparency in space (e.g., more actors will be increasingly able to track others' activities in space). The increasing competence in SSA globally also likely means more vocal participants in discussions related to STM, which will affect the sphere in which the U.S. seeks to demonstrate leadership in space.

Contents

1. Introduction

A. Background and Goals

Fifty years ago, the United States and the Soviet Union were the major players in space; today over 80 countries have space-based interests (Lal et al. 2015). By the end of 2017, there were over 1,700 active satellites—some of them the size of a breadbox—and approximately twice as many as 15 years ago (McDowell 2018). This increase is due in part to the ever-expanding role space systems play in a variety of applications including earth observation and telecommunications (Schroegl 2018). Active satellites themselves comprise only a fraction of the total number of objects in space. More than 90 percent of the objects in near-Earth space are inactive objects such as used rocket bodies and debris, and the number of these objects, often referred to as space debris, has been growing at an increasing rate as well.

The growing population of existing satellites and space debris has created two main challenges for safe space operations. The first lies in the difficulty of detecting and tracking objects in Earth orbit and being able to predict their future trajectories. The second is how to use the information about future trajectories to detect and prevent collisions between space objects, which could damage or destroy functional satellites and generate additional orbital debris.

Meeting these challenges will become more difficult and costly in the future. The coming decade may see the launch of thousands of small satellites for a variety of missions; this number could go into the tens of thousands if even a fraction of the more than 60 constellations being proposed are deployed (Lal 2018). Scholarly studies have attempted to assess the effect of the projected launch rates on future conjunction risks (close approaches between objects). A study conducted by the European Space Agency (ESA) estimates that just one of these large constellations of small satellites could increase the number of conjunctions by a factor of 70 compared to today.[1] And it is not just close approaches that would increase—so would warnings about them (many of them false positives). The same ESA study estimates that the new population of cubesats alone will generate millions of conjunction warnings each year. Most experts believe it is critical to improve the accuracy and reliability of current conjunction analysis techniques.

Up until recently, the U.S. Government was the primary provider of space tracking, referred to as space situational awareness (SSA), providing free access to some information about locations of objects in space, and sending warnings to satellite operators when their assets came too close to

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[1] Virgili, B. et al. 2016. "Risk to space sustainability from large constellations of satellites." Acta Astronautica 126 (2016): 154-162.

others.[2] However, given the growing importance of space in countries around the world, and the prospect of profiting from providing this information, there is growing global and private interest in both providing and using SSA information. The quality and number of both ground- and space-based sensors is increasing worldwide. There are also calls for an internationally-accepted space traffic management (STM) regime.[3] At present, there is no overarching international STM regime that seamlessly incorporates launch, reentry, and on-orbit activities, and many nations are still independently developing their own standards for these processes. This has also led to questions as to whether private space entities globally are being provided continuing supervision in accordance with international treaty obligations, in particular Article VI of the 1967 Outer Space Treaty.

Given concern about the rapid pace of activity in the domains of SSA and STM, the IDA Science and Technology Policy Institute (STPI) identified global trends in SSA/STM with a focus on developments outside the United States.

B. Methodology

Our goal in this project was to explore current and emerging global trends in SSA/STM. In accordance with sponsor interests, our focus was on developments *outside* the United States. U.S. Government activities such as those related to the Air Force Space Fence or the National Space Defense Center were not examined. However, since U.S. companies work internationally, commercial U.S. entities were within our scope of study.

While there are references to radiofrequency interference in the report, and we see it as an important component of SSA and STM, to constrain the scope of the study, our emphasis was on *physical* interference. Lastly, our assignment was to identify trends, and not next steps or other best practices in the domain.

There are no commonly accepted definitions of SSA and STM. As Table 1-1 illustrates, stakeholders use terms that refer to and include different aspects of SSA and STM based on their knowledge of and involvement in the topics. Appendix B provides a sampling of definitions from different organizations and countries around the world. To minimize confusion in interactions with

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2 In 2017 alone, the US Air Force's 18th Space Control Squadron provided data for almost 310,000 close calls in space, and issued 655 "emergency-reportable" alerts to satellite operators. Of these, 579 were in LEO (DoD as quoted in http://www.businessinsider.com/space-junk-collision-statistics-government-tracking-2017-2018-4). The current SSA system is explained in Appendix A.

3 It is important to make the distinction between space situational awareness (SSA) and space traffic management (STM); definitions of these terms provided by different international governments and organizations are provided in Appendix B. SSA can generally be defined as the gathering of information related to the space environment and spaceflight needed as the basis to operate space systems safely and efficiently, to avoid physical and electromagnetic interference, to detect, characterize, and protect against threats (including collisions) and to understand the evolution of the space environment (Schroegl 2018).

stakeholders, we developed a framework that operationalizes the space traffic system, and then used it to communicate with the stakeholders.

Table 1-1. STPI's Survey of Definitions

		SF	ESA	USSTRATCOM	SWF	ASA	JP 3-14	NASA	ESPI	SAIC	IAA	UN COPOUS
Elements	NEOs	SSA	SSA	SSA	SSA	SSA			SSA			
	Space weather		SSA	SSA	SSA	SSA					STM	STM
	Manned assets on orbit/objects	SSA	SSA	SSA	SSA	SSA			SSA		STM	STM
	RFI			SSA							STM	STM
	Space Environment			SSA	SSA		SSA	SSA	SSA			
	Operations				SSA		SSA	SSA		STM	STM	STM
	Risks/threats/Events	SSA		SSA	SSA	SSA	SSA	SSA	SSA			
	Technical provisions			SSA						STM	STM	STM
	Policy									STM		
	Regulatory provisions										STM	STM
	Rules										STM	
	Safety			SSA	SSA					SSA/STM	STM	STM
	Hazard			SSA						SSA		
	Efficiency			SSA	SSA							
	Security	SSA		SSA	SSA							STM
	Sustainability			SSA	SSA							
	Physical interference/collision	SSA		SSA							STM	STM
Activity	Technical tracking		SSA	SSA					SSA			
	Surveilling		SSA	SSA								
	Understanding	SSA		SSA				SSA				
	Predicting	SSA		SSA			SSA	SSA		SSA		
	Monitoring		SSA	SSA					SSA			
	Detecting		SSA	SSA					SSA			
	Knowing		SSA	SSA		SSA	SSA	SSA	SSA			
	Characterizing/Identifying	SSA		SSA	SSA				SSA			
	Cataloging			SSA					SSA			
	Deterring									SSA		
	Cooperating			SSA	SSA				SSA			
	Characterizing	SSA		SSA	SSA							
	Implementing											STM
	Decision making											
	Maneuvering											

Source: Multiple, See Appendix B.

STPI's analytic operational framework is presented in Figure 1-1. The proposed framework divides the space traffic system into roughly six components. The first is *data collection*, that refers to civil, military and commercial sensors, whether space- or ground based. The second is *data processing*, which refers to managing the observations to create a database of resident space objects, analyzing the data to create products such as conjunction warnings, and keeping a data archive. The third is *actions* such as those taken by operators to avoid collisions. The fourth is set of activities that provides *oversight, coordination and management* (we use the shorthand OCM throughout this report) of the environment (including the data sharing environment), and includes regulations, policies, guidelines, standards, and best practices. The fifth is *data sharing* which, as with OCM, spans across the entire continuum of the space traffic system. Last but not least is the *external factors*—the combination of environmental and operational realities that is driving changes both on the technical and coordination sides. Each component is described below in the order presented in the report:

- **External Factors**. The natural and man-made environment and operations in space comprises any aspect—technical, policy, regulatory—that affects the space traffic system. This includes: players: spacefaring countries, commercial entities; objects in space: debris, satellites; space-based activities; technology/architecture changes;

satellite characteristics: size, orbit, applications, capabilities, materials, composition; funding: government space budgets, private sector investments; policies, laws, regulations, treaties—at national and international levels; space weather; satellite maneuver schedule/collision maneuvers and protocols; capabilities acquired from adjacent sectors (e.g., big data capabilities, commodity computer hardware, cloud computing); risks and threats; national security events; and mishaps: accidental collisions. Each of these has a significant role in determining future space traffic system needs and trends and thus contributes to the environment in which these capabilities and decisions are being developed.

- **Systems for data collection, data processing, and data sharing**. The next three elements of the space traffic system include sensors (ground and space-based), and software and systems for data validation, generating a database, and creation and dissemination of SSA products such as conjunction warnings. These technical aspects are often characterized as SSA services. Data sharing is displayed as a separate category in the figure as it crosses collection, processing and action components. In the report we focus more heavily on collection and processing. Sharing is discussed under both technical and oversight headers.
- **Actions**. Actions refer to decision making and response to the space environment. For example, an "action" would include the decision whether and how to maneuver a spacecraft—and who is responsible for doing so—in response to a conjunction assessment (CA). Such actions are subject to the STM regime.
- **Oversight and coordination.** This can take many forms: national and international policies, informal guidelines, formal regulation, standards, best practices—at the national and international levels. Such oversight and coordination is characterized as STM.

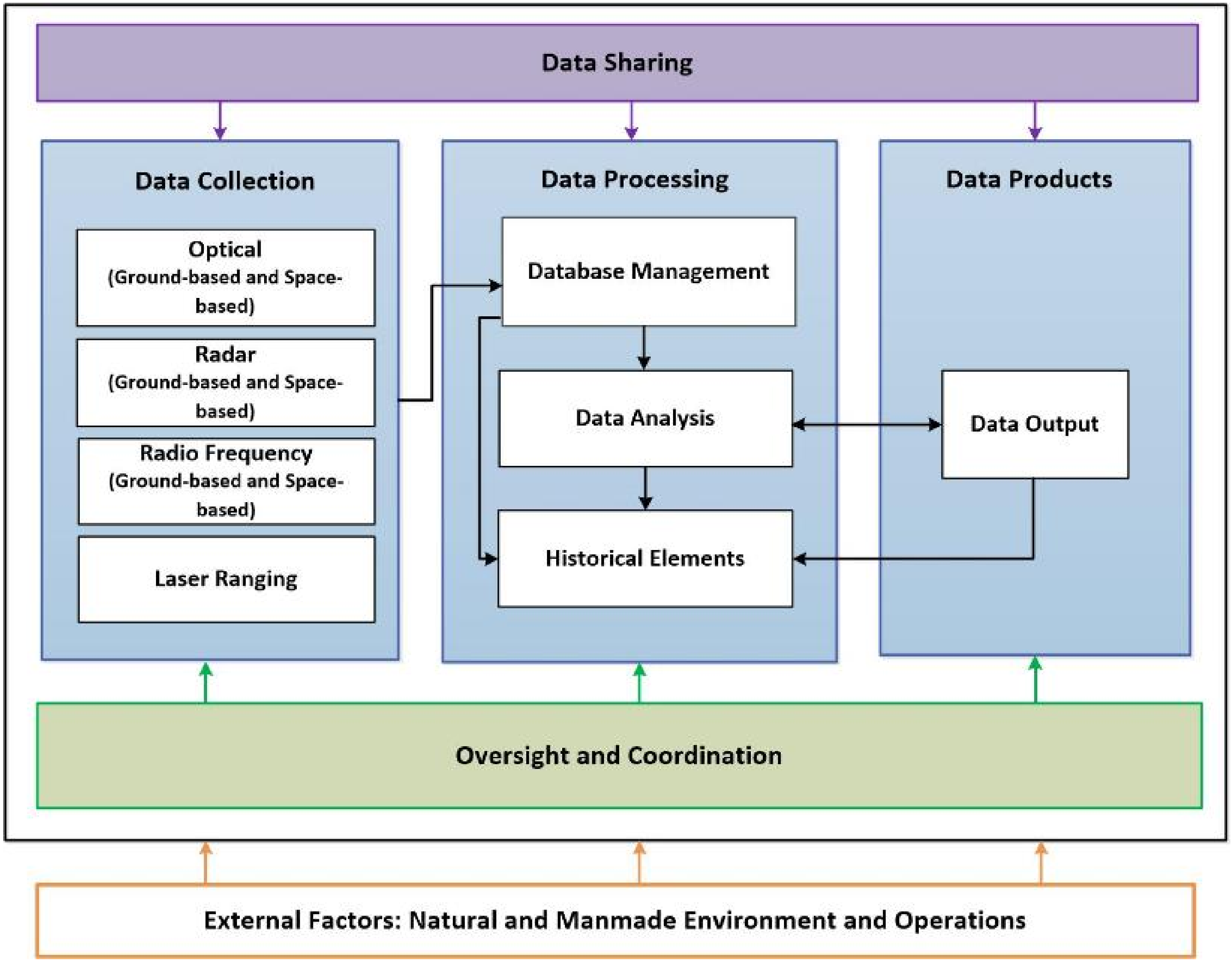

Figure 1-1. Analytic Framework for the Space Traffic System

Table 1-2. Case Study Candidates

Case Study Countries	
Australia	Japan
Brazil	Poland
Canada	Russia
Chile	Spain
China	South Africa
France	South Korea
Germany	Thailand
India	United Arab Emirates
Italy	United Kingdom
Private Vendors and Consortia of Interest	**International Organizations and Projects of Interest**
AGI	APSCO
ExoAnalytic Solutions	APRSAF
LeoLabs	ESA SSA
GMV	EU SST
SDA	ISON

Once an analytic operational framework was ready and tested (and iteratively improved), we used a case study approach to identify trends in the space traffic system in a structured, systematic, and bottom-up manner. We identified 18 countries based on their space interests and policies, ground-based and in-space assets, SSA capabilities, space budgets, and geographic and political characteristics. Our questions covered topics including: definition of SSA; motivations for doing SSA; investments (e.g., domestic, regional consortia) and roles (e.g., private sector, military, civil government) in SSA; technical capabilities in data collection, processing, and products; domestic and international space policies; and regional and international cooperation on SSA as well as space oversight, coordination and management (see Table 1-3). These case studies were driven by a protocol that is included in Appendix C.

The case studies (full text available on request, summary in Appendix D) were conducted via unclassified interviews and a review of the open source literature. Table 1-4 provides the breakdown of the 70 interviewees by sector. Thirty-seven of the interviewees were international, of which 29 were associated with foreign governments. Thirty-three of the interviews were with experts in the private sector or academia—either in the United States or abroad. Interviews were conducted over the phone, in one-on-one discussion, and at venues such as Advanced Maui Optical and Space Surveillance Technologies (AMOS) conference, the International Astronautics Congress (IAC), and the meetings of the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS). The full list of interviewees by name is available in Appendix E.

Table 1-3. List of Interviewees by Affiliation

Affiliation	Number of Interviewees
Government – U.S.	6
Government – International	29
Private sector vendor – U.S.	18
Private sector vendor – International	2
Academia – International	7
Academia – U.S.	1
Other (industry) – U.S.	4
Other (insurance) – U.S.	1
Other (investor) – U.S.	1
Other (nonprofit) – U.S.	1
Other – international	1
Total	**71**

In addition to conducting interviews, we reviewed about 100 papers and reports, including all foundational SSA and STM reports. They are listed in the References section. Interview notes and reports were systematically coded to flag for pertinent information. Nine coding bins were developed: background, definition of SSA, future outlook on SSA/STM, goals of SSA, international cooperation on SSA/STM, number of space assets, role of government and commercial industry, STM policies, and technical capabilities. Information from the coded information was used to inform trends and case studies. Additionally, defense and space policy documents were reviewed for all country case studies where available.

Lastly, to promote constructive dialogue with stakeholders and examine their assumptions, we developed four archetypical SSA scenarios for the next decade. We presented the scenarios to stakeholders, and sought feedback on which scenario is most likely and most desirable. The scenarios are available in Appendix F. The scenarios were also explored at a roundtable dialogue organized by the Secure World Foundation (SWF) with stakeholders attending the 2017 AMOS conference. Names of the attendees, and summarized results of the discussion are available in Appendix G.

C. Organization of the Report

The report closely follows the analytic operational framework presented in Figure 1-1. Chapter 2 summarizes trends in the external environment that affects SSA and STM. Chapter 3 presents trends related to data collection and processing. Chapter 4 focuses on trends in oversight and management. Lastly in Chapter 5, we summarize the trends and present overarching conclusions related to the emerging future of SSA and STM.

2. External Factors

In Chapter 1, we introduced the framework used to describe current and emerging changes in the "space traffic system." In the remainder of this report, we will describe the current and emerging trends in each element of the system. We begin with trends in the environment that are driving the space traffic system.

A. A Changing Space Environment

Emerging changes in the space environment make existing approaches to SSA more challenging. We have identified three sub-trends that fall within this larger trend.

1. Growing Number of Objects in Space

Space is becoming increasingly more crowded: in the last 60 years nearly 8,500 objects have been launched to space, about 1,500 in geosynchronous Earth orbit (GEO) and about 7,000 in low Earth orbit (LEO) (McDowell 2018). A large fraction remains (Figure 2-1) especially in LEO (Figure 2-2). Going forward, LEO is expected to become more crowded. As an illustration, over 6,200 small satellites (satellites weighing less than 500 kg) are expected to be launched between 2017 and 2026 (Euroconsult 2017a). Although the main space players will continue to dominate (85 percent of the government space market will remain concentrated in the 10 countries with an established space industry—U.S., Russia, China, Japan, India, and the top five European countries), the other 50 countries engaged in space will launch almost 200 satellites by 2026, twice the number they launched over the past 10 years (Euroconsult 2017a, b).

The concern is not just the increasing number of satellites and active payloads, but the amount of debris (rocket bodies, other inert bodies, dead payloads) in earth orbit, which comprises more than 95 percent of the currently tracked objects in space.[4] The U.S. Department of Defense (DoD) is currently tracking 23,000 objects larger than 10 cm in diameter in Earth orbit (of these, almost 16,000 are in LEO, of which nearly 13,000 were classified as space debris[5]). An estimated 500,000 objects larger than 1 cm in diameter are not currently tracked, and over 100 million objects smaller than 1 mm in diameter are likely not trackable (NASA Orbital Debris Program Office). It is not

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4 Sheetz, Michael. 2018. "VP Pence: Commerce Department Will Oversee New Space Debris Policy." *CNBC*, April 16, 2018. https://www.cnbc.com/2018/04/16/vp-pence-commerce-department-will-oversee-new-space-debris-policy.html

5 Garnio, Lazaro, Alison Snyder. 2018. "Yes, There Really is a lot of Space Junk." *AXIOS*, April 19, 2018. https://www.axios.com/yes-there-really-is-a-lot-of-space-junk-930b166d-68c4-4803-9bd6-9e23514eb942.html

trivial to identify space debris and other junk, especially objects under 10 cm, using active beacons or other markers (e.g., radiofrequency tracking); they need to be physically spotted and tracked. Starting in 2019, the U.S. Air Force's Space Fence System will bring the catalog of debris tracked by Space Command from 23,000 to an estimated 200,000 objects.[6] Figure 2-1 and Figure 2-2 visually show the overwhelming fraction of debris in space by orbit.

In addition to implications for the safety and sustainability of the future space environment, these capabilities have other policy implications. For example, the principal reason Swarm Technologies' sandwich-sized "Space Bees" did not get a spectrum license from the Federal Communications Commission (FCC) was due to concerns that they might not be tracked consistently by DoD.[7,8]

2. Growing Number of Operators in Space

It is not just the number of satellites that is increasing: the number of satellite operators has been increasing steadily over the last 60 years (Figure 2-3). More countries have become active in space. Figure 2-4 plots data on number of satellites launched by country, and shows the crowding in the 2010s. This changing landscape is driven by two primary trends: increasing State interest in independent national space programs and the globalization of the aerospace industry (Schroegl 2018).

Smaller, lighter, and more capable satellites make Earth observation and remote sensing within the reach not just of countries, but also corporations and individuals. For example, Bank Rakyat in Indonesia has launched a satellite, built by Space System Loral and launched by Arianespace, to manage its 50 million accounts. Another example is the satellite launched by NanoRacks by an individual who wanted to fly a cubesat and was able to afford it. This trend is likely to continue, making the space environment increasingly more crowded.

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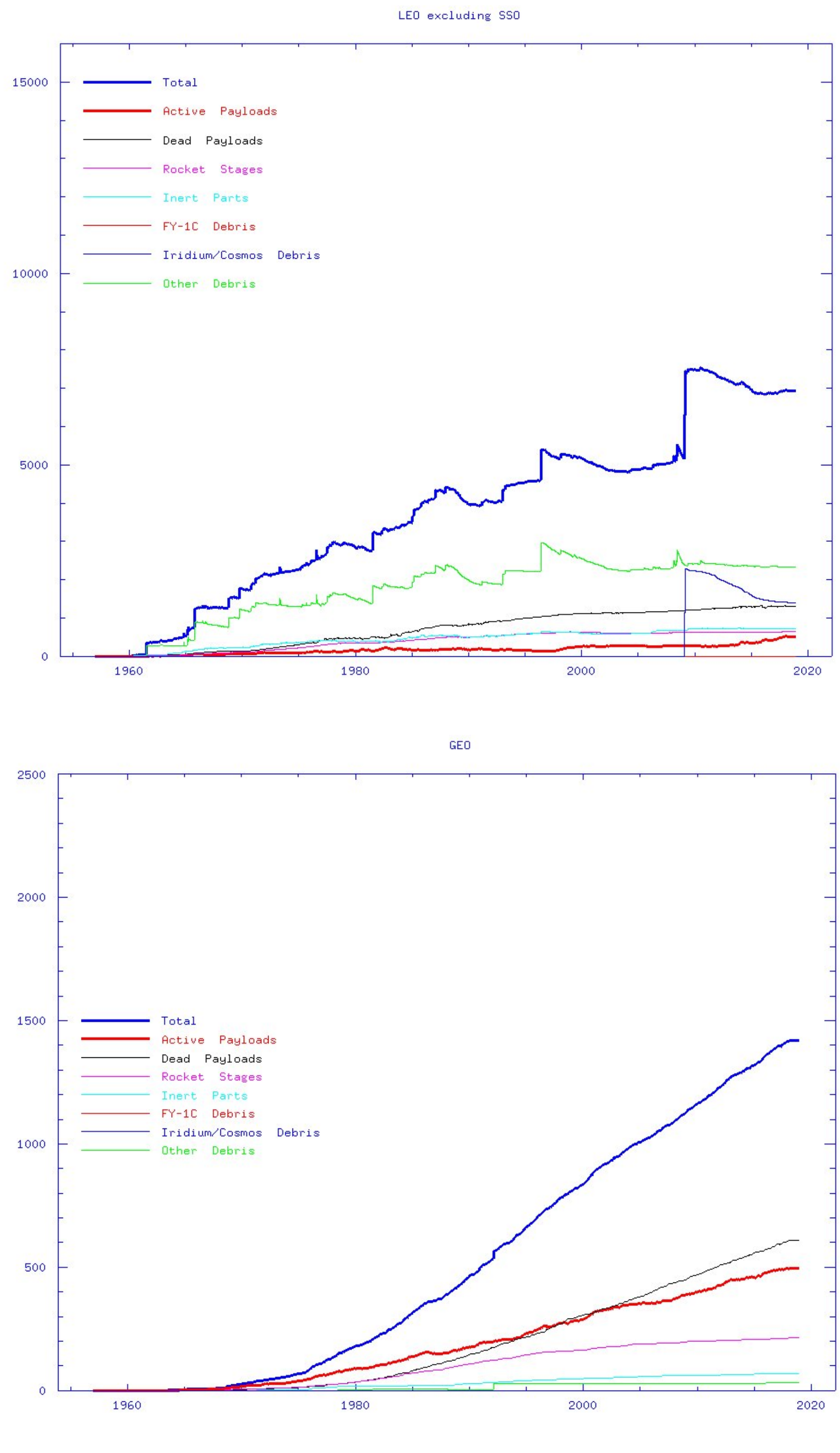
6 Mola, Roger. 2016. "How Things Work: Space Fence." *Air and Space Magazine*, February 2016. https://www.airspacemag.com/space/how-things-work-space-fence-180957776/

7 Federal Communications Commission, Experiential Licensing Branch. 2017. "Dismissed without Prejudice Notice of December 12, 2017." https://apps.fcc.gov/els/GetAtt.html?id=203152&x= http://www.spacenewsmag.com/commentary/commercial-ssa-and-the-case-for-collaboration/ https://spectrum.ieee.org/tech-talk/aerospace/satellites/fcc-accuses-stealthy-startup-of-launching-rogue-satellites

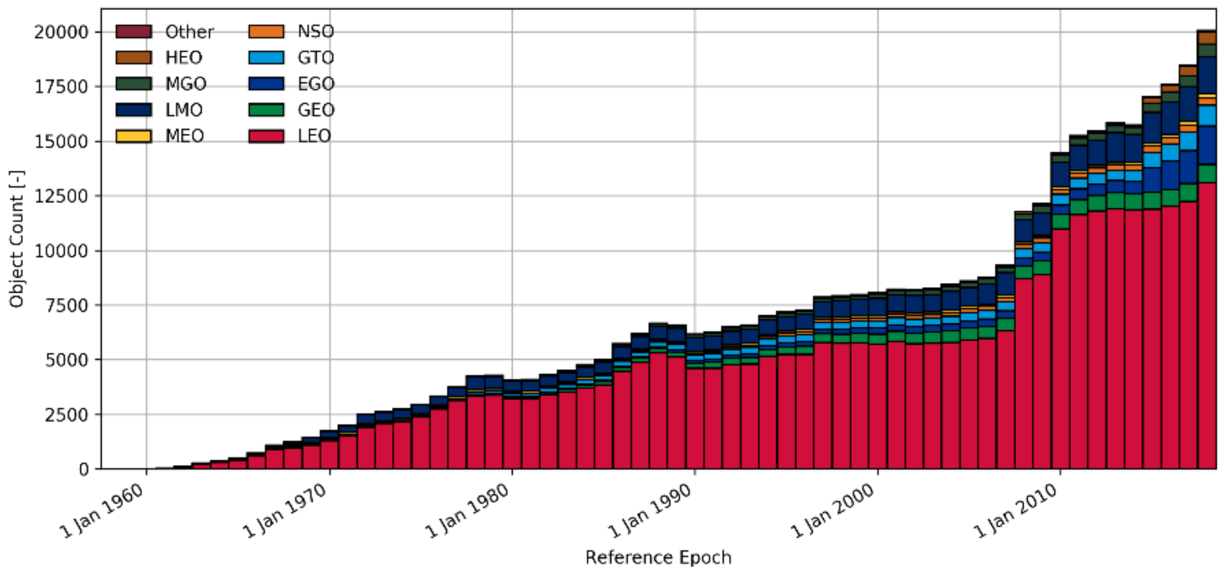
8 They were, however, able to be tracked by the private firm LeoLabs, as well as the 18th SPCS, and are in the public catalog. Also note that the new FCC NPRM on small satellites proposes requiring that only satellites larger than 10 cubic centimeters can be licensed. https://transition.fcc.gov/Daily_Releases/Daily_Business/2018/db0327/DOC-349939A1.pdf



Source: J. McDowell, 2018.

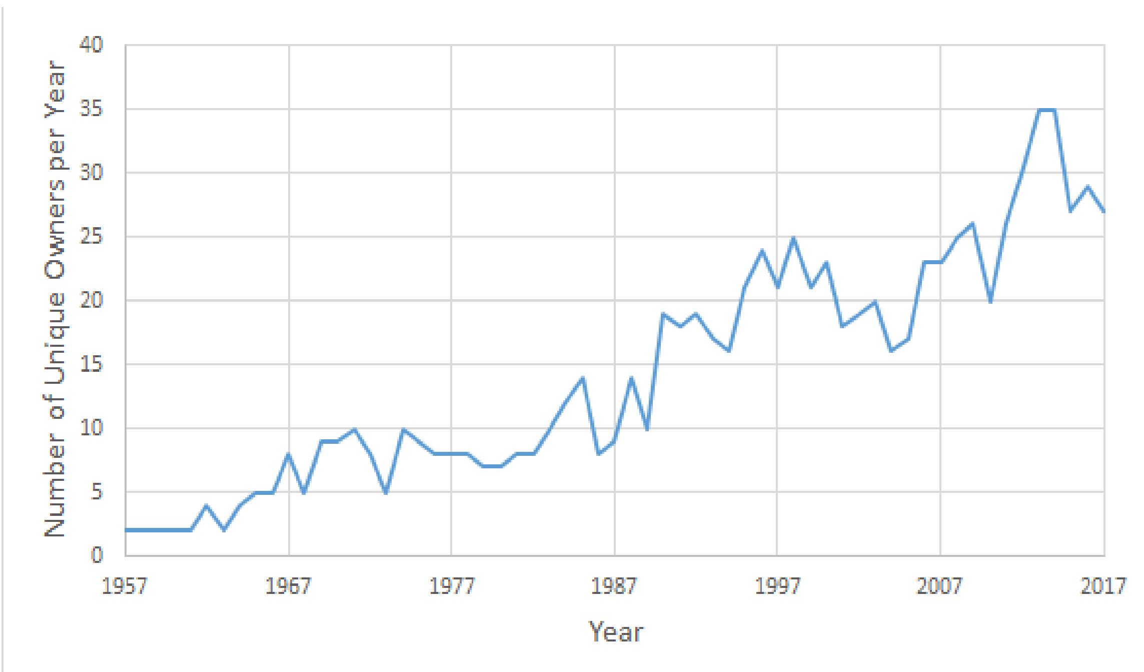
Note: the Y axes for the figures are different

Figure 2-1. Number of Objects in LEO and GEO, by Object Type



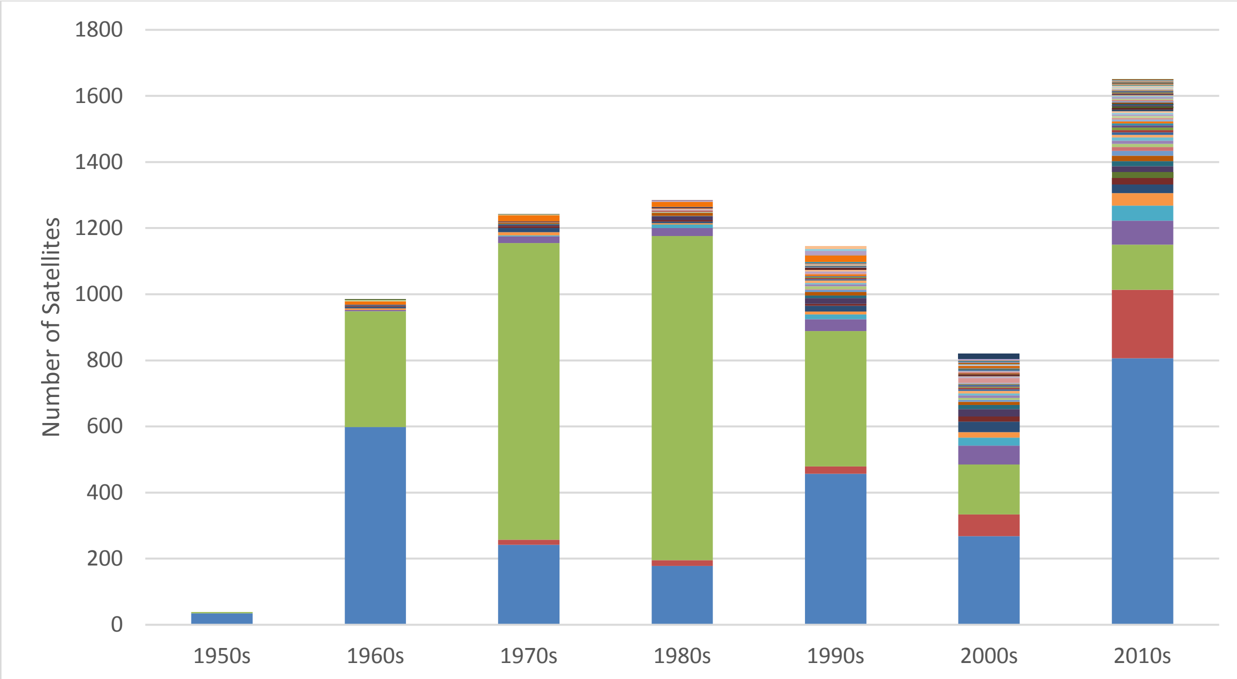
Source: European Space Agency. 2017

Figure 2-2. Count Evolution by Object Orbit



Source: Global Trends in Small Satellites, Lal et al. 2017.

Figure 2-3. Number of Unique Owners per Year



Source: McDowell, 2018

Note: Blue=US, Lime=Soviet Union/Russia, Coral=China

Figure 2-4. Number of Satellites Launched Each Decade, by Country

There is also growing participation in space by the private sector. It is important to note, however, that private space, especially in the near- and mid-term, is primarily a U.S. phenomenon. For most other countries, space is still a strategically-oriented government-run activity. Of the 44 companies that plan to launch constellations between 2017 and 2025, 20 are in the United States (Lal et al. 2017). Of the almost 10,000 satellites that are expected to launch as part of constellations, over 80 percent are from companies in the United States (Euroconsult 2016). More generally, of the 1,700 space companies listed by NewSpace Ventures, about half are headquartered in the United States;[9] the remaining half were distributed around the rest of the world (see Figure 2-5).

The increased number of owners and operators requires more coordination and governance in space, given that a standardization system to coordinate on-orbit behaviors across operators (other than spectrum, which is coordinated by the ITU) does not currently exist. Each private entity (e.g., universities, research institutes, non-profits, commercial companies) is governed by its licensing nation, potentially resulting in a varied set of behaviors in space. This issue could be exacerbated as the number of nations launching government assets as well as licensing private entities continues to increase.

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9 "NewSpace Ventures Analytics." https://mission-control.space/.

3. Changing Space Activities and Architectures

The current U.S. military SSA system relies heavily on sensors originally created for missile warning and works relatively well for tracking satellites in simple orbits around Earth. However, emerging architectures will change the way objects will need to be tracked Emerging applications, including missions related to rendezvous and proximity operations, such as satellite servicing and refueling, inspection, space RF mapping, and space-based spacecraft assembly and manufacturing, will require SSA services that would be qualitatively different than the current system.

For example, formation flying—the ability for satellites to act as single units while they maintain similar orbits and operate within close proximity to one another—poses challenges to current DoD SSA systems, as these systems are not optimized to differentiate objects that are closer together; the space of uncertainty around each object is compromised by each object's closeness to other satellites in the constellation. Additionally, tracking and predicting the orbits of constellations containing hundreds of small satellites may challenge existing systems due to the number and size of objects involved. Going forward, the number of satellites in such systems is expected to increase. Figure 2-6 shows 60 companies that have plans to launch constellations. While only a fraction of these plans are likely to pan out, it is an important driver of changes required in the SSA system. Beyond constellations, further changes in the space sector include growing activity in several other areas beyond remote sensing and communication.[10]

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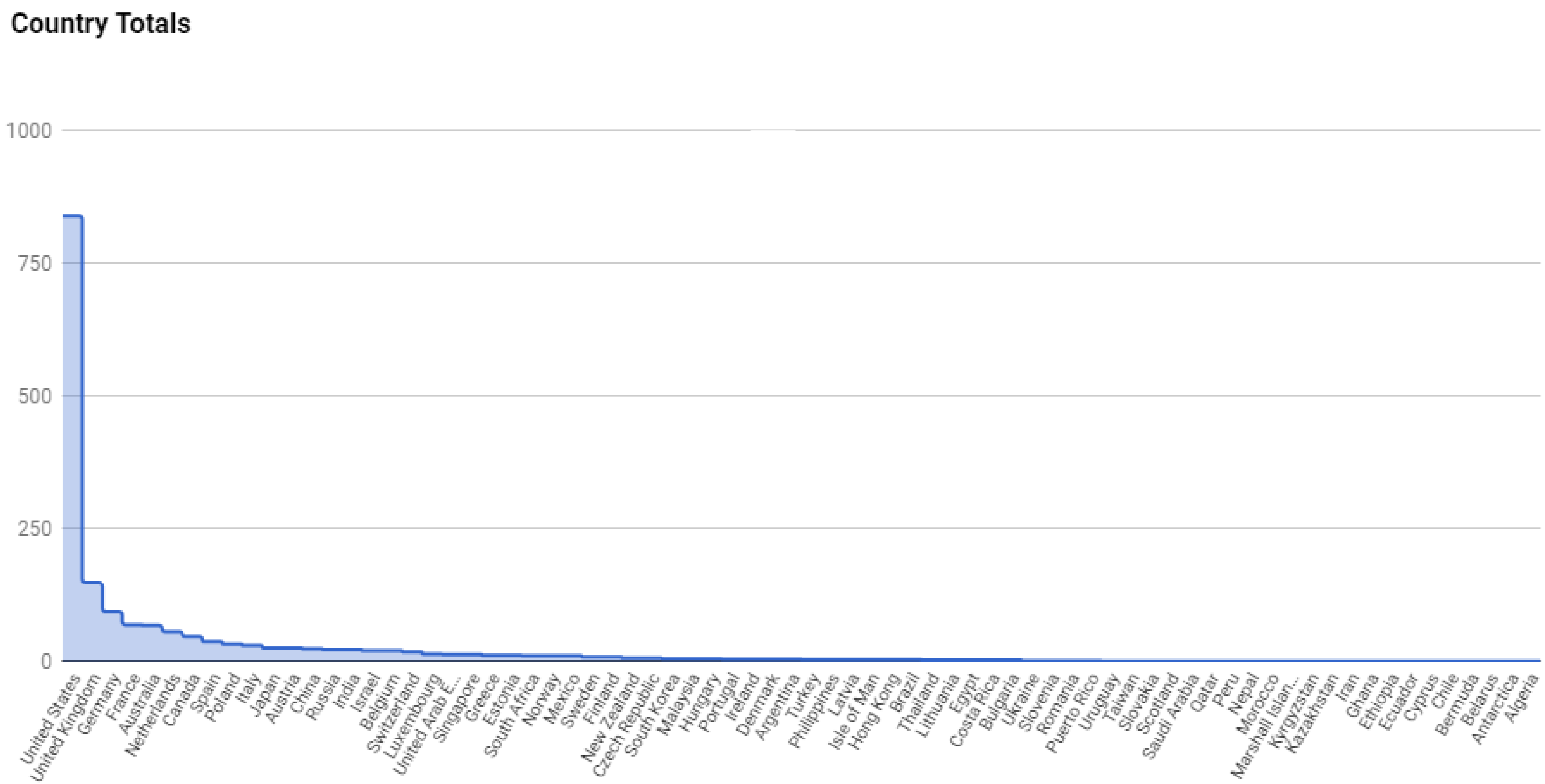
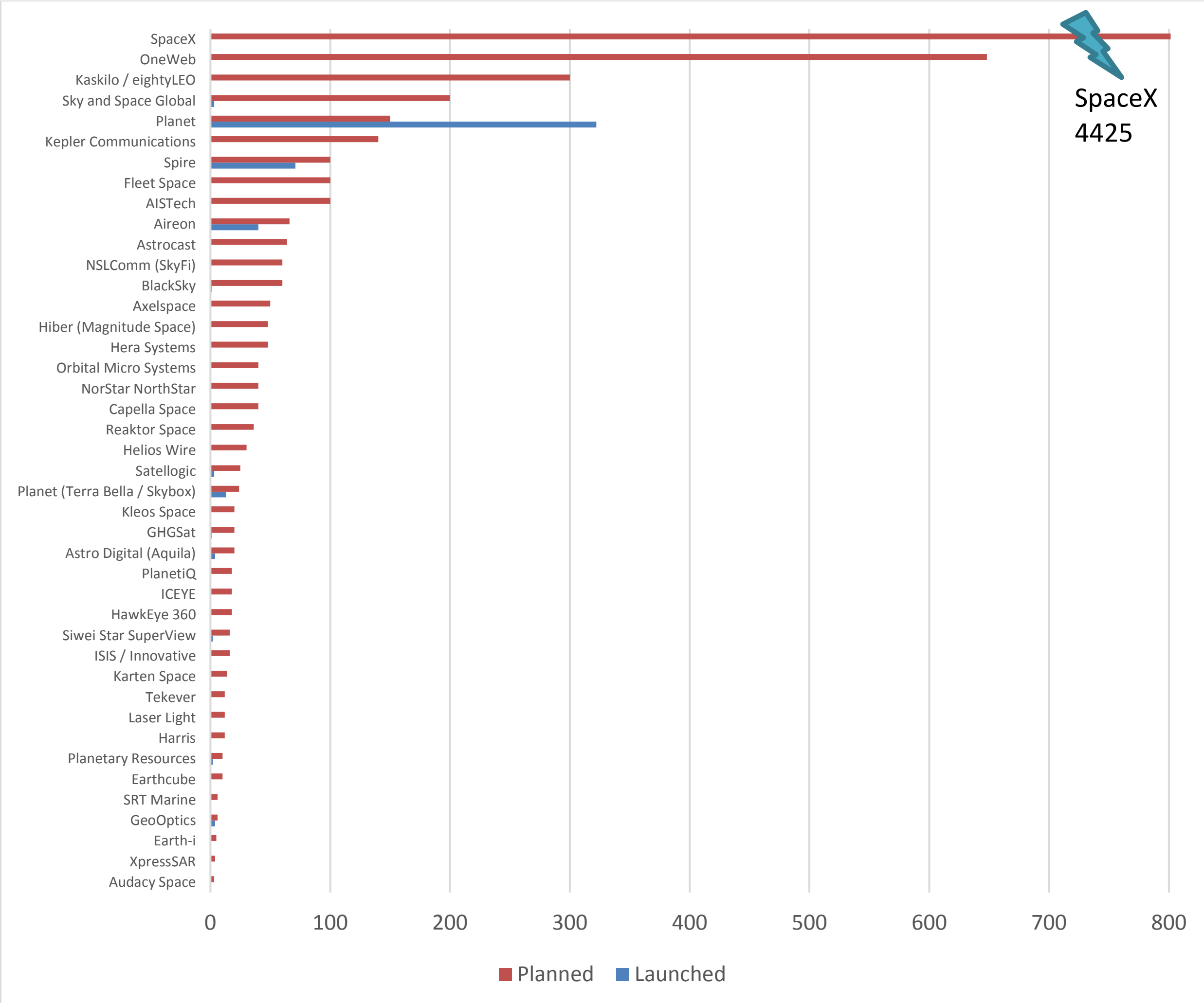
[10] One example of a new activity is the removal of space debris – the goal being to decrease the number of objects in space and thus reduce collision risk. Beyond the technical and regulatory challenges (e.g., restrictions on the ability to move an object even if it is no longer in use), any debris removal action will require more and more accurate SSA.



Source: NewSpace Ventures, 2018

Figure 2-5. Total Number of New Space Companies, by Country



Source: http://www.newspace.im/, n.d.

Figure 2-6. Number of Satellites Per Constellation (n=60)

Countries are operating satellites across orbits with varied capabilities, further complicating orbital prediction as the nature of any object in space becomes further unpredictable. Satellite operations automation, the continuous thrust allowed by electric propulsion, and other non-Keplerian activities for which the DoD system is not optimized make tracking difficult as the satellites' orbits can change any time, compromising the effectiveness of orbit prediction.

The popularity of electric propulsion on satellites has grown since the 1990s and implementation has increased sharply in the last decade; many of the proposed large LEO constellations require electric propulsion (Lev et al. 2017) and many GEO satellites now use electric propulsion as well. Unlike chemical thrusters, which impart thrust at one time, electric propulsion systems can impart thrust over the course of many months. This increases the number of observations needed to understand the satellite's new orbit. It also creates challenges for astrodynamics algorithms that model maneuvers as instantaneous, as well as catalog maintenance routines that only update orbits every several hours (such as that of the 18 SPCS). This capability can also be used to change a satellite's orbit mid-life, further complicating tracking. Although many small satellites do not have an on-board propulsion system, some small satellites in low Earth orbit can change their orbit by orienting themselves in such a way to increase atmospheric drag, again affecting projections of the satellites trajectories. Impulsive maneuvers through chemical propulsion bring their own set of challenges, given that a spacecraft moving with electric propulsion can be reflected in the surveillance data (e.g., through a negative drag coefficient) as long as the thrust is constant. Additionally, impulsive maneuvers can be challenging to account for with existing U.S. military satellite surveillance capabilities; thus, the image from a surveillance system is not reliable, given that more impulsive maneuvers may occur. An accurate prediction of such an object requires operator-level data that details whether a maneuver is taking place. This operator data is often not openly shared with providers; the necessity of this information suggests that cooperation for SSA is inevitable. An example of this is the actions of Space Data Association (SDA) in GEO, and a similar effort is likely in LEO, especially in response to the large satellite constellations that have been proposed (Schrogel, 2018).

Materials and specifics of satellites—e.g., size (smaller satellites and components), composition, and antenna technology both hardware and software (e.g., software defined radio)—can make the satellites more difficult to detect, especially given the limitations imposed by the rotation speeds of telescopes, which minimize the opportunities to sight and track objects. More efficient and smaller space electronics mean that power requirements of systems are shrinking, which in turn reduces the need for large solar panels. This not only reduces the satellite cross section, but may also reduce the reflectivity of satellites.

New technologies and smaller satellite components have enabled satellite operators to increase the capabilities of satellites in ever-smaller form factors. New materials used in satellite composition affect tracking attributes such as reflectivity. Cubesats and chipsats have smaller cross-sections and are thus more difficult to observe. These cross-sections are reduced even further by the improved technologies that allow for smaller antennas and solar panels. The cubesat standard is a satellite architecture based on 10 cm-wide units. This standard has led to an increase in commercial availability of small standardized parts, which in turn has led to a decrease in the price of components for such satellites, which can now be mass produced rather than built individually and/or by hand. Additionally, major providers of launch services have designed satellite deployment units for the cubesat standard, further increasing the number of entities that will use this standard when designing satellites. Chipsats are standalone satellites built onto computer chips approximately the size of a credit card. Because of their size, many of these satellites do not have propulsion units, making predictions of their orbits easier once they are detected. However, due to their small form factors, initial and follow-up detection is difficult without higher resolution telescopes. One reason FCC turned down the Swarm Technologies' license application was that there was concern that their satellites were too small to be reliably tracked by DoD.[11]

Future space activities that allow and often require close proximity of space objects (e.g., rendezvous and docking, on-orbit servicing or assembly) will require even more precise orbital estimations and predictions to avoid collisions. Companies engaged in such activities would need to supplement DoD information with on-board or space-based sensors to more precisely assess their location with regard to other objects in close proximity.[12]

B. Growing Concerns about Increasing Collisions

Although relatively few catastrophic collisions have occurred thus far in space,[13] the likelihood of a collision is predicted to increase in the near future, given the expected growing number of objects in both LEO and GEO and limited ability to track objects' orbits, which will make it difficult for operators to adequately avoid threats. This problem may be exacerbated if any of the proposed constellations of small satellites in LEO (shown in Figure 2-6 above) are launched, as they will dramatically increase the number of objects that require tracking, thus increasing the tracking and computational requirements for SSA in general and conjunction warnings in particular. Some industry representatives interviewed for the project noted that the emergence of constellations is driving the need for higher precision knowledge and services to mitigate the risk of collision: if numerous small satellites are deployed at once, tracking can be difficult, as resolution may not be great enough to distinguish multiple satellites.

NASA projects nearly one collision per year in the next 200 years if there is no debris mitigation. Independently, insurance companies have predicted a total exposure of $1.3 billion in LEO and $18 billion in GEO (Lal et al. 2015).

To estimate the number of collisions resulting from the increasing number of small satellites, several simulations of expected collisions per year for a number of large satellite constellations in LEO over 200 years have been conducted (Muelhaupt 2017). One such exercise evaluated the effect of adding two large constellations—those of SpaceX and OneWeb—to the current constellations in LEO (Iridium, Orbcomm, and Globalstar). The simulations found that within its

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[11] Federal Communications Commission, Experiential Licensing Branch. 2017. "Dismissed without Prejudice Notice of December 12, 2017." https://apps.fcc.gov/els/GetAtt.html?id=203152&x= https://spectrum.ieee.org/tech-talk/aerospace/satellites/fcc-accuses-stealthy-startup-of-launching-rogue-satellites

[12] Note that although better (more precise, more detailed) SSA data would enable slightly easier rendezvous operations, the nature of these activities generally requires on-board sensing for ease of operations, somewhat independent of the data quality.

[13] Graziani and Albrecht,. "since we first started placing objects into space there have been 11 known low Earth orbit collisions, and three known collisions at geostationary orbit. Think of it: 135 space shuttle flights, all of the Apollo, Gemini and Mercury flights, hundreds of telecommunications satellites, 1,300 functioning satellites on orbit today, half a million total objects in space larger than a marble, and fewer than 15 known collisions." http://spacenews.com/op-ed-congested-space-is-a-serious-problem-solved-by-hard-work-not-hysteria/

first 20 years in orbit, the first constellation is expected to cause one collision annually; this number would grow to approximately 8 per year at its peak collision rate, which occurs about 190 years after launch (see Figure 2-7). Although the majority of the collisions in the simulation were due to satellites that failed to be deorbited following end-of-life protocol, satellites that did attempt to be deorbited still accounted for approximately 40 percent of the total collisions.

Given that the systems developed to track space objects were developed at a time there were fewer objects in space, the accuracy of prediction is low. Oftentimes, a DoD conjunction warning message has an error ellipse of 100 km or more; the rate of false positives is high as well. Because of these two factors, as traffic in space grows, both the number of conjunction warning messages as well as the rates of both false positives—and false negatives— are likely to increase. For example, one study estimated that upon launch of its proposed constellation, SpaceX would receive 7.2 million conjunction warnings per year, and Iridium would receive about 384,000 per year. Some operators, aware of the increasing risk of collision, will be more likely to pay heed to notifications. This could result in increased maneuvers as operators attempt to avoid collision, even if the warning is not sound. These maneuvers—even if they are reported to the providers of SSA (e.g., the DoD, or commercial vendors), which may often not be the case—will still contribute to uncertainty regarding objects' paths, thus compromising the resulting predictions. Other operators, especially those with low-value assets, are likely to continue to ignore warnings as they currently do, which is equally problematic as they will collide with debris or put the onus to maneuver fully on the operator of the asset it threatens.

To avoid a significant increase in notifications, operators will increasingly look for higher quality SSA information. This could put further pressure on emerging systems to improve their predictions.

C. Changing National Level Motivations

Space is increasingly recognized as a sector of strategic importance with applications for security, capacity building, and social benefit. The increasing number of countries seeking to use space for science, safety, national security, and commercial purposes means increased threats (both accidental and nefarious) of collision and harm to assets (e.g., through radiofrequency interference).[14]

[14] While governments want to protect their assets (both for the investment as well as the in-space application), private companies are also in SSA both from an operator perspective (protecting their investments) and as a vendor of SSA services (financial opportunity). Involvement of commercial operators is discussed in section 2E, and involvement of SSA providers is discussed in section 2F.

1. Growing Recognition of the Need for Timely and Actionable SSA Services and Products

As space capabilities become integral to more applications (e.g., earth observation, communications, global positioning), a growing number of countries are recognizing the security and economic value of space and increasing their spending in space. The number of countries involved in space continues to increase: a decade ago, fewer than 50 countries were investing in space; today, there are 70. In the coming decade, that number is expected to increase to more than 80 countries, and the annual government space expenditure globally is expected to double, from about $40 billion in 2006 to $80 billion in 2026 (Euroconsult 2017b, c). This increased value (both mission-specific and financial) has led many nations to treat safety of such assets as higher priority, leading to growing efforts to develop norms and guidelines for behavior in space. Additionally, many countries (e.g., Brazil, China, France, Japan, and South Africa) want to be (and be viewed as) responsible stewards of space, and thus support these efforts.

In our dataset of 18 countries, most of those actively pursuing SSA focus on protecting their assets from satellite collisions—due to both the increasing number of assets and the increasing amount of space debris on orbit. Some countries (e.g., Japan, Canada) generally pursue protection of their space assets and interests—either for the sake of those assets specifically, or for the role they play in national security broadly. Some countries are more interested in the application of SSA (e.g., the data products) while others (e.g., Japan) value the collection and analysis side as well. SSA can also help with safe operation and control of assets. Though most are concerned with on-orbit collision warnings, some, such as India, use SSA only to avoid collision on launch.

Interviewees from some nations, such as Germany, noted that SSA can be useful in protecting what has been achieved in space thus far and avoiding major incidents. ESA's SSA program is interested in developing a hazard warning system by federating existing European assets and developing new sensor technology, with the goal of securing Europe's access to space, protecting the involved economies, and strengthening European industry.

Some countries prioritize detection of risks to their territory, and thus seek to detect either threats on reentry such as rogue space assets (e.g., France) or natural threats such as space weather and asteroids (e.g., South Africa). Some are specifically interested in protecting their satellites used for Earth observation; for example, representatives of Brazil note the importance of using space to protect its borders given significant issues with drug trafficking. This increasing reliance on space assets for security necessitates greater interest in and efforts toward SSA. For some (e.g., UK), SSA is seen as underpinning all other space roles in that it details the hazards, risks, and threats to the domain.

Our discussions with stakeholders demonstrated some countries' concerns that if they do not participate in global discussions (e.g., long term sustainability [LTS] guidelines), their national interests will not be appropriately reflected in the rules, and they will miss out on critical opportunities. This involvement suggests that more countries are becoming concerned with safe and sustainable operations in space—keeping space open to activities in the future and preventing problems (e.g., proliferating debris) from adversely impacting or precluding space activities. It is important to note that smaller and less powerful countries benefit greatly from these international discussions, as they are given a voice in the proceedings. More powerful and established nations may not always agree, as these deliberations have to include more players and typically take longer to conclude negotiations. This is specifically true for European countries; stakeholders noted that Europe can only have a voice in future regulations regarding the creation of global space traffic regulation if the EU and ESA work together. They noted that for European industry to become involved in challenging projects and thus be competitive on a global scale, the involved nations need to organize at the European level.

2. Lack of Confidence in DoD-Provided Data

Many stakeholders indicated that they need to have trust and confidence in the data being shared for collision warnings and other SSA products; many acknowledged the usefulness of verifying the information that is part of any database. There are many concerns with the current systems for provision of SSA. Some operators question the accuracy and especially the completeness of the information provided to them by the DoD. For example, some South Korean government officials estimate that their country receives data on only about 40 percent of the objects tracked by the DoD, due to sensitivity of U.S. assets.

This distrust is further complicated by the lack of transparency related to computing outcomes such as probabilities of collision. Owners and operators believe they require more information of high enough quality to make well-informed decisions about maneuvering. But because they do not know the process by which U.S.-provided information on an object's location is processed into a collision assessment or warning, they often do not feel confident maneuvering based on that warning. Skepticism regarding the reliability of the shared information is exacerbated by the nonstandard and nontransparent methods of calculation (often referred to by stakeholders in our discussions as "black box processing"). Beyond the distrust, some users perceive the U.S. DoD systems as limited, given that they are not well-suited to the emerging space environment; additionally, given the separation of the provision of SSA from the DoD's core mission, it is also perceived as overworked and understaffed, leading to further dissatisfaction. There is also some concern that going forward, the United States will either not share data or will charge for it. This last concern has heightened the sense of urgency in some countries to set up parallel SSA systems.

3. National Security Considerations

Many of the 18 countries are interested in developing or strengthening their strategic early warning capacities, specifically regarding space-based intelligence, surveillance, and reconnaissance (e.g., South Korean awareness of potential North Korean targeting, France's goal of detecting objects presenting a risk to its territory). Often the national security goal is twopronged: entities are interested in protecting their own assets while building knowledge of the location and intention of adversary assets.

Beyond threats, some of these countries' concerns have been driven by recent space events—natural and accidental, such as the February 2013 meteor explosion over Chelyabinsk, Russia, and the de-orbiting of Tiangong-1 in April 2018. China, for example, desires increasing information from improved national SSA and strategic early warning capacity.

Some representatives noted interest in strategic early warning capacity. For example, Japan is particularly aware of threats (e.g., ASAT, cyberattacks, jamming), and South Korea is interested in ISR for military due to threats from North Korea. Such precautions can help with safe operation and control as well. Space defense and countering orbiting systems require improved SSA in order to ensure the user can identify the correct targets and engage successfully. Analysts note that for some countries (e.g., China), improved SSA capabilities may be pursued in efforts to support space defense and counter-orbiting systems, as these capabilities ensure the user can identify the correct targets and engage successfully (Cheng 2015).

4. Desire for Self-Reliance

Given their dependence on space for critical national needs and societally critical endeavors, SSA is becoming important enough that some of the countries in our set of case studies want to establish SSA systems that are more independent, with the specific mission of tracking objects in space. Some countries are motivated to develop their own systems to be self-reliant. Others desire an independent system so they can be sure of the data collected and the processing applied, knowing that the information is not affected by another entity's bias, either intentional due to national security reasons, or accidental due to poor data collection and processing technology and methods.

Very few representatives articulated an aversion to using private SSA capabilities to buttress national systems, though most specified that utilization of private providers would supplement rather than replace government efforts. In fact, individuals from quite a few countries (e.g., Australia, South Korea) noted the great economic opportunity that involvement in SSA would offer domestic industry, citing this advantage as a reason for preferring domestic over international private providers. A representative from Australia specified that the country is unlikely to use a domestic commercial provider without approval from the U.S., given the importance of that relationship. A commercial representative from Canada specifically noted that government might find it useful for the private sector to build some of the infrastructure for SSA in a given country.

Some nations are looking to decrease their dependence on the U.S. SSA system due to concerns that it might be the target of an adversary attack. Other stakeholders felt such an attack is unlikely, given the global nature of SSA and the (at least current) widespread reliance on the U.S. system. Some (e.g., France) seek to be self-sufficient for reasons of national pride and sovereignty. Others see it as a means by which to provide leadership in the domain and collaborate with other nations. Many countries that are pursuing their own SSA systems explicitly intend to keep their systems interoperable with others internationally (e.g., Australia, Canada, , Japan, United Kingdom).

Information on whether a country is developing a fully autonomous system, why (e.g., national pride, distrust of U.S. system, dissatisfaction with U.S. system), and how (e.g., international collaboration, global placement of assets, purchasing and integration of commercial services) can guide efforts to both improve the U.S. system and foster collaboration.

5. A Means for International Cooperation/Collaboration

Some countries are pursuing SSA as a means to enable greater international cooperation and collaboration. They recognize that continued participation in the global space governance system may necessitate increased responsibility and have thus begun to contribute space data and assets (e.g., telescopes and radars formerly used for purposes other than SSA). For example, officials from both Poland and South Korea prioritize increased technical capabilities to allow for more data sharing opportunities with other friendly space powers; they note that having something to offer is integral to achieving strong relationships. Others (e.g., Chile, South Africa) see SSA as a way to contribute to international collaborations, using their strategic locations and capabilities as tools for cooperation in space, and on SSA specifically.

SSA can play a role in improving even established partnerships. For instance, Germany seeks technical prowess to better contribute, no longer interested in being a junior partner in the U.S. SSA enterprise. Others want to contribute to regional efforts such as the EU SST and the ESA SSA programs. Some nations see it as an opportunity to improve their relationships with the United States specifically (such as Canada and Australia); for them, interoperability of any capabilities and systems in itself is an important SSA goal. It is also an opportunity to contribute to defense relationships. Interviewees from some countries, including Canada and Australia, believe that their countries need to do more to contribute to the global SSA regime, specifically in support of the U.S. They see increased domestic technical capabilities as an opportunity for burden-sharing. Japan wants to create a system to quickly share images and other data with the U.S. and intends to strengthen SSA capabilities by improving existing partnerships and collaborating with other friendly nations.

Interestingly, official Chinese documents state that SSA is an opportunity to foster international collaborations, and growing their leadership in the domain. For example, the Beijing Institute of Tracking and Telecommunications Technology (BITTT) noted that cooperation in outer space safety is a common interest China shares with the U.S., and suggests that such efforts could enhance mutual trust and support space cooperation (BITTT 2017). Beyond strengthening communication and coordination with the U.S., the Institute also indicates Chinese interest in providing collision warning services for other countries that may need it. Although it is not emphasized in the open information from China, there is likely a national security motivation for Chinese SSA activities. Table 2-1 provides an overview of the rationales for doing SSA.

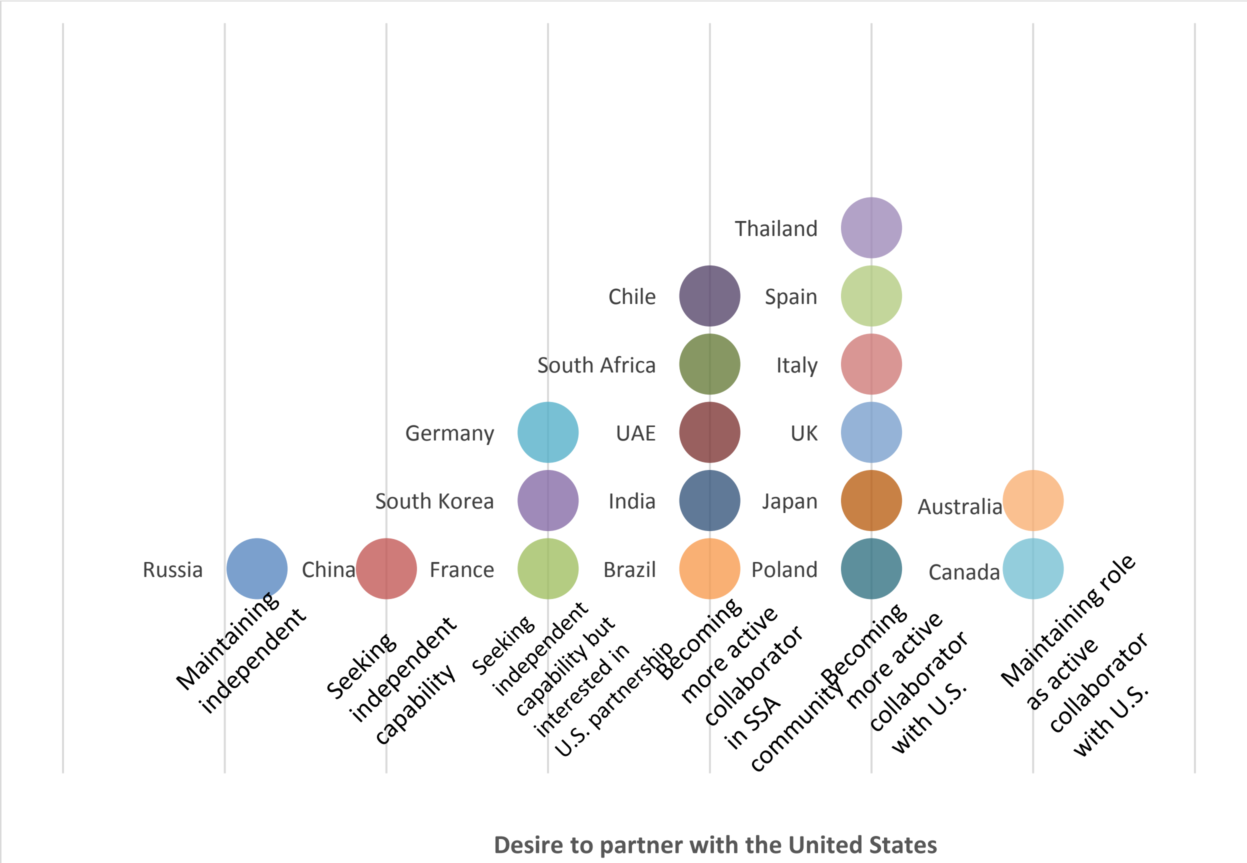

Table 2-1. Rationale for Engaging in SSA Activities

D. Changing Commercial Motivations

It is not just governments whose interest in securing their space assets is growing. The private sector has large equities in space: Space Services is a $127.7 billion sector, according to Satellite Industry Association 2017. As a result, private sector satellite operators have been involved in SSA, largely motivated by their business cases: lost space assets means lost revenue. Many private operators also want to be more responsible stewards of the space environment to ensure access to space in the future. There is now a growing presence of commercial providers of SSA services globally. In discussions, commercial providers specifically noted the need for SSA services that track more objects more accurately, with transparency of orbital information to protect both the SSA systems and the orbital environment in which they are tracking.

Additionally, operators and providers are becoming involved in conversations regarding standards of behavior and best practices in space; some commercial entities have suggested that industry groups are interested in working together to outline these guidelines in the sustained absence of government leadership on the issue. This could be partially due to concern that if they fail to help shape these discussions, they will be subject to the ensuing regulations without having had the opportunity to contribute and articulate the needs and concerns of industry. Some operators note that the international treaties governing space were developed over three decades ago, prior to the types of space assets (e.g., constellations) and uses that are currently expected, and thus emphasize the importance of updating those guidelines.

Although more operators are pursuing SSA services, both free through the DoD and paid through commercial providers (often, insurance companies require an operator to subscribe to some SSA service in order to receive coverage, though multiple interviewees asserted that insurance companies do not favor one provider over another), there may be a limit to this market from a provider's perspective. Currently, many operators of large and expensive GEO assets are willing to pay a premium for SSA services. However, as inexpensive small satellites and large constellations become increasingly common, the value of any individual asset decreases. For example, in many large constellations, the operators plan to replace a few of the satellites over the lifespan of the constellation. Thus, operators may be less willing to pay to track a less expensive, more easily replaceable satellite, limiting the potential customers of SSA products.

E. Growing Functional Modularization of the SSA System

The current dominant SSA "system" (comprising data collection, processing, and creation of products) is vertically integrated, in which the provider of SSA services, DoD, collects data, processes information, creates relevant SSA products, and communicates the information to users. Increasingly, however, technology developments, especially in IT, have enabled the system to be segmented in a way such that the functions can be handled in a more segmented or modularized way. As a result, different organizations can service each part. In other words, organizations collecting data do not need to process it; organizations processing the data into a catalog do not need to collect it; and organizations developing value-added SSA products do not need to collect the data or develop a catalog. Each of these steps can be serviced by different organizations, between which the information can be sold and purchased. This trend—that of a "functional modularization" of large complex systems that were previously integrated—has occurred in other sectors (e.g., computing, Earth Observation[15]), and is diffusing into the space sector (Lal et al. 2015).

With each segment in this functionally modularized system broken up and relatively independent, each step is also less expensive. This has allowed the private sector, including investors, to step in and fund each segment independently. This also allows for specialization: an organization, especially a commercial provider, can develop exquisite capabilities at just one step in the value chain and purchase from or collaborate with other groups that have complementary capabilities. This specialization can also help the quality of the overall system improve, as the lower cost reduces barriers to entry, allowing increased competition at each stage of the value chain. The decreased cost and the opportunity for focus at one step of the system has allowed for

[15] This sort of segmentation mirrors that which has occurred in the Earth Observation sector, where the companies collecting satellite-based data (Planet, BlackSky) are not the ones doing the data analytics (Orbital Insight, SpaceKnow).

increasing involvement from academia at individual steps—in both research and development—as well.

F. Implications

The current SSA system was designed at a time when a few assets managed by a limited number of operators were performing set activities using known technology. In the future, emerging changes in the space environment (e.g., growing number of objects, operators, and activities) as well as the increasing number of players, both from global governments and the private sector, necessitate changes in the way SSA will be conducted. The range of uncertainty around each object makes tracking more difficult in the DoD system, as satellite composition and structure change and new architectures require assets to remain closer together. As a result of growing global interest in participating in SSA, there is and will continue to be growing investment both in the private sector and globally to supplement and supplant U.S. Government data and services.

Countries are motivated to pursue SSA for a number of reasons—primarily national security and protection of space assets. However, many noted the opportunity to collaborate and share data with other nations, meaning future SSA systems will likely be more international and interoperable. Emerging international and commercial systems are generally more agile than the current DoD system, which is limited in the number of assets from which it can ingest information. Emerging SSA systems therefore will need to consider increased processing, more sensors, and higher quality tracking assets.

A greater number of stakeholders in the SSA system (increasing as a result of lower cost to entry), and especially the presence of the private sector, can create more innovation in the individual segments. It may also require more coordination and interoperability across segments of the system. Because of functional modularization, satellite owners and operators (especially governments) can subscribe to services that meet their specific needs.

3. Trends in Data Collection and Processing

The core component of the space traffic system described in the framework above is the analytic engine in which information is collected by a network of sensors, aggregated and fused through processing to create a database of the positions and trajectories of objects, and shared with users and operators of spacecraft. In this chapter, we discuss trends in this analytic engine, occasionally calling it SSA for the sake of brevity.

Before we begin with a discussion of trends, it is noteworthy that in discussions with international stakeholders, definitions of SSA generally included space surveillance and tracking, as per Chapter 1. Interestingly, most of the case study countries included near earth objects (NEO) and space weather in their definitions, as discussed in Appendix D.

A. Growing Capabilities in Data Collection: Growth in the Number of Sensors

Since 2010, the number of sensors of all types—primarily optical, but also radar, and active and passive Radio Frequency (RF) both ground- and space-based—being used for SSA has been growing.[16] The number of sensors will continue to increase in part due to investment from countries and companies to build new sensors, and in part due to countries and companies tasking existing sensors built for other purposes for SSA uses. The growing number of SSA sensors is motivated by a number of drivers: (1) desire to more actively participate in the international SSA community; (2) desire for increased self-reliance; (3) need for global sensor coverage; and (4) increased access to sensor technology, in part due to lowered costs.

1. Optical Sensors

a. Ground-Based Optical

The number of ground-based optical sensors used for GEO observation has been growing for the past decade with an increasing number of countries and companies operating them.[17] There are

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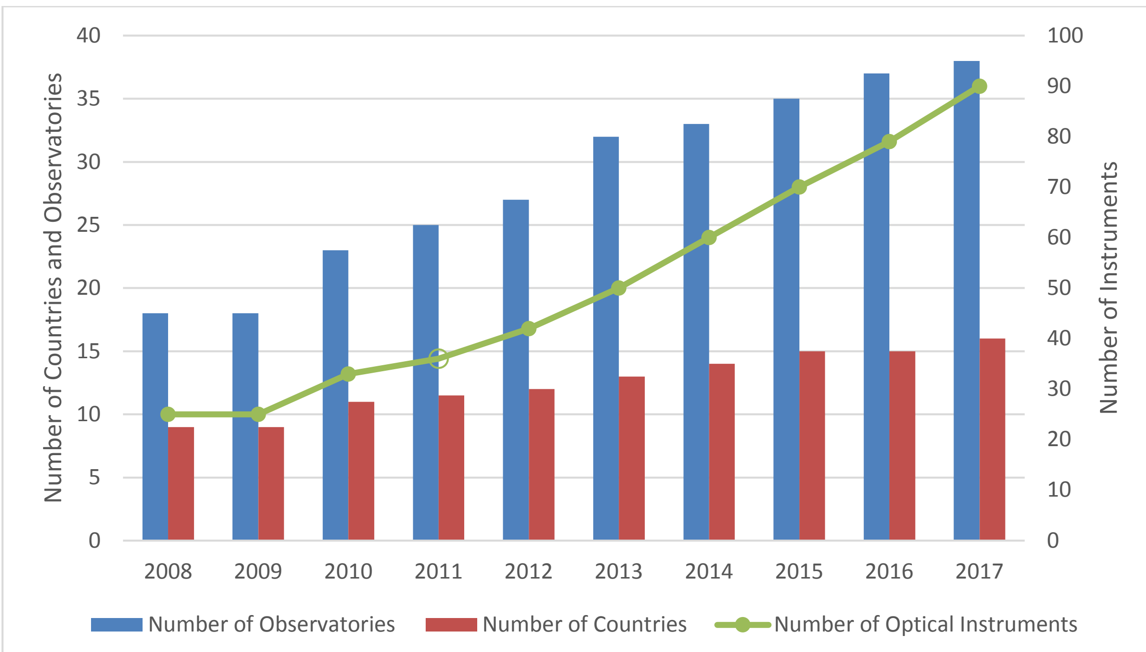
[16] On-board GPS sensors is not included in this report.

[17] The advantage of optical telescopes is they can view far distances (10-20 cm sized objects in GEO from a terrestrial telescope). Traditionally, SSA tracking has been done with radar, but they typically work best to view objects in LEO under 2,000 km. Above 5,000 km only very high powered, expensive radars are capable of tracking objects. The disadvantages of optical telescopes is that they only function in the darkness which limits when they can be used and are affected by weather and pollution. Scientific optical telescopes are typically placed at high altitudes where the air is thinner and freer from contaminates.

several examples of countries and companies installing optical sensors around the world. The increased geographic distribution of sensors is improving the global coverage of the SSA system and enabling greater persistence.

The Russia-based International Scientific Optical Network (ISON) for near-Earth space monitoring, coordinated by Keldysh Institute of Applied Mathematics (KIAM) of the Russian Academy of Sciences, has doubled the number of observation facilities, and has increased the number of instruments by 3.5 fold across the world since it started in 2008 (see Figure 3-1). ISON may have the second largest network of ground-based optical sensors after ExoAnalytics. This has grown two-fold in the last decade (Figure 3-2) and the number of measurements has grown over 200 times (Figure 3-3). Russia also operates additional electro-optical sensors through its Russian Space Surveillance System (RSSS), separate from ISON.[18] Additionally, Russia plans on expanding their sensor network.[19]

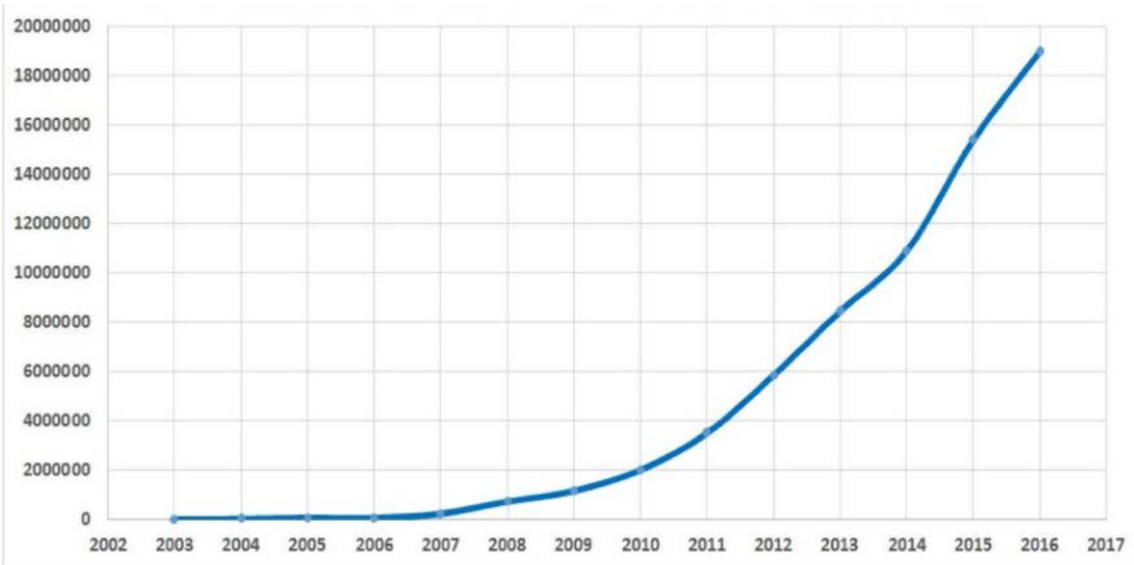


Source: UNCOPUOS 2017 Technical Presentation

Figure 3-1. Number of Countries, Observatories and Optical Instruments within the ISON Network over Time.

[18] "Russian Space Surveillance System (RSSS)." nd. *Global Security*. https://www.globalsecurity.org/space/world/russia/space-surveillance.htm

[19] Sputnik. 2016. "Russia to Deploy New Space Surveillance System Elements in Four Regions." *DEFENCETALK*, November 30, 2016. https://www.defencetalk.com/russia-to-deploy-new-space-surveillance-system-elements-in-four-regions-68624/



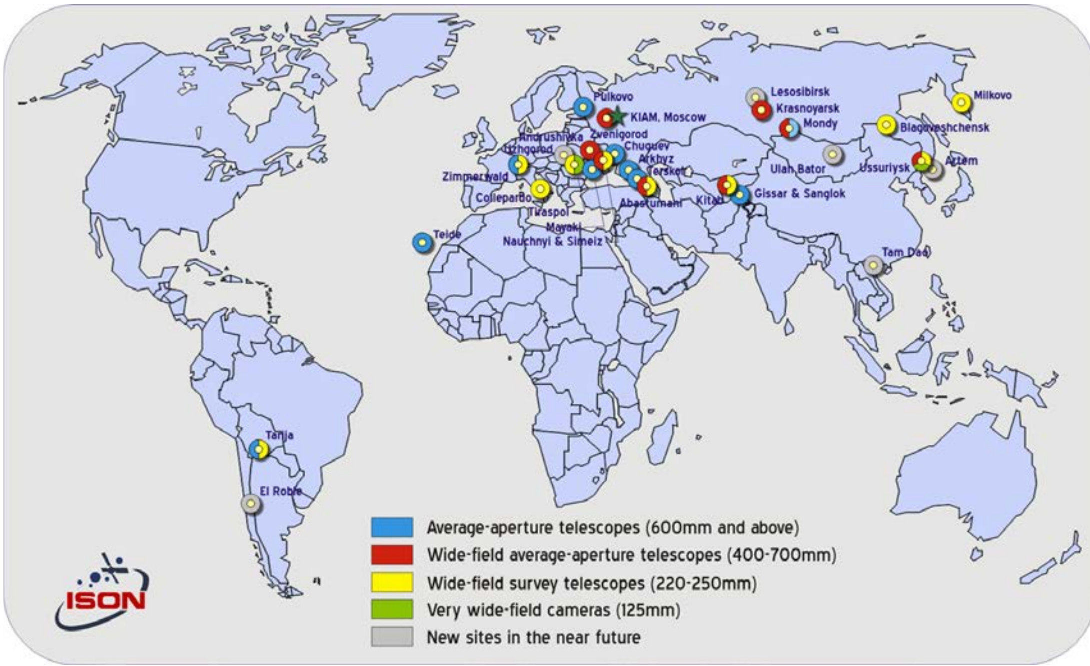
Source: UNCOPUOS 2017 Technical Presentation

Figure 3-2. ISON optical measurements over time, 2003 to 2016

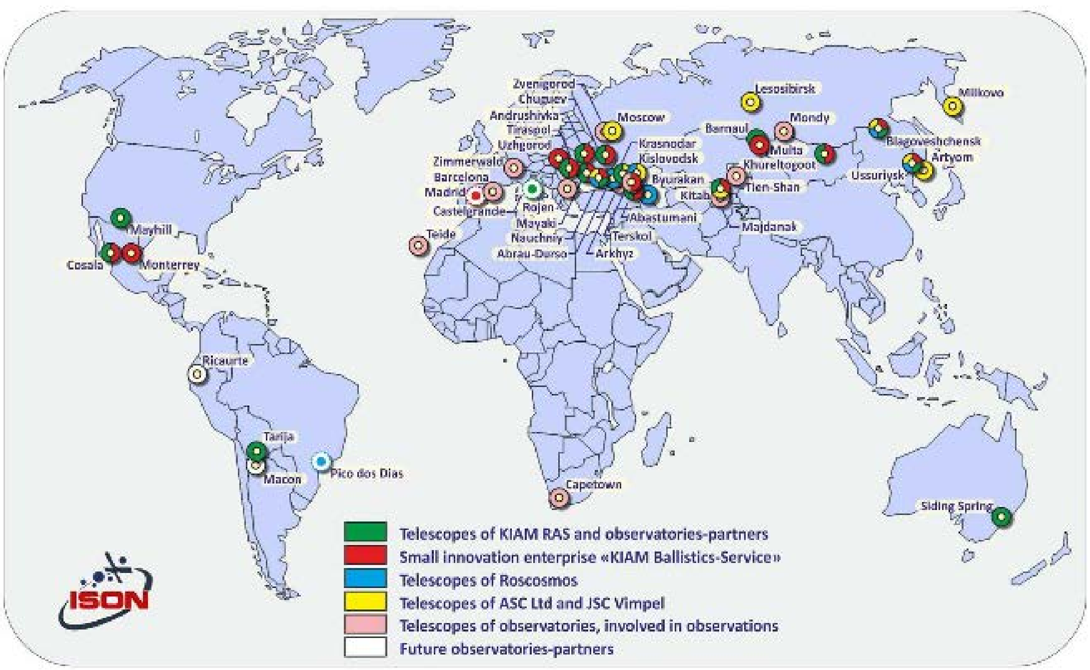
Less is known about China's sensor networks, but its Purple Mountain Observatory is operating telescopes in at least four locations, is associated with their space debris tracking efforts, and has tracking ships that can deploy to support specific missions such as new satellite launches (Weeden et al, 2010). China is also beginning to collaborate with countries around the world. They are using data from sensors both within China as well as in New Zealand and Spain. Additionally, they are working on building or planning on using optical sensors in Mexico, South Africa, and Chile (Section E below discusses China's APOSOS network).

Other countries such as Japan and Poland are beginning to consider optical sensors used for scientific and other purposes. Polish entities, for example, own almost 20 optical telescopes (mostly tracking, with 4 surveillance-capable) that form a world-wide network which can add an important information and thus – a value to the satellite securing activities.

The most interesting developments have been in the private sector. U.S.-based company, ExoAnalytics, with a global customer base, is distributing their network geographically, particularly in the southern hemisphere where there has traditionally been a dearth of sensors. By July 2017, ExoAnalytics had installed 169 optical ground based sensors at 23 different sites around the globe. The network has been growing rapidly. In Feb 2018, they had more than 200 telescopes at 24 sites. Their plans are to continue leasing sites and placing commercial off-the-shelf (COTS) telescopes in different parts of the world. Private companies in other countries have made progress as well. France-based ArianeGroup has installed (without support from the French government) GEOTracker, a network of six optical stations (two in France, two in Australia, one in Spain and one in Chile), which has coverage of the entire geostationary arc, and can detect objects in GEO down to one meter in size.



ISON map of observations, 2010



ISON map of observations, 2017

Source: UNCOPUOS 2010 and 2017 Technical Presentations

Figure 3-3. Map of Observatories that Send Data to KIAM, 2010 and 2017

Growth in SSA optical sensors is driven principally by the cost of optical telescopes and cameras with similar capability, which has decreased over time due to savings realized through

COTS telescopes (that are more strongly driven by Moore's Law) and optical sensor parts, particularly for optical sensors that have adequate capability, but are not exquisite. This cost savings enables governments and the private sector to purchase more optical sensors for the purpose of SSA.[20] Growth is also driven by need—better global coverage is needed to better view and track objects in GEO. An interesting recent development has been the repurposing of existing sensors previously used for astronomy and other scientific research. This proliferation of sensors is building resiliency, persistence, and redundancy in data collection in all orbit categories.

b. Space-Based Optical

Space-based optical systems have a few advantages over ground-based optical data collection in that challenges with time of day lighting are somewhat mitigated, and weather/atmospheric conditions are not an issue. Sensors in space are also more sensitive, and allow for the detection of dimmer objects including space debris. Space-based SSA assets are typically a single satellite or a constellation of satellites conducting SSA on space objects using optical sensors. Only a handful of government-owned and operated dedicated space-based SSA assets exist today, including the United States' Space-Based Space Surveillance (SBSS) and Canada's Sapphire satellite, which was launched in 2013. Going forward, several governments are planning on having their own space-based SSA capabilities. In our discussions, for example, we learned that Thailand is aiming to start a program to develop a satellite for LEO that would be used for SSA. If approved, the program would be funded at $30 million. Additionally, China has a strong desire to improve their SSA and strategic early missile warning capacity; by some indications they intend to use space-based sensors for SSA in addition to early missile warning.[21]

The private sector is actively looking into building networks of space-based sensors or adding SSA sensors to planned constellations. Several companies that have plans for space-based operations expect to leverage their capabilities to collect SSA data. An example is U.S.-based remote sensing provider Planet. The scale of Planet (200+ satellites) requires automation of operations for scheduling satellite and ground-station activities, imaging, and fault detection. Only a small team of operators spend their time monitoring these automated operations, running experiments, or troubleshooting new issues.[22] With future Planet Doves including onboard SSA sensors, Planet (and other companies such as SpaceX/LEO and Chandah Space Technologies/GEO) could emerge as the next generation of SSA vendors. Other companies that

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[20] Stahl et. al. has developed a parametric cost model for ground and space based telescopes and estimates cost of telescopes are reduced by 50 percent every 20 years mainly due to improvements in the technology and manufacturing processes (Stahl et al, 2016). Furthermore, he estimates that space telescopes cost 50 to 100 times more than ground based telescopes.

[21] Dean Cheng, Testimony before U.S.–China Economic and Security Review Commission on February 18, 2015, https://www.heritage.org/testimony/the-plas-interest-space-dominance

[22] Nicolls, M. 2017. "Conjunction Assessment For Commercial Satellite Constellations Using Commercial Radar Data Sources." LeoLabs and Planet Labs.

plan to remove debris would include onboard sensors, and can likely collect SSA data if needed. These companies include Effective Solutions/Israel, D-Orbit/Italy, and Astroscale/Japan. As these plans come to fruition, the amount of data and accuracy of data collected from space-based sensors will increase.

2. Radar Sensors

a. Ground-based Radar

The advantage of radar systems for SSA is that they can actively measure the distance, the speed of a target, and are not adversely affected by weather. [23] In some cases, radars can be very good at tracking several objects at one time. Radar is best suited for object tracking in LEO, but some very high powered radars are capable of tracking objects beyond LEO.

While the United States has the most extensive radar network in the world, other governments are increasing their investment in radar systems for SSA, and also expanding the use of existing radar systems developed for other purposes such as scientific research and missile defense.

Though dedicated radar systems for SSA are costly, especially when recurring operating costs are included, and their costs do not appear to be decreasing, some governments are nonetheless increasing their investments in radar. Several governments have announced new or repurposed radars for SSA. For example, Japan's Aerospace Exploration Agency (JAXA) announced in January 2018 that it was developing a radar capable of detecting space micro-debris of about 10 centimeters (3.9 inches).[24] Its current system is only capable of detecting debris of over 150 centimeters. Japan's Defense Ministry is also preparing to construct another radar capable of detecting the space debris in GEO. Grande Reseau Adapte à la Veille Spatiale (GRAVES) radar, owned by the French military, and the German Tracking and Imaging Radar (TIRA) system are examples of government-owned radar used for space surveillance tracking and orbital debris. Other countries, like India, recently constructed a Multi-Object Tracking Radar (MOTR) for use in both missile defense and space debris tracking. India also relies on MOTR for conjunction assessments during their launches—an important aspect of India's space program. India also has a long-range tracking radar that is part of their Ballistic Missile Defense capability and has potential to be used for SSA (Schroegl 2018).

Governments are also leveraging existing radar already built for other purposes such as science or missile defense for SSA use. Russia uses its extensive radar system put in place during

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[23] A radar system transmits electromagnetic waves and analyzes energy reflected back to it by a target. A receiver measures the waves and is able to locate the target relative to the location of the radar. Phased array radars scan large areas very quickly tracking multiple objects at once as the radar energy is steered electronically, not mechanically. Conventional radars have tracking antennas that move and can follow a satellite's location.

[24] "New Japanese Radar to Spot Small Space Debris." 2018. *The Japan News*, January 8. 2018. https://www.lmtonline.com/news/article/New-Japanese-radar-to-spot-small-space-debris-12481300.php

the Cold War for missile warning and missile defense to track objects in LEO. The UK and Norway operate radar systems that are part of the U.S. Space Surveillance Network (SSN).

Radar facilities developed for scientific purposes are increasingly being considered for SSA. For example, European Incoherent Scatter Scientific Association (EISCAT) is an international organization funded and operated by research councils from Norway, Sweden, Finland, Japan, China and the UK. It was established in 1975 "to conduct research on the lower, middle and upper atmosphere and ionosphere using the incoherent scatter radar technique" and has radars located in Finland, Sweden and Norway.[25] The system is being upgraded with new radar technology, called EISCAT 3D, and will contribute to atmospheric monitoring, polar aircraft communications, meteor trail decay and space debris tracking. [26]

Given the high construction and operations and maintenance costs of radar systems, there are few commercial vendors offering radar, unlike the ground-based optical sensors. One U.S.-based company, LeoLabs, plans to build a network of private radars. At present they have two radar systems: repurposed science radar in Alaska and a new radar system in Texas. LeoLabs is not focusing on building exquisite capability for all orbit regimes—they focus solely on LEO. Instead, their approach is to use existing technology, expand their network, and use advanced software to process the data. They plan to install four more radars near the Poles and the Equator by the end of 2019.[27] The new radars will be aiming to track smaller debris—down to 2cm in LEO. The cost of LeoLabs technology has been said to be orders of magnitude lower than traditional radar system. One reason for this cost reduction is that they are dedicated SSA systems intended to be provide adequate detection, and not meant for other purposes such as missile defense or missile warning. Because the quality of information and coverage of orbits increases with the increase in the number of locations of radar facilities, their goal is to get as much data from as many locations as possible.

Commercial capabilities are already demonstrating value. For example, in March 2018, a U.S. company was denied a spectrum license because of concerns that they could not be tracked by DoD sensors due to their small size (about the fourth of a cubesat), and were therefore a collision risk. However, the satellites were acquired by LeoLab sensors "almost immediately after launch" and are being spotted once or twice a day—a frequency sufficient to plot their orbits for collision avoidance.[28]

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[25] EISCAT Scientific Association. 2018. "About EISCAT." Accessed April 1, 2018. https://www.eiscat.se/about/

[26] Vollertsen, Arne. 2016. "EISCAT 3D—the Biggest Nordic Capacity Challenge Yet." *NORDUnet*, June 24, 2016. https://www.nordu.net/article/eiscat-3d-%E2%80%93-biggest-nordic-capacity-challenge-yet

[27] Nicholls,M. 2017. Conjunction Assessment for Commercial Satellite Constellations Using Commercial Radar Data Sources, Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), Sept 2017.

[28] Harris, Mark. 2018. "FCC Accuses Stealthy Startup of Launching Rogue Satellites." *IEEE Spectrum*, March 9, 2018. https://spectrum.ieee.org/tech-talk/aerospace/satellites/fcc-accuses-stealthy-startup-of-launching-rogue-satellites

b. Space-based radar

At present, there is little to no focus on using space-based radar for SSA. However, space-based radar capabilities exist for other purposes, and in the future could be used for SSA purposes. Outside of the United States, countries such as China, Russia, and Germany have active military radar satellites, and other countries, such as Italy, have Earth observation radar satellites that could be used for SSA. On the commercial front, the U.S.-based company XpressSAR is looking to use a synthetic aperture radar (SAR) satellite in an equatorial orbit in LEO, and would be able to collect SSA data (including imaging space-based objects). They have indicated that foreign governments such as Israel, the UK, France, Germany, and Australia have expressed interest in their services. Thus far, the company has raised $360 million in private funding.

3. RF Sensors

RF Sensors can track satellites transmitting signals, but cannot identify or track objects that do not transmit a signal such as debris, dead systems, and passive cubesats without signals. Unlike optical sensors, and like radar, RF sensors are weather-independent. However, they work only with cooperative systems (i.e., active satellites) that emit RF waves. There is growing interest and associated activity in using existing ground-based RF sensors and radars, as well as new space-based SSA sensors for SSA observation and tracking. Historically, RF has not been widely used or established for SSA, however, going forward as the need for higher quality SSA increases, RF capabilities might be pressed into service.

a. Ground-Based RF

Traditionally used for telemetry, tracking and command (TTC), ground-based RF systems are being repurposed for alternative uses, in particular SSA. For example, Italy, Sweden, South Africa, and Australia have vast arrays of RF sensors, and are looking to take advantage for SSA tracking. China also has a TTC system that operates in the S band, relying on three Chinese ground stations and ground stations in Namibia, Pakistan and a fleet of maritime satellite tracking and control stations (Schroegl 2018). In the university and non-profit sector, there has also been some exploration of using upcoming Square Kilometre Array (SKA) in Australia, New Zealand and South Africa for SSA. SKA has 10 member countries—Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands and the United Kingdom (the United States is not an institutional member).[29] The main purpose of the Murchinson Widefield Array (part of SKA) in Australia is astrophysics and space weather; however in 2015, a research group was said to be exploring the option to also use it for passive RF detection.[30]

[29] Square Kilometre Array. 2018. "Participating Countries." https://www.skatelescope.org/participating-countries/

[30] Bessell, T. Australian Space Situational Awareness Capability Demonstrations. 2017, Amos Conference.

There is growth in the commercial sector as well. Expecting demand for international and commercial SSA, RF companies are planning to expand their footprint to include provision of SSA services. For example, in 2016, U.S.-based Kratos began expanding their existing RF infrastructure, adding seven new worldwide monitoring sites that would host more than 60 antennas.[31] By 2018, they have 13 sites with 80 sensors worldwide. By taking advantage of their existing global network, Kratos is repurposing their existing RF sensors, adding more RF sensors and building analytical capacity to provide SSA monitoring for active satellites.[32] In Europe, companies such as Zodiac GmbH and Siemens AG are similarly looking to use their RF networks for SSA tracking.

b. Space-Based RF

Outside the U.S. Government, few countries have space-based RF systems, but in the future, this could be an area of growth, especially if smallsat constellations become a reality. With space-based RF, commercial companies are beginning to take a lead, and looking for international customers. U.S-based HawkEye 360 and Chandah Space Technologies are planning on placing RF sensors onboard their constellations. HawkEye 360 is a developing a network for global intelligence based on RF signals. They seek to operate their own smallsat constellation and in May 2017, signed a Memorandum of Understanding with Kratos to link their space-based and ground-based RF capabilities. Orbital ATK, with support from the U.S. Air Force, developed a project using GSSAP satellites in sub-GEO orbits that contained RF sensors to characterize GEO orbits using radio emissions from satellites. While these space-based SSA services are still being realized, it is a feasible that coming years may provide a stronger commercial business case to do so.

4. Laser Ranging

Satellite Laser Ranging (SLR) is an emerging technology in managing and mitigating orbital debris, and is an area of R&D for SSA. Laser sensors use light reflection on LEO satellites to compute their distance and speed. It was initially used to measure Earth's gravity through orbiting reflectors, but the technique has been applied to determining the range and speed of orbiting objects in LEO. Germany's space agency DLR, has an R&D effort underway to develop lasers for detecting orbital debris. ESA's Space Debris Office, along with other partners, is also exploring

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31 Kratos Defense and Security Solutions, Inc. 2016. "Kratos Awarded $6.2 Million Contract Modification to Expand Global Satellite RF Interference Monitoring for U.S. DoD." https://globenewswire.com/news-release/2016/10/24/881974/0/en/Kratos-Awarded-6-2-Million-Contract-Modification-to-Expand-Global-Satellite-RF-Interference-Monitoring-For-U-S-Department-of-Defense.html

32 Another US-based company Rincon owns exquisite RF capabilities and can improve the standard conventional capability as Geostationary Orbit maneuver determination occurs in a matter of minutes as opposed to hours to days. With the RRC current site, the company claims that can get an accuracy of 10 meters within one day of tracking a satellite. However it is unclear if Rincon would be providing its services globally.

laser ranging initiatives by combining optical sensor data with laser ranging observations to form hybrid observations.[33] Their research goal is to demonstrate that laser ranging techniques can contribute to observing and tracking space debris in LEO.

On the commercial side, Electro Optic Systems (EOS), an Australian defense contractor, is developing and testing a ground-based laser to track and alter the orbits of space debris to avoid collisions.[34] The work is still in the R&D phase, and they plan to start with tracking and then increase the laser's power to nudge debris.[35] Though laser ranging for SSA appears to be nascent, there appears to be growing interest in adopting and exploiting the capabilities to track and remove space debris.

B. Growing Capabilities in Data Collection: Increasingly More Capable Sensors

It is not just the number of sensors that is increasing. The sensors are increasingly more capable—at comparable costs—and R&D is underway to make them more versatile and useful (e.g., optical sensors to track assets in LEO). Our discussions also found that the quality of SSA would improve not only because of improved technology in sensors, but also because of an evolving philosophy.

1. Sensors Becoming Increasingly More Capable

With the right sensor hardware and data processing capabilities, optical sensors are already able to achieve an accuracy of about 1 arcsecond (Torres J., 2017).[36] Capability in the commercial sector is notable. ExoAnalytics, for example, indicated they have optical sensors with that can achieve an accuracy of about 0.1 to 0.25 arcseconds in GEO. As compared with the U.S. Ground Based Electro-Optical Deep Space Surveillance (GEODSS), the accuracy of the ExoAnalytics sensors are 4–10 times greater for tracking objects in GEO.[37] Additionally, ExoAnalytics has eight times as many sites at GEODSS and 20–30 times more telescopes. LeoLabs has indicated that its radars can currently track 10 cm sized debris in LEO, and that their next generation of radars will

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33 Jilete, B., et al. 2015. "Laser ranging initiatives at ESA in support of operational needs and space surveillance and tracking." Laser 3 (2015): 001. https://cddis.nasa.gov/2015_Technical_Workshop/docs/papers/3.1_Flohrer_paper.pdf

34 Lackey, Brett. 2018. "Australian Military Defence Contractor Develops Laser Powerful Enough to Take Out Space Junk Hurtling Towards Earth." *Daily Mail Australia*, March 21, 2018. http://www.dailymail.co.uk/news/article-5527033/Australian-scientists-plan-use-lasers-shoot-space-junk.html

35 Grimm, Nick. 2018. "Scientists Plan to Use High Powered Lasers to Track and Shoot Away Space Junk." *ABC News Australia*, March 22, 2018. http://mobile.abc.net.au/news/2018-03-21/scientists-plan-to-shoot-down-space-junk-with-a-laser/9573066?pfmredir=sm

36 1 arcsecond accuracy translates to about 170m accuracy in Geosynchronous Orbit

37 For comparable capability of latency and sensitivity, Exo described that their cost per observation is nearly 100 ($21.92/$0.20) to 500 ($24.32/$0.05) times less expensive than observations by the US government.

be able to detect 2 cm sized debris. LeoLabs currently tracks 13,000 objects, and is aiming to track 250,000 objects.

Companies are incorporating sensor capabilities with algorithmic improvements. U.S.-based Analytical Graphics Inc. (AGI) indicated that their maneuver processing can detect 0.5 mm delta-v maneuvers with their algorithms.

The growth in SSA data collection systems is mostly in optical systems that are most suitable for making observations of objects in the GEO belt, yet the projected growth in satellites and systems is in LEO. RF sensors and laser ranging work effectively in LEO, but are still nascent technologies for SSA tracking. Recognizing this gap, some private and nonprofit organizations are looking into new ways to harness the growing amount of optical sensing data for LEO tracking. Companies including AGI, ExoAnalytics, and others are attempting both software and hardware approaches to aggregate data from both ground- and space-based optical sensors. With ample data and very capable software techniques, they are finding ways to spot LEO objects with optical sensors.

Another promising R&D effort is the development of new imaging devices termed event-based sensors. Artificial vision systems are increasingly using such sensors, which are informed by biological retina and computation used by the brain in the human vision system (Cohen, 2017). The traditional approach to imaging is to employ CCD-based sensors that produce discrete frames at a regular time interval from which the light intensity of each pixel is measured. Each frame from the conventional CCD device contains redundant information. In contrast, the pixels in the an event-based sensor operate independently and asynchronously from one another, therefore disregarding the need for exposure times and shutter speeds used in traditional cameras. These devices operate continuously, and produce images with a high temporal resolution. Such sensors have demonstrated the ability to observe RSOs from LEO to GEO during both nighttime and daytime offering much greater capability for ground-based optical sensors. While this technology is still in its R&D phase, preliminary testing has yielded promising results, and it is feasible that in 10 to 15 years, it will transition into the operational SSA domain.

Additionally, RF providers such as Kratos, currently using their network for GEO and MEO tracking, are looking to develop a LEO product by combining sensor placement with software. The academic astrodynamics community is also working on how to calculate orbits for objects using optical data.

This is an area to watch because when it becomes feasible to use optical telescopes and RF sensors to track LEO traffic, it will rapidly grow LEO tracking capabilities around the world (currently a key U.S. advantage).

2. An Emerging New Paradigm

There is growing recognition that the entry point for SSA need not be based on exquisite and expensive technology. Having several, geographically distributed, even lower-quality ground-based optical sensors can enable the development of an effective sensor network for certain missions that rivals the USG network. Having a distributed network with many lower quality sensors can not only provide adequate SSA capability, but also help augment sensors affected by weather impact, and offer redundancy in the system that helps if a sensor fails.

Using this emerging paradigm, space-based objects can be detected more frequently, enabling more effective and timely tracking. The ISON network, with 38 locations and nearly 90 optical sensors, already provides a useful example of how the paradigm might work in the future. While not as good, it has more optical sensors than the radar and optical sensors in the USG network, combined. Companies such as the Spain-based GMV purchase data from networks such as ISON, and fuse it with data from other sources to create value-added SSA products as part of a profitable business model.

C. Growing Capabilities in SSA Software: Growing Number of Software for Data Processing

SSA software refers to the software needed to task a sensor, receive information about the sensor and other associated metadata, fuse the data, and ultimately generate SSA products. SSA products refer to catalog of objects, reentry estimates, ephemerides, orbital determination and orbital determination products such as covariance and position, probability of collision (P_c) at closest approach, conjunction assessment, conjunction assessment risk analysis, covariance, and collision avoidance, among others. In this section, we focus on trends related to growth in the number and diversity of software/algorithms for processing data, and creating value-added SSA products.

1. Developing Independent Software Capabilities

While data is increasingly being shared—via informal sharing as well as formal country-level data sharing agreements—most countries are not openly sharing software/algorithms, including the United States. While the U.S. Government provides free SSA services to the world (see Appendix A), it does not share its SSA models or provide insights into how SSA products are developed. There is growing desire for more flexibility and transparency into the processing systems, and ultimately the SSA products, which is driving the development of software capabilities outside the United States. This development is both through indigenous activity and/or purchase of software from commercial entities.

There are countries that are just entering the SSA realm that rely heavily on DoD data, and are doing some internal processing to better understand some of the SSA products they may be receiving from the DoD. Today, countries and companies are usually either providing a valuable or a "middleman" service, using their own software to interpret information from the other entities' SSA products (often DoD); or seeking to develop or purchase independent software capabilities that allow them to develop their own data products. For example, UAE has a data sharing agreement with the DoD and is looking to incorporate their own O/O data using some basic processing capability to better understand SSA for their own satellites. Similarly, India relies on spacetrack.org data and incorporates their own sensors to determine conjunctions for launches.

a. Growing demand and availability of value-add services

Countries are increasingly developing software that adds value to products already available with the goal to eventually generate their own SSA products. ESA, some European countries and Japan are among those developing software that is more beneficial than what they receive from the DoD. ESA is developing software technology including correlations, collision assessment algorithms, and software to turn sensor data into a database object. Japan, France, Germany, and Spain are also working on developing in-house software capabilities, but rely on DoD data.

France receives data from multiple sources (such as CDMs from DoD and from their national catalog Almanac, which contains data from the French radar sensor GRAVES). They take these inputs, in addition to inputs from satellite Owner/Operators (O/Os), and feed them into their "middleman" service called the Conjunction Analysis and Evaluation Service, Alerts, and Recommendations (CAESAR) that can autonomously take into account most of the maneuvers of the satellites for which they deliver CAs. The French also offer Java for Assessment of Conjunctions (JAC) which contributes to the collaborative work environment for CAESAR. JAC addresses the needs of teams responsible for managing in-orbit collision risks for one or many satellites. JAC helps to retrieve and analyze close approach alerts by providing a synthetic vision of each close approach described by CDMs. It helps the user to evaluate the level of risk according to its own criteria and to take and validate a decision.[38]

Similarly, in Germany, DLR's Institute for Simulation and Software Technology is working on a software framework for distributed computing for the Backbone Catalog of Relational Debris Information (BACARDI) project using high performance computer (HPC) technology. BACARDI is the informational system used to process the data generated by the sensors. In Japan, JAXA is able to do database compilation of orbits, approach analysis, conjunction assessments, and reentry analysis via TLEs, 60 day_msg, and TIP_msg from DoD.

Software development to provide value-added services is a growing area in the private sector as well. SpaceNav, a U.S.-based firm, has developed software and algorithms providing subject matter expertise to LEO and GEO satellite operators, including U.S. Government customers such as NASA and NOAA. SpaceNav's Web-based Space Situational Awareness (WSSA) software automatically processes DoD flight safety data with satellite O/O ephemerides and other data daily, if not more frequently. CS Communication and Systems in France offers software solutions for a range of space sector applications including command and control, flight dynamics and onboard

[38] France offers different versions of the software: JAC Basic (support for CA) and JAC Expert (relying for CA). JAC Expert is used by several nations including Canada, the United States, Malaysia, and the UK. Additionally, users for JAC Basic include: Canada, Japan, France, the United States, Malaysia, South Korea, Indonesia, Germany, Spain, Luxemburg, Taiwan, Brazil, Qatar, the UK, Monaco, and Israel.

satellite software. They have adapted their flight dynamics software to developing algorithms to support SSA, which is now being used by the French government. They have a unique model as their product is open source (similar to U.S.-based GMAC).

AGI and ExoAnalytics are among those that have independent software capabilities with no reliance on DoD data. AGI's software applications allow entities to take in data, whether from their own sensors or from others, and model the space environment. They offer the System Tool Kit (STK) "providing four-dimensional modeling, simulation, and analysis of objects from land, sea, air, and space in order to evaluate system performance in real or simulated-time."[39] AGI also offers other software packages that provide analysis support to O/O for decision making.

Some countries who are seeking more autonomy and independent capabilities are not developing SSA software in-house, but are purchasing software from the private sector. For example, Japan recently purchased AGI software to process their own observations along with the data they receive from the DoD and other partners. Thailand is also implementing AGI's STK software into their system.

2. Growing Customizability

There is growing demand for more customized SSA products and services. Interviewees at the country-level indicated that they found DoD products to be one-size-fits-all products, in which they can neither obtain nor offer input as to how the SSA products are generated, nor how and when they receive SSA products. Commercial providers are filling this gap in the market by offering customizable products and products that facilitate decision making. This trend is likely to strengthen as demand increases.

In terms of customizability, the private sector is leading the way, and likely to continue. For example, LeoLabs offers the ability for satellite O/Os to prioritize satellites and set parameters, such as when they would like to be notified of a close approach based on distance from nearest satellite. Lockheed Martin uses different algorithms to customize analysis when preparing SSA reports for each of their customers. For data collection, ExoAnalytics does custom tasking of their sensors. For example, they will work with customers to do custom tracking on a secondary object when the customers get a conjunction warning. AGI also offers customizable products as a service for its customers. France's CS Communications and Systems offers open source software Orekit for SSA solutions, and has acquired more users as a result. They use their open source software as a building block (the "core") for custom built software (e.g., for the Canada's defense community).

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[39] https://www.agi.com/products/engineering-tools

3. Growing Number of Countries and the Commercial Providers Developing Catalogs

Due to perceptions related to lack of transparency with DoD data, and motivated by the desire for increasing self-reliance, some countries and companies either by themselves or through consortia are developing their own SSA catalogs.[40] The United States has the largest public catalog with over 23,000 space objects.[41, 42] Russia, having the second-largest network of sensors, has a relatively complete catalog of space objects larger than 10cm as well.[43] Aside from the catalog that leverages Russia's Space Surveillance System (SSS), the Russian-led ISON partnership also maintains a catalog of objects, primarily in GEO, using data from its sensor network. This catalog maintains orbits for 5545 space objects (2277 in GEO, 2926 in HEO, and 342 in MEO). Additionally, ISON offers catalog services for the Vympel Corporation,[44] and at least one other company outside Russia has indicated that they have also purchased information from the ISON catalog.

In Europe, the French military with Centre National d'Etudes Spatiales (CNES) maintains their own catalog, separate from the United States, though it contains information received from DoD fused with data collected in-house. In addition, Germany has a catalog that aggregates data from open sources, international cooperation (e.g., USSTRATCOM), civil organizations (e.g. ESOC), domestic sensors, military intelligence,[45] and space weather reports. The Chinese probably have a catalog as well, though we have no specific information on its quality. In tracking the recent Tiangong-1 entry, Chinese predictions were the most precise, which may be an indicator of their orbit propagation capability (or perhaps just better tracking).

On the commercial side, the Space Data Association (SDA) maintains the Space Data Center (SDC) through the AGI-run ComSpOC.[46] SDC utilizes the ComSpOC commercial catalog, which has been expanding the number of objects it can detect and track over time. The aim for the next version of the SDC (SDC2.0) is to include RSOs 20 cm and larger in the GEO arc.[47] Another stated

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40 A catalog is a fused product providing locations of satellites and debris. Information from the satellite catalog allows the performance of predictive orbital analysis to anticipate conjunctions and other threats to satellites.

41 SWF Space Situational Awareness Fact Sheet. https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf

42 "18 SPCS CONOPS and Year in Review." *18th Space Control Squadron.* https://advancedssa.com/assets/img/workshop/presentations/JSpOC-18SPCS_CONOPS.pdf

43 SWF Space Situational Awareness Fact Sheet. https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf

44 SWF Space Situational Awareness Fact Sheet. https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf

45 Na. 2011. "German Space Situational Awareness Centre." *Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee*

46 SDA is a non-profit association of civil, commercial and military spacecraft operators that "supports the controlled, reliable and efficient sharing of data that is critical to the safety and integrity of satellite operations."

47 Oltrogge, D. 2017. "The Commercial Space Operations Center (ComSpOC)." ITU Satellite Communication Symposium 2017, Bariloche, Argentina.

goal is to maintain a high accuracy catalog of 100,000 or more objects by 2019.[48] LeoLabs collects their own radar data, and uses calibration constants to fuse it with other data streams and creates their own catalog of objects in LEO.

D. Growing Capabilities in SSA Software: Better Software

Through tools that enable data fusion, faster processing, automation and other techniques, SSA software is increasingly more capable.

1. Data Fusion

There is recognition that global coverage is needed for robust SSA products. The trend toward fusing data from multiple data sources (not just optical-optical, but also optical-RF, optical-radar, and other) will likely grow in the coming years as more countries and companies independently collect and share data, and as SSA consortia continue to emerge and mature. Countries through partnerships, the private sector, and/or non-profit or regional consortia are able to develop more robust catalogs of RSOs with rich, phenomenologically diverse information. However, fusing data is not trivial; it requires curating data sources that could include having information on the sensors from which the data came, and validating the data and/or sensors.

Some commercial entities have dedicated operations centers that have the ability to fuse data from multiple sources.[49] For example, AGI's COMSpOC, through its contract to manage SDA, is able to intake and fuse data from SDA members to be used for SSA products.[50] COMSpOC's reported capabilities indicate that they can fuse satellite-tracking measurements from over forty sensors.[51] Lockheed Martin is developing software to take traditional and non-traditional sources of RSO data and fuse them together. This technology is aiming to take higher volumes of SSA data from multiple sources, in addition to doing validation and fusion.

The power of data fusion was demonstrated after a debris-causing event in 2016. In the days following Digital Globe's World View-2 satellite breakup, Applied Defense Solutions (ADS), LeoLabs, University of Arizona's Space Object Behavioral Sciences program and other partners collaborated to perform orbital determination and characterization on the debris.[52] Their analysis

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48 AGI. 2014. "2014 Status Report of AGI's Commercial Space Operations Center and other AGI SSA Initiatives." https://www.agi.com/resources/white-papers

49 Weeden, Brian. 2017. "Space Situational Awareness Fact Sheet." *Secure World Foundation*. https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf

50 Swarts, Phillip. 2017. "Space Data Assn., AGI Working to Improve Commercial Space Traffic Center." *Spacenews*, March 10, 2017. http://spacenews.com/space-data-association-agi-working-to-improve-commercial-space-traffic-center/

51 STPI Global Trends Report Vol 2, Oltrogge 2015.

52 Kubancik, Thomas. 2016. "Commercial SSA and the Case for Collaboration." *Spacenews Magazine*, September 12, 2016. http://www.spacenewsmag.com/commentary/commercial-ssa-and-the-case-for-collaboration/

relied on fusing radar and optical data from less expensive and more autonomous systems than what DoD provides, thus demonstrating the capabilities of using data from many sensors paired with good processing. This kind of activity is likely to further improve the quality of SSA.

There are research programs conducted by agencies within the United States (e.g., DARPA) that are developing software for a testbed of tools to fuse multiple data sources and simulate potential actions. Should these breakthrough capabilities be put into operations (as is likely to be the case in commercial operations), the time required to provide accurate, timely and relevant information would continue to decrease.

2. Other Improvements in Data Processing

Advances in computing have led to improvements in SSA performance while decreasing in cost. The speed and quality of SSA data processing is increasing as a result of increased use of automation, machine learning, and other artificial intelligence (AI) techniques, as well as the availability of low-cost and secure cloud storage (advances that have occurred in sectors outside space). Processing power is required both in processing data into a combined catalog and in analyzing the data to develop SSA products such as CDMs. For example, LeoLabs manages its radars remotely. Currently, the data collected will feed automatically into a cloud-based platform at which point it will be processed, and data products will be distributed to its customers. As the network of observations grows and adds redundancy, the cloud-based platform will scale accordingly.[53,54] As databases grow with an increased number of objects to track and increased number of observations, companies and countries are looking at automation and machine learning to make timely assessments. Similarly, the SDA's Space Data Center is a cloud-centric service that is also managed remotely.

Leveraging automation and taking humans out of the loop decreases workforce burden while potentially increasing the timeliness of processing data and delivering SSA products to end users.[55] Currently, DoD invests resources to perform high accuracy catalog screenings in deep space every 24 hours, and near-Earth every 8 hours. For ephemerides, high-interest screenings are performed on demand, deep space routines every 12 hours, and near-Earth routines every 8 hours.[56] In contrast, other entities, particularly those in the private sector, have discussed their ability to process data more effectively and efficiently. For example, an interviewee described how their sensors can close and reopen with inclement weather, allowing them to optimize their data

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[53] Werner, Debra. 2017. "Satellite-tracking Firm LeoLabs Opens for Business with $4 Million Banked." *Spacenews*, February 27, 2017. http://spacenews.com/satellite-tracking-firm-leolabs-opens-for-business-with-4-million-banked/

[54] United Nations, The. "Space Situational Awareness." Space Safety and Sustainability Working Group.

[55] "Space Situational Awareness: It's Not Just About the Algorithms."

[56] "18 SPCS CONOPS and Year in Review." *18th Space Control Squadron.* https://advancedssa.com/assets/img/workshop/presentations/DoD-18SPCS_CONOPS.pdff

collection for improved processing. As a result of these innovations, timeliness of processing has improved, and is likely to continue to improve. An international provider described their system that ingests DoD data as well as other data, and is able to produce conjunction assessments 14 days in advance rather than the 3 days provided by DoD. Another interviewee described how the French service CAESAR can autonomously take into account most of the maneuvers of the satellites for which France delivers CA automatically, and will do automatic screening of the catalog in the future.

3. Entities Would Continue to Make Tradeoffs Between More Data Collection and Theory-Based Prediction Algorithms

A larger number of observations can reduce the urgency to acquire/develop sophisticated physics-based prediction models (e.g., atmospheric drag modeling). When there is less observational data, astrodynamics models reconstruct a trajectory and predict what happens between observations.

The increased observations approach can be enabled by deploying a large number of inexpensive sensors around the world. This may also decrease a country's willingness to fund exquisite capabilities globally. While propagation works well for systems that are predictable and do not change, it is difficult to rely on these types of systems as satellites start maneuvering more. Commercial SSA providers are focusing on developing sensor networks, aggregating data from multiple sources, and in general, increasing data volume to improve SSA tracking.

On the commercial side, some companies, such as ExoAnalytics, are focusing on using software to aggregate high volumes of data from a large optical sensor network for SSA services and products. Similarly, organizations such as AGI and SDA are using software to synthesize high volumes of data by aggregating data from multiple sources.

In terms of relying more on predictions and propagation, academia is continuing to study effects of certain variables on space objects in order to develop models to better account for variables such as thermal profiles, solar/earth radiation, earth albedo, and outgassing, among others.[57] Certain nascent areas of research, such as the effects of space weather and space weather events on space-based objects, are also being pursued by academia.

4. SSA Products Improving

As technology improves, SSA products such as SSA catalogs, CAs, TLEs, and P_c are expected to continue to improve. One example of an improved product was offered by AGI. They indicated that the use of ComSpOC is decreasing the uncertainties of orbits by producing a time dynamic 6x6 covariance matrix (as compared to the 4x4 covariance matrix provided by 18th

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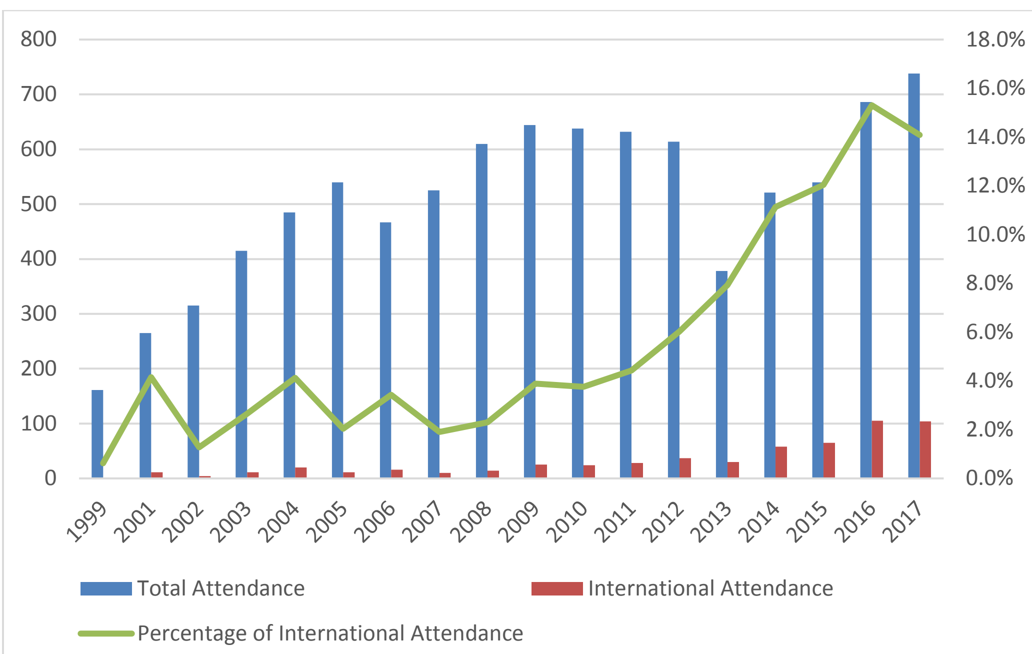
[57] Jah, M. "Space Surveillance, Tracking, and Information Fusion for Space Domain Awareness." *NATO Lecture Series SCI-292.*

SPCS). Also, a growing number of value added services, referred to in earlier sections, result in better products for owner/operators, and enable improved decision making.

SSA products will continue improving as a result of several drivers: data volumes increasing with greater global coverage, increasing sensor capability, increasing ability to fuse different data types, improved understanding of theory-based modelling, and improved data processing capabilities that allow the provision of value-added actionable information.

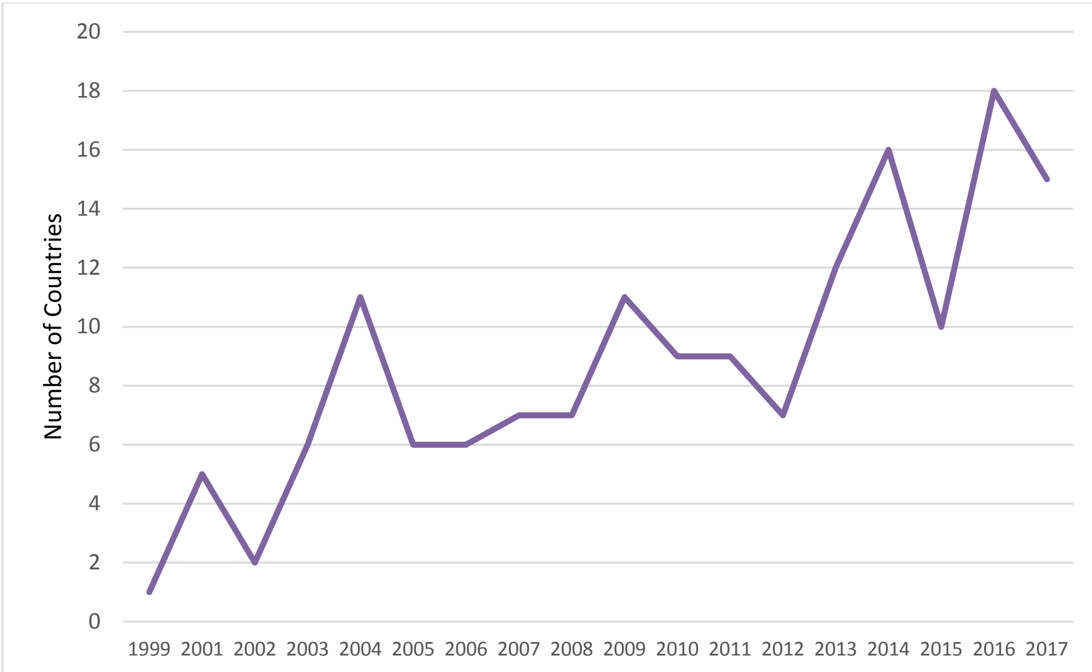
E. Growing International Community and Partnerships

The SSA community is s growing globally. This growth is evident in the number and proportion of foreign attendees at one of the principal technical conferences in the SSA community, the annually-held Advanced Maui Optical and Space Surveillance Technologies (AMOS) conference in Hawaii. In 2006, four percent of the attendees came from outside the United States, by 2016, this fraction had grown almost four-fold—to 15 percent (Figure 3-4). The number of countries attending has gone up from 1 in 1999 to 18 in 2016 (Figure 3.5a). Australia, Japan and United Kingdom send the most number of attendees (Figure 3-5b), and there are large variations by sector for the countries (Figure 3-6). For example, most attendees from Italy come from industry, but attendees from South Korea are dominated by academia. The sectoral distribution changes by year may also be a good indication of the role of a particular sector in a country. For example, growing fraction of military participants from Japan may be a sign of the growing role of the ministry of defense in Japan in SSA activities.



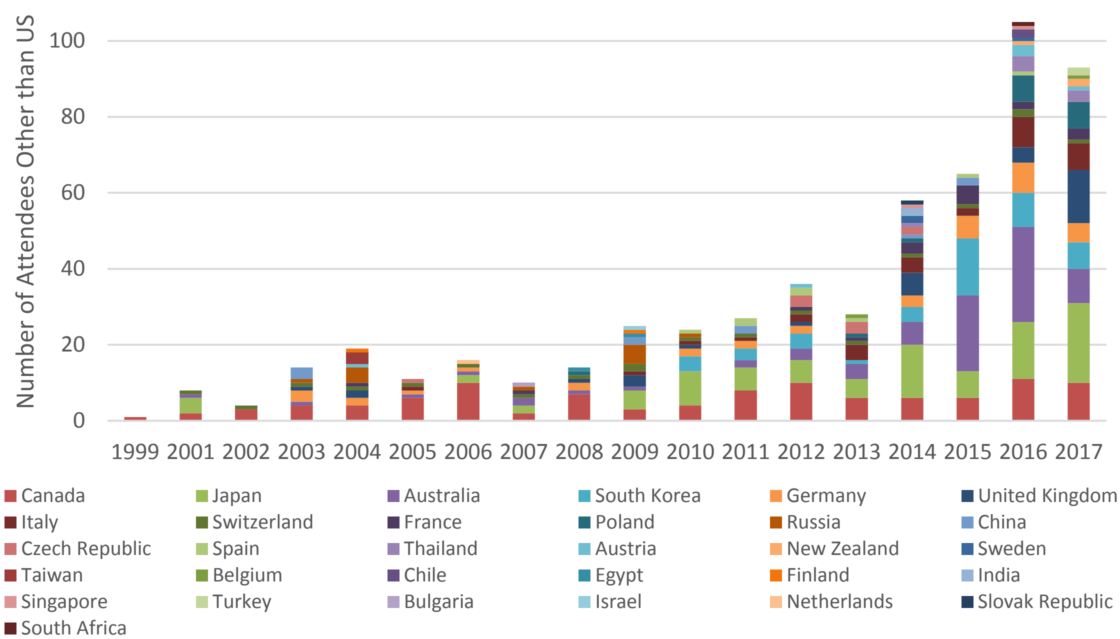
Source: AMOS

Figure 3-4. International Attendee Statistics at AMOS, 2006 to 2017



Source: AMOS

Figure 3-5a. Number of Countries Participating by Year



Source: AMOS

Figure 3-5b. Number of AMOS Non-US Attendees by Country and Year

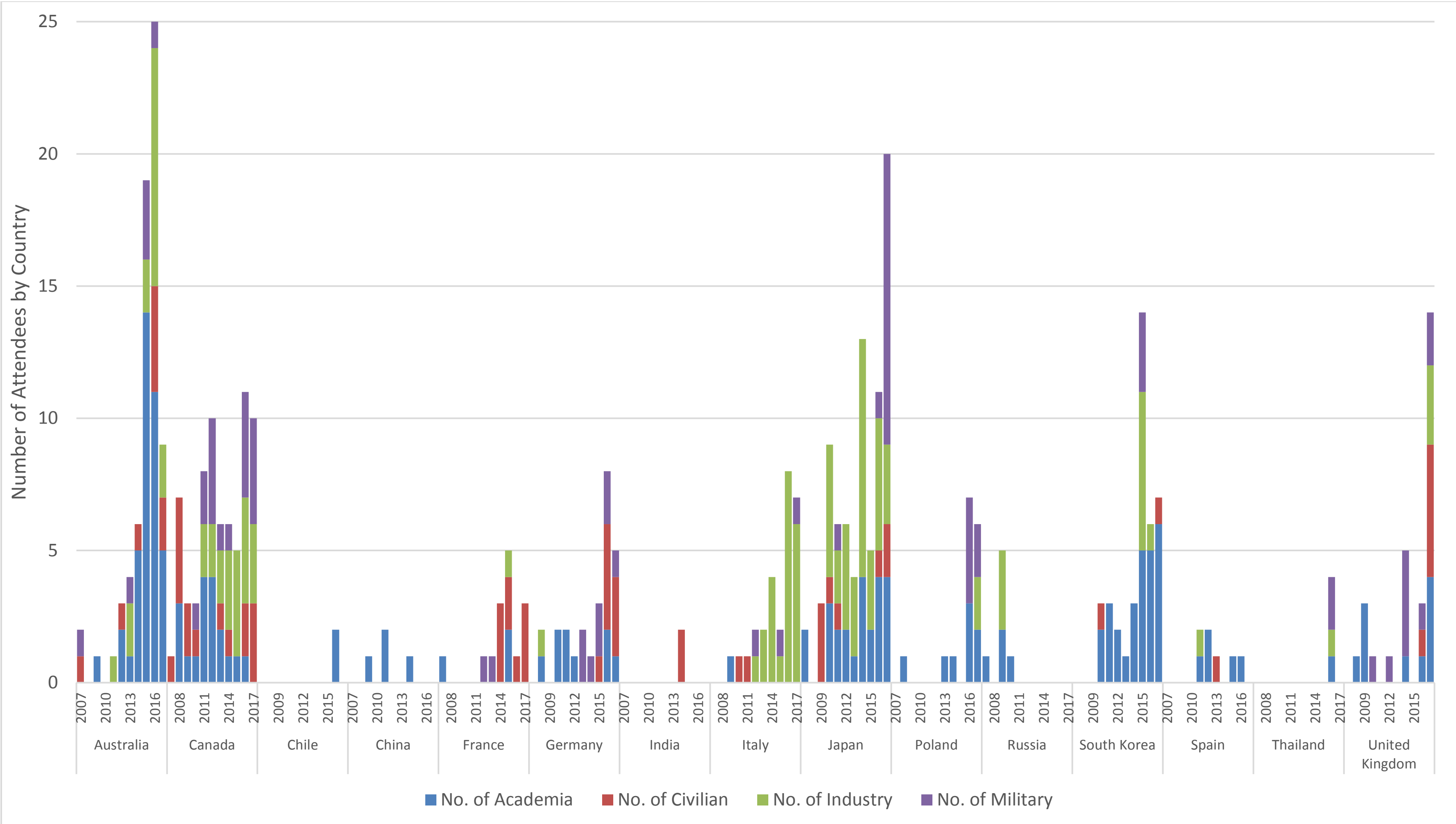
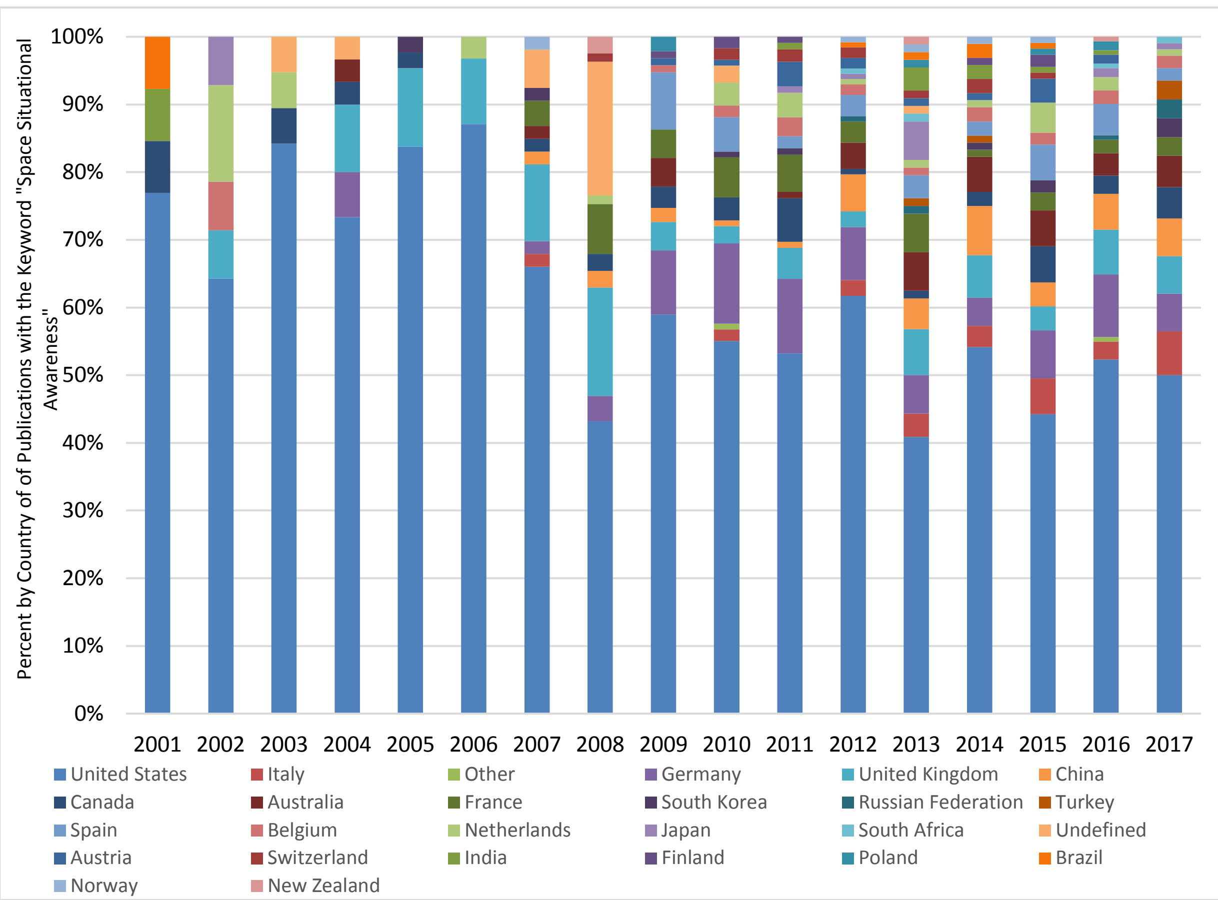


Figure 3-6. International Attendees by Sector by Year (Case Study Countries Only)

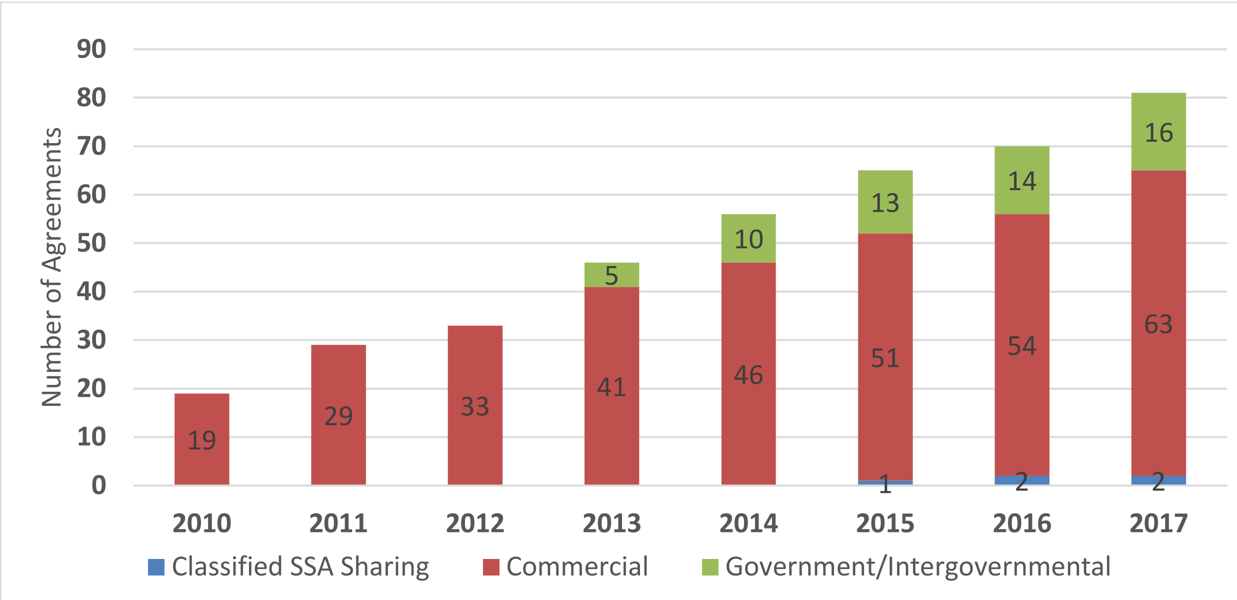
Publications as a Proxy for Growing Capabilities

We conducted a Scopus review to identify trends not evident in discussions. Details on the approach and key findings are available in Appendix I. The review looked at all publications that had the term “space situational awareness” in the title, keyword list, or abstract (n=1,238).

The figure below plots publications by country normalized to 100 percent. The United States has been a dominant contributor to SSA publications, contributing to well over half of the total publications indexed by Scopus. In recent years, however, the number of publications from the international community has increased. In 2001, three countries, not including the United States, had SSA publications. Since then, 50 other countries have published on SSA. Germany is the most published country after the United States with 88 publications. The United Kingdom started publishing in 2002, and has since published 78 SSA-related papers or articles. Other countries, such as Italy, Netherlands, Belgium, Austria, Japan, Switzerland, and South Korea, have at least 10 publications, most in the past decade. There are some notable surprises in the dataset. Russia, for example, has mature capabilities in data collection, data software, and SSA products, but few publications. They may either not be publishing, or their publications may not be getting indexed by Scopus.



Partnerships among countries interested in conducting SSA are also increasing. Other countries and companies are looking to place sensor networks in locations around the world to gain better global coverage, and are partnering with countries either with pre-existing sensors or opportunities to place sensors. Though U.S. data sharing agreements with countries and private sector users and vendors have been increasing as well (Figure 3-6b), the United States is no longer the only partner of choice for countries. Such partnerships among non-U.S. nations are also fostering a growing independence from the U.S.



Source: Department of Defense

Figure 3-6b. Data Sharing Agreements with JSpOC, 2010 to 2017 by Organization Type

For example, the South African National Space Agency (SANSA) has partnered with the German Aerospace Centre (DLR) to host a space debris tracking station within the Optical Space Research (OSR) Laboratory.[58] The facility includes a space debris tracking telescope as part of SMARTnet™ (Small Aperture Robotic Telescope Network), a dedicated sensory network based on telescope systems.[59] Another example of a partnership is between Russia and Brazil, who have cooperated to set up a telescope to monitor space debris at Pico dos Dias Observatory in Brazópolis, Minas Gerais. Russia will provide a $2.7 million investment, whereas Brazil will provide the facilities to operate the equipment and cover operating costs including energy and

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[58] The OSR Laboratory, in Sutherland South Africa, hosts the South African Astronomical Observatory.

[59] SANSA.org. 2012. “Another Eye Towards the Sky—Unveiling South Africa’s Optical Space Research Laboratory.” http://www.sansa.org.za/careers/17-spaceoperations/spacescience/resource-centre/news/1622-another-eye-towards-the-sky-unveiling-south-africa-s-optical-space-research-laboratory

internet. Japan has also signed agreements with France and Germany, and the Europeans have established the EU SST.

Through the Asia-Pacific Space Cooperation Organization (APSCO), China is leading the Asia-Pacific Ground-based Optical Space Objects Observation System (APOSOS).[60] The goal of APOSOS is to build a network of optical observation facilities around the world for SSA use (Figure 3-5). Currently, the APOSOS effort is mainly in training and experimentation, but APOSOS aims to have at least one observation facility in each of the eight APSCO member state countries and elsewhere in the world.[61] Most current partnerships relate to sharing sensor data, but as the APOSOS effort indicates, partnerships are starting to include other aspects of SSA (and STM as the following chapter indicates). As Figures 3.5a and 3.5b indicate, China has sensors is all APSCO member countries as well as Brazil and Ukraine. By 2017, Mexico had joined the APOSOS network.

Source: Japan Space Forum (2016)

Figure 3-5. APSOS Sensor Network Map as of 2015

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[60] APSCO was established in 2008 with the goal of fostering multilateral cooperation in the Asia-Pacific region.

[61] In addition to China, APSCO members include Bangladesh, Iran, Mongolia, Pakistan, Peru, Thailand, Indonesia, and Turkey

F. Growing Country-Level Capabilities

The sections above focus on technology trends related to data collection, processing and analysis. In this section we aggregate these trends by country, and attempt to assess country-level capabilities. Almost all the countries in our set of case studies have increased spending devoted to data collection and processing. While it is not feasible to get comparable spending on SSA partly because the activities include different things in different countries and partly because the data is not available, it is evident that for many of these countries, SSA is a priority. For example, in 2017, Japan invested ¥1.7 billion ($16M) and requested ¥1.8 billion ($17M) in 2018 for SSA activities.[62] Australia intends to spend $1B to $2B on SSA activities from 2018 until 2035. The EU SST has committed €70M ($87M) between 2015 and 2020, and is expected to invest more money after 2020.[63]

1. Data Collection

Some countries in our case studies are not participating in any data collection efforts. Some countries have ground-based sensors that could be used for SSA but currently are not. Others do not currently have data collection capabilities, but are interested in or building sensors for part-time or dedicated SSA use. Similarly, some countries may be thinking about repurposing existing sensors for part-time or dedicated SSA use. Countries and consortia with data collection capabilities are either keeping the data to use domestically or within their consortium, or are actively sharing their data in some form with one or more countries. On the commercial side, some vendors are either not participating in any data collection, or are not operating sensors but pulling data from other sources. Other companies are planning or building sensors to operate, while others already operate sensor networks. To the extent possible, as discussed in the Australia case study, countries would prefer to mature and engage their own private organizations rather than international ones.

2. Data Processing

We looked at software capabilities for countries and commercial vendors—this includes software used to process raw data, fuse data from multiple sources, as well as software used to develop SSA products. To understand the maturity of software capabilities, we looked at countries' and companies' levels of autonomy. For example, some countries are in the nascent phases of developing software. Others are developing their own software but rely heavily on the use of outside tools or services; others who are developing their own software capabilities are mostly autonomous but still use some outside tools and services. A couple of countries in the matrix have

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62 All monetary values converted to USD in FY19

63 De Selding, Peter B. 2015. "A European Space Surveillance Network Inches Forward." *Spacenews*, June 17, 2015. http://spacenews.com/a-european-space-surveillance-network-inches-forward/

been identified as having fully autonomous software capabilities. Commercial vendors fall in similar categories.

3. Data Products

Some countries have basic product abilities such as calculating launch and reentry trajectories. Countries and vendors able to deliver products beyond launch and reentry are considered more mature. These countries did not necessarily need to have a "comprehensive" list of SSA products to be considered mature. Instead, the groupings were based on ability to develop products autonomously, similar to the groupings for SSA software. For example, some countries and vendors can deliver their own products based primarily off of information from 18th SPCS. However, other countries and vendors are developing or have developed products that add value or duplicate what 18th SPCS provides.

In some cases the three categories—data collection, data processing, and SSA products—are inherently intertwined. Based on the country case studies, we have attempted to capture the degree of sophistication of different countries' SSA systems. Table 3-1 represents our judgement of where each country stands in terms of data collection, data processing and data products.

Table 3-1. Country Technology Maturity Matrix

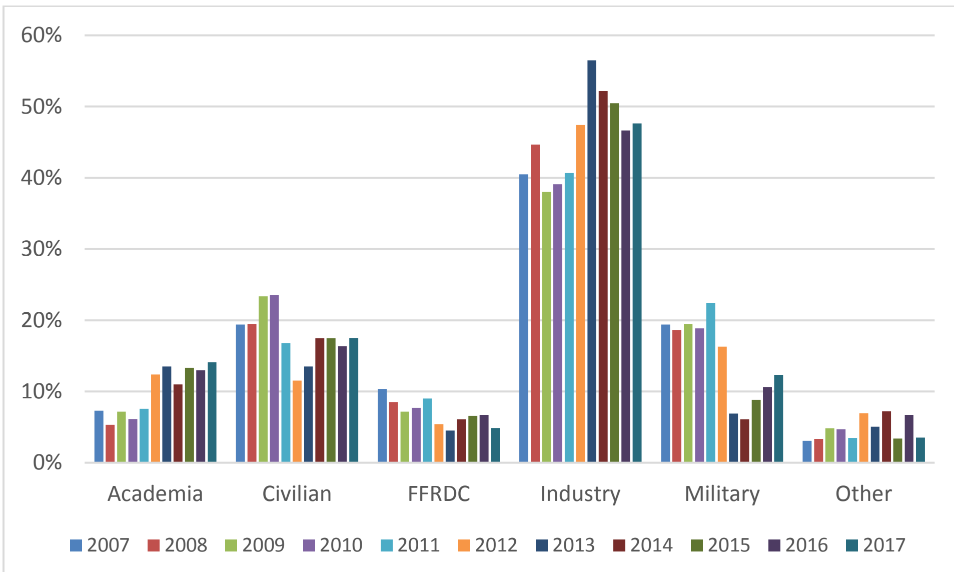
	Data Collection	Data Processing	Data Products
Australia	Actively involved in sharing with one or more countries	Has some processing capabilities	Deliver products based on 18th SPCS data
Brazil	Building/using or planning to build/use one or more SSA sensor(s)	Has some processing capabilities	unknown
Canada	Actively involved in sharing with one or more countries	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Chile	Have one or more sensors, but not used for SSA	No data processing	No data products
China	Has domestic SSA sensor capability or sharing within consortium	Processing in-house data with outside capabilities	unknown
France	Has domestic SSA sensor capability or sharing within consortium	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Germany	Has domestic SSA sensor capability or sharing within consortium	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
India	Have one or more sensors, but not used for SSA	Processing in-house data with outside capabilities	Products limited to launch and/or re-entry
ISON	Actively involved in sharing with one or more countries	Has full in-house processing capabilities	Can deliver value-added products, but not still reliant on outside data

	Data Collection	Data Processing	Data Products
Italy	Have one or more sensors, but not used for SSA	No data processing	No data products
Japan	Actively involved in sharing with one or more countries	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Poland	Building/using or planning to build/use one or more SSA sensor(s)	No data processing	No data products
Russia	Has domestic SSA sensor capability or sharing within consortium	Has full in-house processing capabilities	Can independently deliver products
S. Africa	Has domestic SSA sensor capability or sharing within consortium	No data processing	No data products
S. Korea	Has domestic SSA sensor capability or sharing within consortium	Has some processing capabilities	Can deliver value-added products, but not still reliant on outside data
Spain	Has domestic SSA sensor capability or sharing within consortium	Has some processing capabilities	unknown
Thailand	Has domestic SSA sensor capability or sharing within consortium	Has some processing capabilities	Deliver products based on 18th SPCS data
UAE	No data collection	Doing or planning to do some data processing (relying on outside tools)	No data products
UK	Has domestic SSA sensor capability or sharing within consortium	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
US	Actively involved in sharing with one or more countries	Has full in-house processing capabilities	Can independently deliver products
APOSOS	Has domestic SSA sensor capability or sharing within consortium	unknown	unknown
ESA SSA	Has domestic SSA sensor capability or sharing within consortium	Has some processing capabilities	No data products
EU SST	Actively involved in sharing with one or more countries	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data

G. Growing Capabilities in the Private Sector

The preceding sections have provided illustrations of the speed at which private sector capabilities are increasing, by their location in the space traffic system (collection, processing, products). In this section, we provide an assessment of the role the private sector is playing in changing the structure of the SSA system. It important to note first that the private sector has always been a significant part of the SSA enterprise. Industry attendance statistics at AMOS are a good illustration of this role (Figure 3-6).

What has changed however in recent years is that the SSA sector is beginning to undergo a functional modularization the integrated "end to end" SSA process—data collection, processing, generation of SSA products and value added services—that was previously controlled by a large government military organization (DoD) is being broken up into segments. This breakup into segments—data collection, analysis, etc.—is allowing more players, especially in the private sector that can sell piecemeal information, to enter the system, and there is a growing number of companies offering SSA data, software, and services.



Source: AMOS

Figure 3-6. Attendee Statistics at AMOS by Sector

A growing number of these companies are privately funded (though most likely serve government customers, at least for now). For example, spin-off LeoLabs in the United States is funded by several venture capital firms including Horizons Ventures, based in Hong Kong, and Airbus Ventures, Airbus's early-stage investment group. There is not much information on sources of funding for other firms, as most of them are either privately held (examples include companies such as AGI, ExoAnalytics, ExpressSAR) or parts of larger conglomerates (such as Airbus).

Private companies serve both private satellite owner/operators as well as governments globally. There are many organizations involved in data collection. Together, AGI and ExoAnalytic, have over well over 200 telescopes around the globe. France's ArianeGroup similarly has global coverage of GEO. Some private organizations involved in SSA data processing have developed fully commercial catalogs using purely commercial, scientific, and international data. By some accounts, these databases provide better information than DoD. Some companies (e.g., Airbus/Europe, SDA/multinational, Space Nav/US) also provide additional data processing services to augment DoD's conjunction warnings to satellite operators. As the preceding sections have indicated, the private sector, which includes not just commercial firms but also non-profits and academic institutions, is on track to match and exceed USG capabilities, at least what the U.S. releases publicly. Not only are many of these companies' capabilities comparable or better than the U.S. Government, they are cheaper as well.

The private sector is finding willing international customers leveraging commercial capabilities to grow indigenous capabilities. U.S.-based firms have both direct customers and resellers in a growing list of customers internationally. And the list of providers is growing.

Table 3-2 presents a high-level assessment of the about 25 companies we were able to identify in the course of this project. Our interviews found there is little interest from foreign private companies in providing end-to-end SSA services; those who are offering services are typically companies that work under the umbrella of their governments (e.g., IHI in Japan). More "commercial-like" foreign companies (e.g., GMV) are, however, starting to develop. The table illustrates a key trend identified in this study: that private sector SSA provision is primarily a U.S. phenomenon, and will likely remain so over the next decade, however, some foreign vendors are starting to emerge with support from their governments. This trend tracks a general trend related to commercial activities in space—that in general, commercial space activities are primarily a U.S. phenomenon.

Table 3-2. Commercial Technology Maturity Matrix

Company	Affiliated Country	Data Collection	Data Processing	Data Products
Innovor Technologies	Australia	(space-based SSA)	unknown	unknown
Silentium Defence	Australia	(ground based passive SSA radar)	unknown	unknown
CEA Australia	Australia	(S-Band radar)	unknown	unknown
EOS	Australia	Operates own sensors	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Fujitsu	Japan	No data collection	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Mitsubishi	Japan	unknown	Doing or planning to do some data processing (relying on outside tools)	unknown
NEC	Japan	unknown	Doing or planning to do some data processing (relying on outside tools)	unknown

Company	Affiliated Country	Data Collection	Data Processing	Data Products
IHI	Japan	unknown	Doing or planning to do some data processing (relying on outside tools)	unknown
Deimos	Spain	Building/using or planning to build/use one or more SSA sensor(s)	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
GMV	Spain	No data collection	Doing or planning to do some data processing (relying on outside tools)	Can deliver value-added products, but not still reliant on outside data
CSS	France	No data collection	Processing in-house data with outside capabilities	Can deliver value-added products, but not still reliant on outside data
Airbus	France	No data collection	Processing in-house data with outside capabilities	Can deliver value-added products, but still reliant on outside data
ArianeGroup	France	Operates own sensors	No data processing	No data processing
AGI	US	Operates own sensors	Has full in-house processing capabilities	Can independently deliver products
Boeing	US	Building/using or planning to build/use one or more SSA sensor(s)	Has full in-house processing capabilities	Can independently deliver products
Numerica	US	Operates own sensors	Has full in-house processing capabilities	Can independently deliver products
Exoanalytics	US	Operates own sensors	Has full in-house processing capabilities	Can deliver value-added products, but not still reliant on outside data
Lockheed	US	No data collection	Has full in-house processing capabilities	Can independently deliver products
SpaceNav	US	Have no sensors but pulling in data from other sources	Has full in-house processing capabilities	Can independently deliver products
SDA (nonprofit)	UK/Multi	Have no sensors but pulling in data from other sources	Has full in-house processing capabilities	Can independently deliver products
LeoLabs	US	Building/using or planning to build/use one or more SSA sensor(s)	No data processing	No data products
Applied Defense Solutions	US	Operates own sensors	No data processing	No data products

H. Implications: Data Collection, Data Processing, and Data Products

As a result of the increasing number and improved performance of all SSA sensor types and software, the quality of SSA tracking for decision making will continue to improve. While optical sensors have become cheaper and more ubiquitous, radar technology remains expensive and mostly limited to governments. Other technologies such as ground-based and space-based RF, and laser ranging are rapidly improving and adapting for SSA applications. The expected increase of space-based sensors, optical and RF, will also have an impact on the overall quality of SSA tracking. Software is rapidly improving with respect to falling cost, growing timeliness, and increasing performance. In this section we discuss the implications of these trends.

1. Falling Dependence on the USG for SSA

Globally, countries are increasing their investments in SSA capabilities. In a couple of instances, notably with Russia and China, investments in in-house SSA capabilities reflects a desire to develop and maintain an SSA system independent of the U.S. SSA system. Their ability to process these data and use in-house software to develop SSA products, however, is not clear and is not likely as mature as that of the United States. China and Russia's interest to develop independent systems is likely strategic, and any improvements to the U.S. system, even increased transparency, is unlikely to dissuade countries such as China and Russia from continuing to develop their own capabilities.

However, in other instances, such as in Europe, Japan, and elsewhere, the desire to develop in-house SSA capabilities reflects the desire to increase autonomy and be improved stakeholders. Thus, it is likely that countries will continue developing their own independent capabilities regardless of whether the United States improves SSA products shared internationally. An analogy to this is GPS. After the United States developed GPS, and despite sharing its capabilities with the rest of the world, other GPS alternatives independently emerged: Galileo (EU), BeiDou, (China), GLONASS (Russia), QZSS (Japan), IRNSS (India).

Figure 3-7 shows a cross-analysis of countries' technical capabilities and motivations or interest in international collaboration.

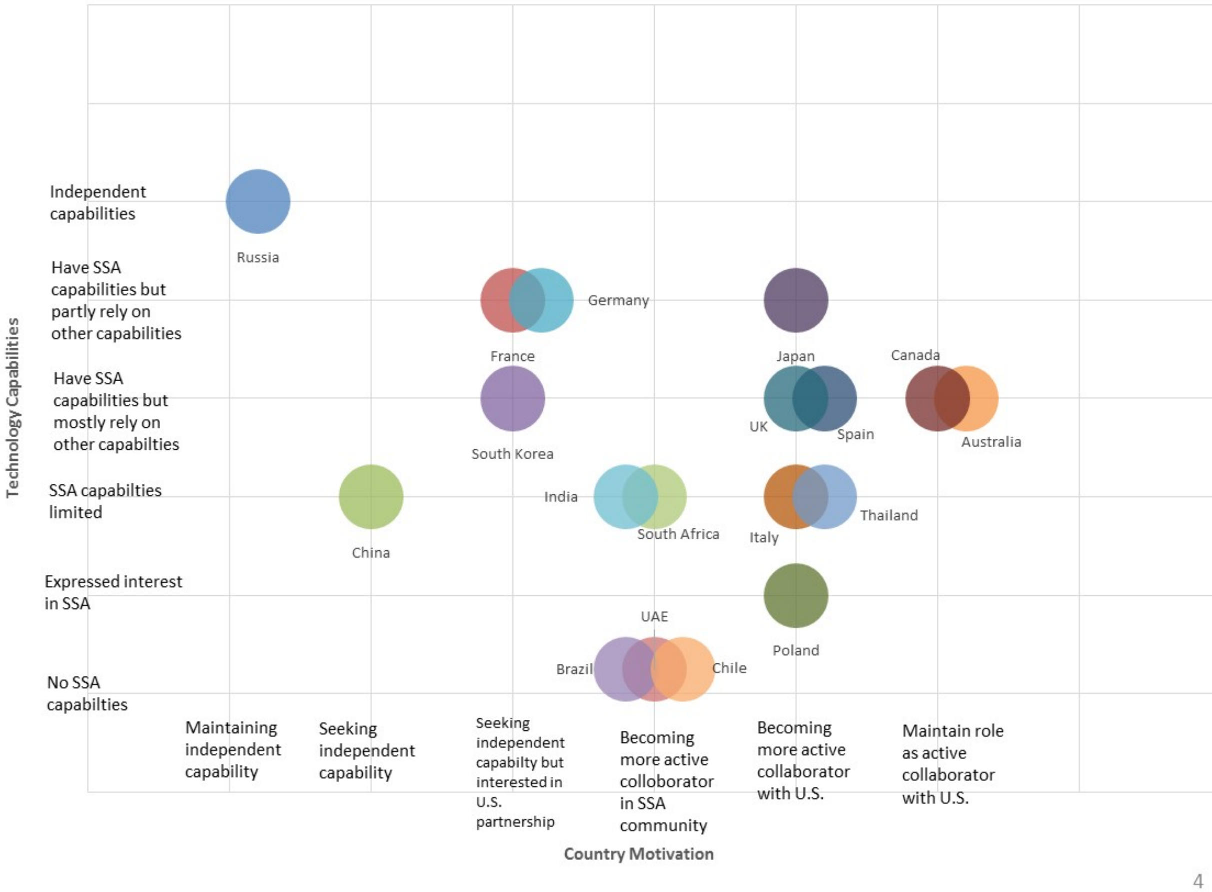


Figure 3-7. Country technical capabilities by country motivation and desire for collaboration

2. Increased Data Sharing May Lead to a Push for International Data Standards

As data is increasingly shared among nations or aggregated within SSA consortia, and as data fusion becomes increasingly more common, there may be a push to develop data standards to increase the ease with which data fusion can occur. Data standards could be developed by consensus or by countries taking the lead of their consortium or SSA partners.

3. SSA Data Will Eventually Become a Commodity

Exquisite data from expensive telescopes or radars will always be needed, but growth in the amount of data available, together with software advancements like the ability to fuse data from disparate sources and automation, will likely lead to the commoditization of most SSA data. In other words, SSA data will become a commodity when an O/O can replace one company or country's data with another, and value comes from the products derived from the data, not from the data itself. O/O and those developing their own catalogs already have choices on where to get their data, but as more data becomes available, the options for purchasing data will grow.

4. SSA Products Will Become More Sophisticated

There will likely be increasingly more sophisticated SSA products, with fewer false negatives and positives, more confidence in CAs, and lower covariance. While DoD CSMs are currently the best available without cost, this may not always be the case. Driven by the growth in the number of globally placed sensors, improvements in the accuracy of data, growing fusion of object characterization data of different phenomenologies, and sharing of data among partners, data products are well poised to become more accurate, usable and customizable. Developments in the commercial sector—as evident in SDA's algorithms and ephemerides—will ensure continuing sophistication SSA inputs, processing, and products.

5. Space Assets Will be Harder to Hide

The proliferation of SSA sensors and development of independent and open-sourced software capabilities means that commercial vendors, even those with nascent capabilities, will be able to see and track assets in space, particularly in GEO. Additionally, because some SSA software is open-sourced, and because optical sensors have become more accessible, amateur observers will increasingly be able to make more precise observations in GEO. While there will still be mechanisms by which to hide assets in space, it will be more difficult.

6. SSA Will Increasingly Become a Service (Though Some Countries May Prefer a Hybrid Service/Ownership Model)

Currently SSA is treated by countries as a system wherein one needs capabilities to operate sensors, develop and use software, create SSA products, and maintain international partnerships. However, commercial providers have emerged for each essential piece of the system; there are companies that operate SSA sensors, provide SSA software, and provide SSA products. Thus, SSA could increasingly emerge as a "subscription service" similar to how acquiring Earth observation data is growing as a service that used to require owning the entire system from collection to processing to images or data. This trend is already underway: SDA provides services to its members, and charges fees based on a sliding scale of the number of satellites to get RFI mitigation support, avoidance maneuver planning, and on-demand conjunction analysis. This trend is likely to accelerate as more operators (private and government) realize that generating these products is not trivial, and that there may be cost-effectiveness to treating SSA as a service.

For many operators and some countries, a subscription model may be adequate. However, some countries may not be willing to pay private sector entities for the full service, given the national security implications and need for self-reliance, and would prefer to keep the service in-house. In these countries, the private sector is likely to enter into a hybrid model where private companies sell their software product and train governments on how to use their software so that countries can do in-house processing.

7. SSA Service Provision is Seen as Essentially a National Security Oriented Government Function

Internationally, SSA tends to be a function led by the national militaries, with technical support and input from civil agencies. National militaries will likely continue leading these functions because of the national security implications associated with SSA. A move toward civilian agencies leading is distinctly American.

In Germany, for example, the Ministry of Defense (MOD) operates the German Space Surveillance Center (GSSC). The DLR works on research and development, and supports the operations of the GSSC. Similarly, in France, the Space French Command under the supervision of MOD does the overall coordination of SSA for the country. Additionally, they operate the surveillance system (GRAVES) and the tracking radars. CNES leads SSA research. CNES is also in charge of station-keeping for civilian and military satellites, on-orbit collision risk monitoring, launch collision risk monitoring, prediction of atmospheric reentries, and flight dynamics to support the French Air Force. In Japan, JAXA had traditionally been in charge of SSA. However, trends indicate that while JAXA will remain involved in SSA activities, it is likely that MOD will start taking a lead on the operations side.

While governments in most countries are likely to own SSA, they will continue to be willing to work with private entities for some of their SSA needs. Many U.S. firms sell products in other countries either directly or through domestic resellers. And as with the space sector broadly, national governments would continue to see SSA as an avenue to grow their private sector.

4. Trends in Oversight and Coordination

As of this report, there is no consensus definition for space traffic management (STM) or broad understanding of the concept of STM globally.[64] Even within a given country, there is sometimes no standard definition for the term. The lack of a standard understanding of the concept of STM across interviewees or in the literature led this study to choose the term Oversight, Coordination, and Management (OCM) in its Space Traffic System Framework, instead of STM. Appendix B provides a list of definitions gathered from literature. The individual case studies include country definitions when they were available.

Several interviewees voiced concerns that any definition could result in an important aspect being excluded, with no entity responsible for overseeing that component. Others did not seem clear about the goals of STM, e.g., whether it is primarily for space safety, tracking of large space debris, avoiding collisions, or something else entirely. Without understanding what the goals of STM are, it is challenging to develop a system, especially a global one.

Regardless of the definition, STM as a concept and approach is still evolving, and one interviewee noted that STM seemed like more of a vision than an approach. In Europe, countries are still determining what STM is and how to approach it; according to an interviewee from ESPI, the EU recently hosted a meeting on this topic, and stakeholders are still determining the path forward and distilling what STM should comprise. Some interviewees noted that this system in Europe is referred to as "space traffic control."

Russia has also been developing a narrative around a suggested global approach to STM. For example, the Russian government has proposed to the UN Committee on the Peaceful Uses of Outer Space (UN COPUOS) the establishment of an international information sharing mechanism, run by the United Nations Office of Outer Space Affairs, that would support efforts to manage space traffic. In this mechanism, countries (sometimes referred to in this chapter as States), intergovernmental organizations, operators, and national and international NGOs would contribute their data to be integrated, resulting in a central information base for monitoring objects and events in outer space (Russian Federation, UN COPUOS 2017). While this proposal has not been accepted by Member States of UN COPUOS, the concept of data pooling and an open architecture by which to access SSA data continues to gain traction by both governments and non-governmental entities.

[64] The 2006 IAA Cosmic Study provided a definition for STM for the purposes of the study that is sometimes referenced as being a primary definition for STM

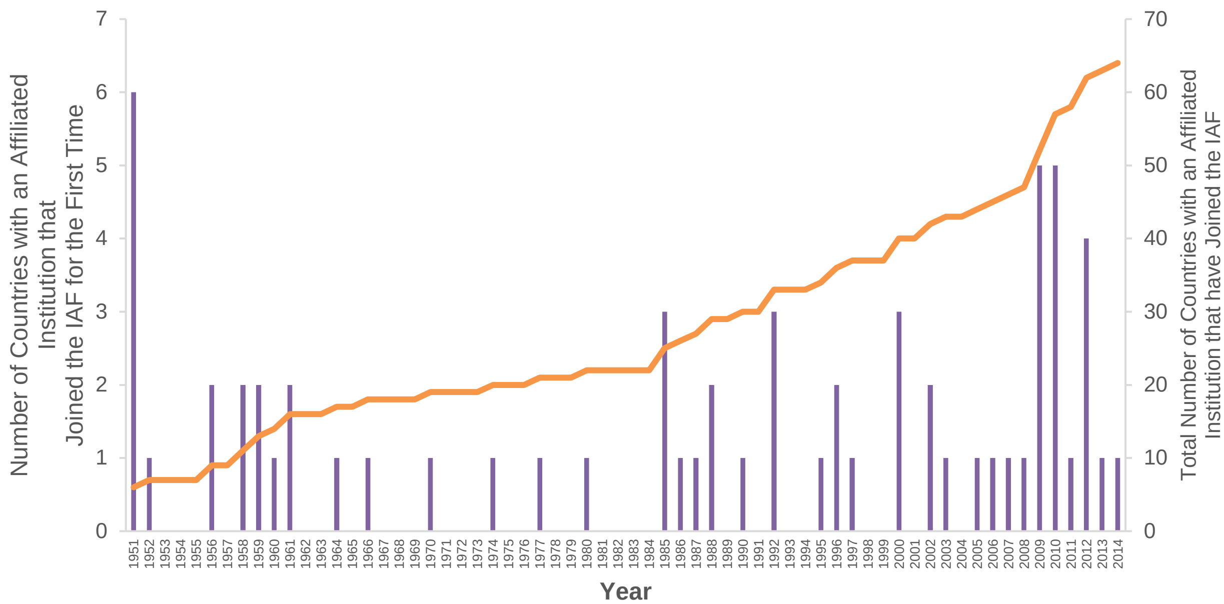
Several interviewees perceived STM to be a U.S.-driven initiative that may have implications, good or bad, on the willingness of other nations to adopt it as an approach on a multilateral scale. Some interviewees acknowledged the logic behind this perception that STM is a U.S.-led initiative, given that the United States has the most assets in space and therefore the desire to protect these assets. However, several interviewees, including those from emerging spacefaring nations, perceived STM as a mechanism for restricting access to space and space activities. In particular, the word "management" was perceived by some interviewees as being centered on control, usually by the United States. Going forward, it was suggested the term "management" be changed to "coordination" as it better reflects the collaborative nature of space activities.

There also does not appear to be global agreement on whether there needs to be an entity controlling space traffic or offering on-orbit authority, which is an aspect of the STM approach. At a national level, no government has designated an on-orbit authority, and it is not clear based on interviews and literature that this will change in the next decade. Several government interviewees insisted that this was not needed, as operators would simply move to protect their assets. However, some interviewees stated that certain countries only care about SSA during launch, so the assumption that operators will always move, especially with operator plans to launch mega-constellations, may not be sufficient in the future space environment.

At the international level, perspectives varied—one interviewee stated it is not unreasonable that a general supervisory authority be created, given that at some point there will likely be too many satellites to manage. However, developing such an entity may be challenging in the global arena as it would require countries to give up a certain amount of freedom to act in space. Given that many governments are actively seeking to build up their capabilities, it is unlikely that countries would be willing to curb their growing space programs unless there are sufficient trade-offs or benefits to doing so. In the sections below, we discuss three emerging trends in OCM and assess the implications of these trends.

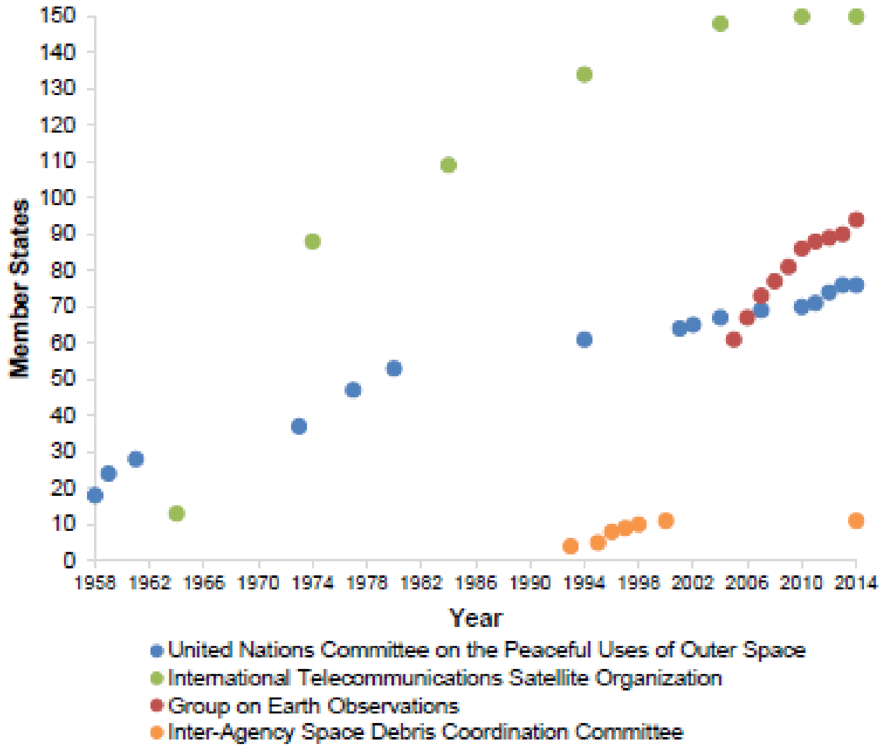
A. Growing Agreement on the Need for Oversight, Coordination and Management

As discussed in previous STPI reports (Lal et al., 2015; Lal et al., 2017), the increased availability of space technology and capabilities is enabling both governments and non-governmental entities to leverage space in new and innovative ways. The growth and diversification of space activities, especially in the commercial space sector, is driving efforts internationally and nationally to improve existing or develop new mechanisms to share data and to oversee, coordinate, and manage space activities. These efforts include developing best practices for safe space operations and revising or establishing legal frameworks for space activities. In these organizations and other venues, there is growing agreement on not only the need to share data but also the need to oversee, coordinate, and manage space activities both domestically and internationally. Figures 4-1 and 4-2 show growing participation in international organizations. The authorship pages of the two IAA reports on space traffic management from 2006 (the "Cosmic" report) and 2018 feature a near doubling of the number of authors and reviewers. The 2018 report also had representation from 22 countries, 14 of which were not part of the 2006 publication.



Source: Lal et al 2015.

Figure 4-1. Number of Countries with Members in the International Astronautical Federation, by Year Joined



Source: Lal et al 2015

Figure 4-2. Membership in Space Governance Related Organizations

Forums such as the UN COPUOS have proven valuable opportunities for their members to address the complexities of the evolving space environment. For example, since 2011 the COPUOS Long Term Sustainability (LTS) Working Group has worked to develop best practices and voluntary guidelines for space activities. The LTS Guidelines call for steps such as enhancing registration processes, performing conjunction assessments during all orbital phases of controlled flight, and other actions to ensure the long term sustainability of space for all interested players.[65] Several interviewees noted the importance of the LTS Guidelines to build towards a more comprehensive and coordinated approach for overseeing, managing, and coordinating space activities. As of March 2018, 21 of the LTS Guidelines have been approved by the Working Group for adoption by COPUOS. Other interviewees cited the importance of such forums in promoting transparency and trust among Member States.

Other entities such as the Inter-Agency Space Debris Coordination Committee (IADC), the Consultative Committee for Space Data Systems (CCSDS), and the International Standards

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65 The purpose of the guidelines is to assist States with better mitigating the risks of conducting space activities and promoting international cooperation in outer space. http://www.unoosa.org/res/oosadoc/data/documents/2018/aac_105c_12018crp/aac_105c_12018crp_18rev_1_0_html/AC105_C1_2018_CRP18Rev01E.pdf

Organization (ISO) also serve as multi-lateral forums to coordinate efforts on space activities. The 13-member IADC exchanges information and facilitates cooperation on space debris research and activities.[66] The IADC was critical to informing international efforts to set standards for space debris mitigation,[67] and while these guidelines are non-binding, they have been incorporated into many national legislative frameworks. ISO is an independent, non-governmental international organization that coordinates to develop voluntary, consensus based guidelines to address global challenges.[68] Under ISO TC 20/SC 14 on "Space systems and operations" a technical committee has worked to develop standards on myriad topics to promote safe operations in space. Additionally, the CCSDS is a forum for both governments and industry associations to develop standards and best practices for communications and data systems. The goal of this group is to enhance governmental and commercial interoperability and reduce costs for spaceflight operations.

Our interviews with representatives from governments and our review of national policies indicate that domestically, governments are seeking to develop or streamline legislation to better coordinate efforts and develop space capabilities, including SSA capabilities. While the rationale for these efforts varies across governments, a key driver is that countries bear international responsibility for authorizing and providing continuing supervision for national space activities, even those conducted by non-governmental entities.[69] As commercial activity continues to grow, governments are both seeking ways to adhere to international treaty obligations and to attract commercial sector investment. This is a delicate balance that will continue to present opportunities and challenges for domestic regime-building.

To comply with international treaty obligations, most countries are developing legislation domestically to oversee and manage space activities, specifically through licensing and registering processes. Though each country varies with respect to what is required to obtain and maintain a license for space activities, financial stability, liability (e.g., proof of insurance), and demonstration that the activity will not adversely affect public health and safety or the environment are common issues addressed during the licensing process (Jahku 2016). As space is increasingly seen as a strategic sector, beneficial to national security, economic, and societal activities, efforts have been steadily increasing to revise existing or establish new legal and regulatory mechanisms for space

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[66] Inter-Agency Space Debris Coordination Committee. 2018. https://www.iadc-online.org/

[67] Unoosa.org. 2007. "IADC Space Debris Mitigation Guidelines." http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC_space_debris_mitigation_guidelines.pdf

[68] International Organization for Standardization. "About ISO." Accessed April 2018. https://www.iso.org/about-us.html

[69] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty) http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

activities. As detailed in Table 4-1, over half of the countries that were reviewed for this study are undertaking efforts to revise, update, or establish new legal frameworks for space activities.

Table 4-1. Status of National Policy Frameworks for Space Activities

Country	Space Policy/Strategy/Plan[70]	Regulation/Law Governing Space Activities[71]	SSA Included
Australia[72]	Undergoing revision	Undergoing revision	Yes
Brazil[73]	Undergoing revision	Undergoing revision	Unknown
Canada[74]	Recently revised	No recent revisions	Yes
Chile	Unknown	Unknown	Unknown
China[75]	Recently revised	Recently revised	Yes
France[76]	No recent revisions	No recent revisions	Yes
Germany[77]	No recent revisions	No recent revisions	Yes
Italy[78]	Recently revised	No recent revisions	Yes

70 This column refers to any national space policy or strategy (to include civilian and defense space strategies or whole-of-government space strategies).

71 Regulations or laws governing space activities (to include licensing processes, registration, and launch/re-entry/disposal requirements) are covered here. Note: many countries have incorporated provisions of the OTS into their national laws to comply with treaty obligations. http://www.unoosa.org/documents/pdf/spacelaw/activities/2014/pres06E.pdf

72 There is recognition of the need for a National Space Strategy and/or Policy in Australia; it is expected that this would be under the purview of the civil space agency. On October 24, 2015 the Australian Government announced it was reforming the Space Activities Act of 1998. https://industry.gov.au/industry/IndustrySectors/space/Pages/Review-of-the-Space-Activities-Act-1998.aspx

73 In October 2017, the Brazilian Ministry of Defense announced the drafting of a new blueprint to revamp the country's space program. This proposal includes establishing a national council for space affairs (Conselho Nacional do Espaço: CNE) and an executive committee for space (Comitê Executivo do Espaço: CEE). A 2013 publication from Brazil's Space Agency references a Brazilian Space Policy. http://www.aeb.gov.br/wp-content/uploads/2013/01/PNAE-Ingles.pdf

74 Space Advisory Board. 2018. https://www.ic.gc.ca/eic/site/ad-ad.nsf/eng/h_ad03983.html

75 Tsujino, Teruhisa. 2016. "Chinese Space Policy and Space Related Activities." International Symposium on Ensuring Stable Use of Outer Space, March 4, 2016. http://www.jsforum.or.jp/stableuse/2016/pdf/27%20Tsujino.pdf

76 "Hearing of the French Join Commander for Space." 2018. https://satelliteobservation.net/2018/02/05/hearing-of-the-french-joint-commander-for-space/

77 Germany released a space strategy in 2010 and is still in the process of implementing including the establishment of a legislative framework for space activities.

78 "Strategic Vision Document 2016-2025." Agenzia Speziale Italiana. https://www.asi.it/sites/default/files/attach/dettaglio/dvs-ing_web.pdf

Country	Space Policy/Strategy/Plan[70]	Regulation/Law Governing Space Activities[71]	SSA Included
India[79]	No recent revisions	Undergoing revision	Unknown
Japan[80]	Recently revised	Recently revised	Yes
Poland[81]	Establishing	Establishing	Yes
Russia[82]	Recently revised	No recent revisions	Yes
S. Africa[83]	No recent revisions	Undergoing revision	Unknown
S. Korea[84]	Recently revised	Undergoing revision	Unknown
Spain[85]	No recent revisions	No recent revisions	Unknown
Thailand[86]	Establishing	Establishing	Yes
UAE[87]	Establishing	Establishing	Unknown
U.K.	Undergoing revision	Recently revised	Yes

These efforts are an attempt to streamline existing and develop new processes and policies, in particular for industry growth and national security. As more non-governmental entities become involved in space and challenge existing international liability and enforcement mechanisms, there is also growing recognition among governments that more focused efforts may be needed to oversee activities.

79 "Draft Space Activities Bill." 2017. Government of India. http://www.prsindia.org/uploads/media/draft/Draft%20Space%20Activities%20Bill%202017.pdf

80 Japan released Basic Plan for Space Policy in 2015, has recently undergone reinterpretation of existing policies that is seeing increased role of military in space affairs. Their space policy and strategy specifically highlights need to develop SSA capabilities.

81 Wheeler, Joanne et al. 2017. "Satellite Bulletin May 2017: Publication of Polish Space Strategy." *Bird & Bird*, May 31, 2017. https://www.twobirds.com/en/news/articles/2017/poland/publication-of-the-polish-space-strategy

82 Zak, Anatoly. 2016. "Russia Approves its 10-year Space Strategy. *Planetary Society*, March 23, 2016. http://www.planetary.org/blogs/guest-blogs/2016/0323-russia-space-budget.html

83 South African Space Council is finalizing new space legislation, "South African Outer Space Draft Legislation"

84 There were plans to develop and implement new space strategy and policies but recent domestic political shifts have halted efforts. Their National Space Development Plan was revised in 2013. https://www.globalsecurity.org/space/world/rok/intro.htm

85 Spain is working to develop a space law. http://spacenews.com/spains-launch-startups-make-a-case-for-hosting-a-european-spaceport/

86 According to an interviewee the Thai Government is looking to draft a space law. Previously in 2014, the Thai Government was looking at drafting a Thai Space Law and Thai Space Master Plan. http://www.unoosa.org/documents/pdf/spacelaw/activities/2014/pres14E.pdf

87 UAE is in the process of establishing its regulatory framework for space activities.

1. Industry Growth

The economic benefit of space activities has spurred government efforts to identify ways to not only build domestic capabilities but to also attract foreign investment. As part of these efforts, some governments (e.g., France, Japan, United Kingdom) are looking at how they can enhance oversight practices to include on-orbit activities, such as specifying the requirements ahead of launch so users do not need to undergo completely new processes. Other countries are also revising their legislation to include new licensing processes for space activities. For example, the United Kingdom passed a bill in March 2018 that included new licensing procedures for suborbital spaceflights and laid the regulatory groundwork for the UK to develop spaceports by 2020.[88]

Other countries that are in the process of establishing their frameworks are seeking to develop flexible licensing procedures to capture a broad range of space activities. For example, UAE is working on laws to promote commercial sector investment in the country, to include topics such as mining. India recently produced a draft bill of space activities that promotes the country as a hub for commercial space activity, positioning India as a place to make satellites and encouraging the use of Indian rockets to launch satellites. India is intending to use this bill to establish a stable regulatory regime from which to build a base for private sector opportunities and to generate jobs in the country.

2. National Security

Countries are beginning to revise or update policies based on the increasing importance of space to national security interests. As a result, militaries are generally gaining additional responsibilities for space activities, especially with respect to SSA. For example, a proposed revision to Brazil's space policy calls for the creation of a National Space Council to be led by the Ministry of Defense (MOD) and to include more responsibilities for the MOD for space activities, which is a shift from traditional responsibilities. Other countries, such as Japan and South Korea, have also had recent shifts whereby the military is being given an expanded role with respect to space activities. Another observation worth noting is the focus in national space policy documents on developing or enhancing SSA capabilities (e.g., 2015 Japan Basic Plan for Space Policy, 2017 Canadian Defense Strategy, 2018 Polish Space Strategy), which indicates growing recognition of the importance of SSA to achieving space goals. As discussed earlier in this report, the motivations to engage in SSA vary but as States come to progressively rely on space, protecting these assets is becoming increasingly critical.

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[88] Butcher, Mike. 2018. "As UK Fires-up Private Space Industry, Space Camp Accelerator Launches. *TechCrunch*, March 29, 2018. https://techcrunch.com/2018/03/29/as-uk-fires-up-private-space-industry-space-camp-accelerator-launches/

B. Growing Collaboration on Space Activities and Data Sharing (including for SSA Data)

As Lal et al. (2015) showed, governments are increasingly developing and engaging in bilateral and multilateral agreements to collaborate on space activities and to share data, including for SSA. Burden-sharing and capacity building are two primary drivers for growing collaboration, especially as emerging spacefaring nations seek to build up their own capabilities and leverage the capabilities, resources, and assets of more established spacefaring nations. Through such mechanisms as university exchanges and technical interchanges, emerging spacefaring nations are able to more rapidly develop domestic space capabilities and achieve their goals. It should be noted that while several interviewees mentioned the importance of university exchanges with established spacefaring nations, these critical partnerships are also occurring between emerging spacefaring nations. For example, a new Pan African Institute on space sciences is due to open pending final signatures on the agreement.[89] A South African interviewee pointed out that this institute would further promote collaboration in Africa on space, and SSA could potentially be a topic for consideration going forward.

For established spacefaring nations, burden-sharing is a consideration when engaging in these partnerships, but it is also a means to gain access to geographically desirable locations by which they can enhance their understanding of the space environment and improve their SSA networks. For example, the Chilean government has an agreement with the European Southern Observatory, which has been granted land and operates three observation sites in Chile for astronomy. In return, Chilean university students and researchers are granted access to these sites. In general, the Southern Hemisphere remains an area of interest for countries seeking to improve their SSA networks, and it is likely that the need for geographic diversity for SSA will continue to be a driver, or at the least a consideration, for established spacefaring nations when pursuing collaboration on space activities.

As detailed in Figure 4-1 and Figure 4-2 below (developed based on data collection efforts from this study), collaboration in space activities has been steadily increasing over the past few decades and will continue given its benefits and the global nature of the space environment.

[89] Waruru, Maina. 2017. “Pan African Space Sciences Institute Forges Ahead.” *University World News*, Issue No. 463, June 9, 2017. http://www.universityworldnews.com/article.php?story=2017060808522673

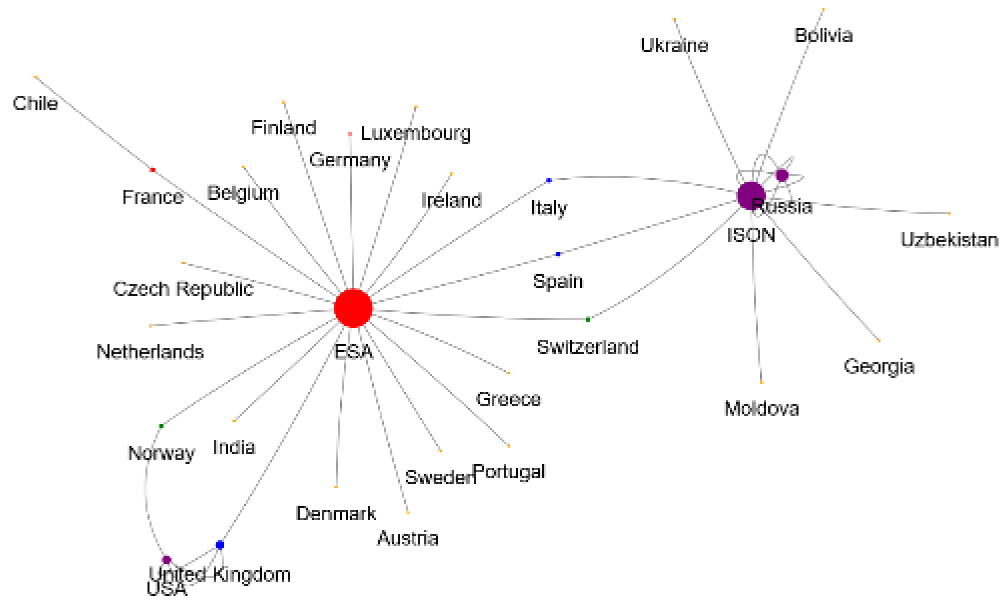

Figure 4-1. Partnerships on Space Activities Prior to 2010, particularly for SSA

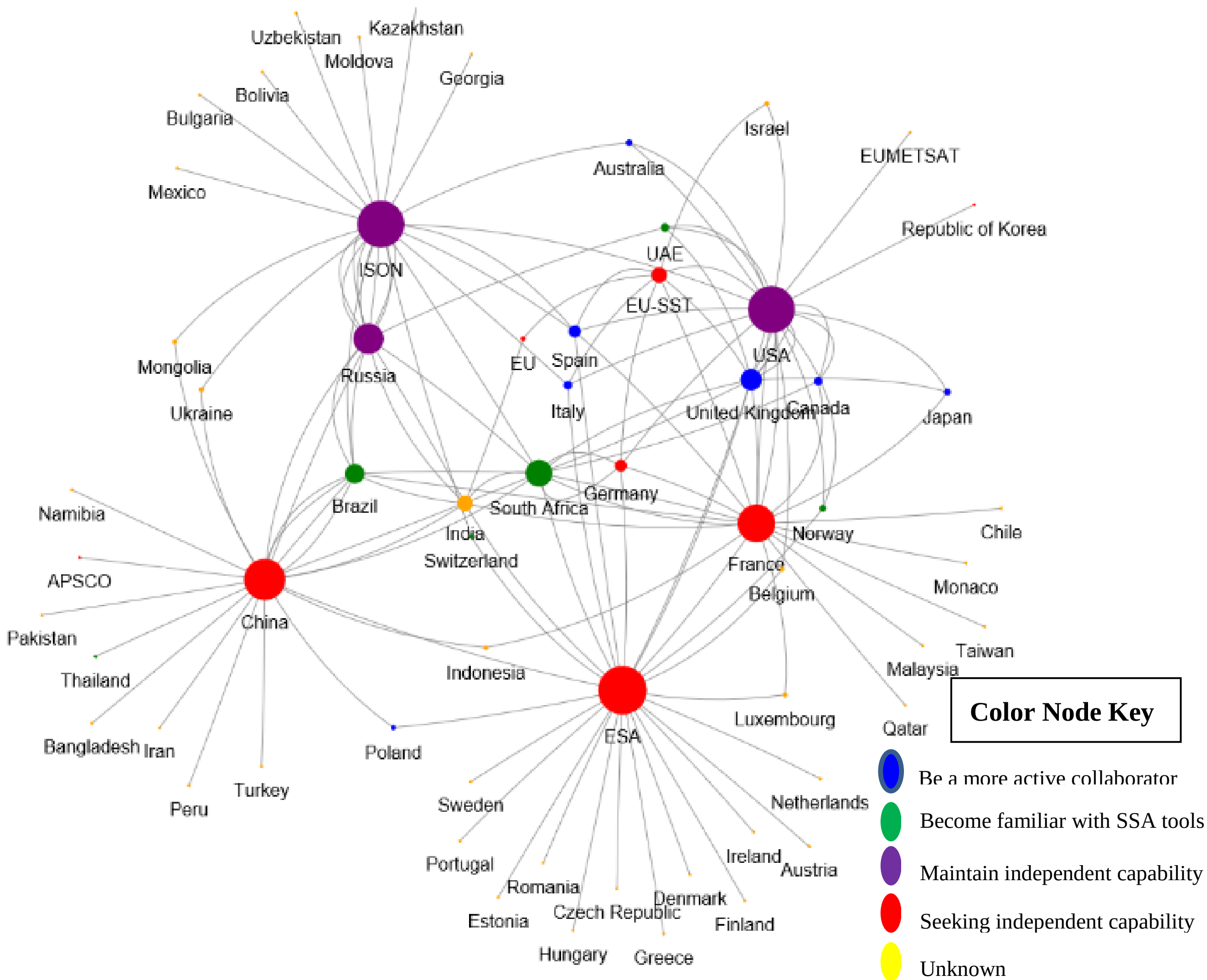

Figure 4-2. Partnerships on Space Activities, particularly for SSA from 2010 to Present

As the global space governance system continues to shift toward a more multipolar system, the United States will likely not be "central organizing entity" for partnerships in space. As new options to collaborate in space present themselves, countries are identifying their needs and pursuing opportunities to directly engage with other entities that can help meet these needs, without the involvement of the United States. In some instances, such as with China-Brazil Earth Resources Satellite Program,[90] these partnerships have been in place for decades. In other instances, new geopolitical realities and opportunities are encouraging new partnerships, an

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90 Kelly, Sean. 2017. "This Is How China Is Slowly Creeping into Latin America." *Hudson Institute*, December 28, 2017. https://www.hudson.org/research/14092-this-is-how-china-is-slowly-creeping-into-latin-america

example being the recent 2016 agreement between the BRICS (a term commonly used to describe the emerging economies of Brazil, Russia, India, China, and South Africa) to develop a remote sensing satellite constellation.[91]

These broader partnerships can be seen as laying the foundation for collaboration on SSA as established and emerging spacefaring countries make arrangements of mutual benefit. Space cooperation in other areas (e.g., remote sensing) will likely form the building blocks for partnerships on SSA, given regional, political, and now technical alliances that may influence involvement of and collaboration between certain countries. In general, many of the government interviewees noted that they would be open to partnering with Europe, Russia, China, and others on space and SSA specifically, especially if it provided an opportunity for them to improve their domestic capabilities. Detailed below are examples of some regional efforts to collaborate on space activities, including for SSA.

1. European Union Space Surveillance and Tracking (EU SST) and the ESA SSA Program

European efforts to coordinate on SSA are currently the most mature from a regional cooperation perspective due in large part to their existing political and economic cooperation. In general, space activities in Europe take place on three levels: national programs, ESA, and the EU. It should also be noted that members of ESA and the EU are not mutually exclusive (i.e., not all members of ESA are members of the EU). The ESA SSA program began in 2009 and has efforts for space weather, near-Earth objects, and SST.[92] The ESA SSA program primarily focuses on science, research and development, and developing the infrastructure to improve European SSA capabilities.[93] ESA is funded by Member States, and some members (e.g., Italy, Spain, and the United Kingdom) invest substantially in the SSA program in support of their own domestic goals. Several interviewees noted that ESA is the best entity to support SSA from a technical standpoint, but it may not be the right entity for operations, particularly from a national security perspective.

The EU SST Framework began in 2015 and is implemented by the EU Consortium, which consists of five European member states (France, Germany, Italy, Spain, and the United Kingdom).[94] The goal of the Framework is to develop a European capability to protect European space assets. The Framework leverages Member States' national capabilities to coordinate and

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91 Raziya, Tabisa. 2017. "SA Joins BRICS Space Programme." *IOL*, July 4, 2017. https://www.iol.co.za/news/politics/sa-joins-brics-space-programme-10127283

92 European Space Agency. 2018. "SSA Programme Overview." http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/SSA_Programme_overview

93 European Space Agency. 2018. "About SSA." http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/About_SSA

94 Through this effort, the EU assumed greater responsibility for SST operational functions for EU. Member States ESA continues efforts to look at future technologies and sensors for SST. The EU recently approved applications from Romania, Portugal, and Poland to join the SST Framework.

share data to deliver SSA services for Europe. As these capabilities are developed, other nations such as Poland are also seeking to develop national SSA capabilities to contribute to the EU SST.

However, a few interviewees compared the lack of transparency of data in the EU SST Framework to the issues some countries have with DoD data. According to one of the interviewees, classification schemes are applied to the data because sensors are primarily operated by military entities, which are only willing to release "white listed" data, which may or may not be useful. Given that concerns for national security were a primary driver for the EU undertaking this effort, and given military equities, these issues are likely to remain in upcoming iteration of the EU SST. However, as the new budget for the EU is negotiated and the follow-on to the EU SST Framework determined, it is possible that some of these concerns may be addressed and mitigated.

2. APSCO and APRSAF

With respect to initiatives in the Asia-Pacific region, it is worthwhile to note the Asia Pacific Space Cooperation Organization (APSCO), led by China, and the Asia-Pacific Regional Space Agency Forum (APRSAF), led by Japan. Both serve as collaborative forums to cooperate on space activities, particularly for space applications. APSCO is arguably more institutionalized and structured than APRSAF. APSCO is modeled after ESA, with a permanent council and secretariat, and has legal status.[95] It has formal rules and requires that its members pay dues. In contrast, APRSAF appears to be more flexible and open with a set of overarching principles; it does not have paying members, but rather has both government and non-governmental participants. Through APSCO, China is leading the Asia-Pacific Ground-based Optical Space Objects Observation System (APOSOS).[96] The goal of APOSOS is to build a network of optical observation facilities around the world for SSA use. APOSOS aims to have at least one observation facility in each of the eight APSCO member countries and elsewhere.[97]

These two organizations have been seen by some experts as mechanisms to spread their respective influences (e.g., China and Japan) across the region.[98] While this cannot be stated for certain, several interviewees cited geopolitical issues as a potential barrier for their country participating in a regional SSA effort.[99] The geopolitical rivalry between China and Japan will

[95] Aliberti, Marco. 2013. "Regionalisation of Space Activities in Asia?" *ESPI Perspectives*, No. 66, February 2013. https://www.files.ethz.ch/isn/163952/ESPI_Perspective_66.pdf

[96] APSCO was established in 2008 with the goal of fostering multilateral cooperation in the Asia-Pacific region.

[97] In addition to China, APSCO members include Bangladesh, Iran, Mongolia, Pakistan, Peru, Thailand, Indonesia, and Turkey

[98] Pekkanen, Saadia M. 2016. "China and Japan Vie to Shape Asia's Approach to Outer Space." *Forbes*, October 31, 2016. https://www.forbes.com/sites/saadiampekkanen/2016/10/31/china-and-japan-vie-to-shape-asias-approach-to-outer-space/#11a402992606

[99] South Korea, Thailand (although Thailand is a part of APRSAF), also see: https://www.mcgill.ca/iasl/files/iasl/mlc-2014-zhao.pdf

likely limit the development of an integrated regional SSA effort, though it does not preclude the possibility of cooperation on space activities. The extent to which these entities may begin to collaborate on SSA remains to be seen.

3. Growing Regional Collaborations in Africa and Latin America[100]

There are also growing efforts in Africa[101] and Latin America to cooperate on space activities. For example, the African Union released a space strategy in 2017 that calls for strengthening regional collaboration on space to deliver benefits nationally and to develop indigenous capabilities more broadly. In Latin America, the Union of South American Nations (UNASUR) previously discussed establishing a South American Space Agency; however, this has not yet been created.[102] Conferences, notably those with an academic focus, continue to remain primary avenues for regional cooperation in Africa and Latin America respectively.[103]

C. Growing Recognition that Creating a New or Revising Existing International Organization and Coordination Frameworks Will be Complex

The increasing number and variety of players in space, each of which has its own priorities, perspectives, and goals for the structure of the global governance system for space, complicates the development or revision of frameworks. There is ongoing debate among governments and non-governmental entities regarding how to build or restructure the global system to address expanding space activities. This debate includes who should be involved in these discussions and to what extent, as well as whether the continued use of forums such as the United Nations is the most efficient way to achieve the desired changes.

1. Perspectives on Structuring New and Restructuring Existing Global Frameworks

There is ongoing debate with respect to the best approach for revising existing organization and coordination frameworks, and developing guidance to address new and evolving operational realities. "Top-down" or "bottom-up" approaches are debated at both international and national levels and across various stakeholders, with no consensus on which system is most suitable. Some interviewees noted that binding international laws were unlikely to be accepted and adopted, and

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[100] There is also collaboration between the two regions (e.g., Africa-South America Summit), though the extent to which it is focused on space activities seems minimal.

[101] African Union. 2017. "African Space Strategy." October 23, 2017. https://au.int/sites/default/files/newsevents/workingdocuments/33178-wd-african_space_strategy_-_st20445_e_original.pdf

[102] Geospatial World. 2012. "UNASUR Wants South American Space Agency." March 2. 2012. https://www.geospatialworld.net/news/unasur-wants-south-american-space-agency/

[103] Global Space Governance (2016).

even so, would not be the most efficient means of coordinating actions in space. As a result, it is more likely that regulations will be enacted at a national level. A palatable next step toward these domestic standards would be to harmonize national space laws, ensuring a platform for space access for those interested.

Other interviewees noted that some higher-level guidelines or principles (such as the LTS) were needed even if more binding rules were difficult to implement. There are also those who argue both aspects are necessary for a holistic approach for global organization and coordination frameworks.[104] The takeaway is that issues of structuring or restructuring global frameworks is being approached from multiple avenues based on the equities and interests of various stakeholders. At some point, to have an overarching and comprehensive organization and coordination framework that can better address the needs of individual actors as well as maintain the long-term sustainability of space activities, there will need to be a harmonization of both top-level and national-level efforts.

2. Perspectives on Involvement in Global Organization and Coordination Frameworks

Opinions on who should lead and be involved in the structuring or restructuring of new and existing frameworks also varies greatly based on the stakeholder group. From the perspective of government representatives, governments are the natural choice to lead efforts. Several interviewees noted that Article VI of the Outer Space Treaty is the clear guide—governments should lead, given that they are responsible for supervising space activities and liability lies with them. Under the Treaty, States should continue to regulate and authorize activities within their jurisdiction, including supervision of non-governmental entities. While government interviewees tended to assert that governments should lead efforts, several interviewees, especially from the United States, did raise the point that perspectives of commercial operators, and industry more broadly, should be included since they have significant knowledge and expertise and will offer insight into what is realistic or desirable regarding oversight and regulation. Their recommendations need to be considered to develop appropriate guidelines for spaceflight safety.

Perspectives of private sector stakeholders also varied. Some interviewees believed commercial operators should self-organize and develop industry best practices and standards to guide broader international efforts. Efforts are already occurring as both global and U.S. domestic trade associations seek to develop best practices and guidelines for safe operations in space (e.g., Satellite Industry Association, Global VSAT Forum). Efforts to encourage responsible behavior through bottom-up approaches are also underway at a global level.[105] Some interviewees from the

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[104] Schaffer, Audrey M. et al. 2017. “The Role of Space Norms in Protection and Defense.” *National Defense University Press*, October 1, 2017.http://ndupress.ndu.edu/Publications/Article/1325996/the-role-of-space-norms-in-protection-and-defense/

[105] For example, correspondence with members of the WEF Space group revealed work underway to develop a space version of the LEEDS energy efficiency certification for buildings. It would establish a rating system and

private sector observed that industry self-organization is being spurred on as a result of the perceived lack of leadership and limited progress offered by governments and forums such as the UN: commercial operators are forced to act out of a need to protect their investments. Stakeholders who held this view felt governments generally lack the ability to make changes that will keep up with the changing space technologies, while industry entities are not encumbered by the bureaucratic processes and restrictions faced by government.

Some private sector providers of SSA services also suggested that it may be sufficient for satellite operators to determine amongst themselves who moves in the event of a conjunction. Many stakeholders acknowledged that the government should regulate to a certain point, though this should be at a minimum and should not interfere with operators' ability to act in and benefit from space. Some suggested government should provide a framework for operators and regulate at a minimum level to ensure safety; others suggested that governments can provide ideas and guidance for space operations but should not impose criteria of behavior.

A smaller subset of industry believed that technologies will progress to an advanced enough state (e.g., autonomous organizational systems) such that oversight and coordination can be done without a human in the loop. For example, satellites will be built with on-board sensors, similar to AIS technology on ships that will enable them to communicate directly with other assets, making the relative position known and enabling more autonomous movements.

3. Perspectives on the UN as a Forum for Structuring and Restructuring Global Frameworks

The UN serves as a useful forum for States to come together and discuss organization and coordination issues, but some reservations remain about using this as the primary mechanism to address growing challenges of space traffic. Many interviewees, including government representatives, mentioned that because the UN operates on a consensus basis, deliberations can be slow and it can sometimes be difficult to achieve more substantive progress. For example, one interviewee noted that an individual country or bloc system (e.g., BRICS – Brazil, Russia, India, China, and South Africa[106]; Group of Latin American and Caribbean Countries or GRULAC) can allow for a level playing field in developing governance rules, but can also lead to a "lowest common denominator" whereby items get watered down in an effort to achieve consensus. These interviewees noted that though the UN has laid the foundation for cooperation in space, it is unlikely that it will be able to innovatively respond to the rapidly changing environment. Non-

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companies could voluntarily certify that their satellites/constellations meet a certain set of standards for sustainability.

[106] The term "BRICS" was coined by a Goldman Sachs chief economist in 2001 to discuss the rapid development of four countries (Brazil, Russia, India, and China). South Africa was added to this list in 2010.

government interviewees also felt that the UN was government-centric, and equities from industry or academia were not always well-represented.

Many of the interviewees noted that the UN could serve as an initial forum to negotiate best practices and standards but that to achieve more substantive progress, other mechanisms need to be considered. For example, one interviewee suggested an expert group be developed, similar to the UN SPIDER[107] effort. The key takeaway is that while the UN serves as a critical forum for achieving international consensus from governments on many issues, other avenues, either through the UN or external from it, may need to be pursued to approach the development of more binding rules and guidelines on space activities.

D. Implications of Current and Emerging Trends

1. It Does Not Appear from Current Trends That There Will Likely Be Agreement on a Binding Global STM Framework in the Next Decade

Based on current trends, there will likely continue to be an increasing amount of technical data sharing agreements across countries. However, a binding legal or political framework in which States voluntarily give up a certain amount of control over their space activities is unlikely to happen within the next decade. In particular, there will likely not be an overarching global "STM" framework, barring the political will of countries or a an external event such as a significant collision in space.[108] Reasons this is not likely to occur include lack of a standard definition or understanding of STM, lack of consensus that STM is a viable approach to address expanding space activity, and lack of consensus on how to model an STM system.

2. There Will Likely Be Many Competing Examples to Model an STM System

If there is an STM regime in the next decade, many examples have been proposed and considered in domestic and global discussions. Although there is not likely to be a formal STM regime in the next decade, ongoing global, regional, and national activities (e.g., the LTS efforts) can address some of the challenges facing space activities today. As noted by one interviewee, these initiatives could serve as the building blocks towards the development of more binding guidelines and rules. It should also be noted that the legal aspect of space traffic management is a topic of discussion at the April 2018 Legal Subcommittee meeting of COPUOS. If enough political

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[107] The UN Platforms for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) initiative was established in 2006 to improve efforts to reduce disaster risk and better support disaster response operations. The groups serves as an information-sharing platform and facilitates cooperation among both users and providers of satellite data (see also: http://www.unoosa.org/oosa/en/ourwork/un-spider/index.html)

[108] However, it should be noted that several interviewees did not think even a collision in space would be sufficient to bring about such a framework.

will is developed this timeline could shift, though, based on current trends, this does not appear likely.

In a previous report, relevant examples for STM in other sectors were reviewed and considered for the lessons learned they could provide in support of developing an STM system (Nightingale, Lal et al. 2016). Based on literature review and discussions with interviewees, some key considerations for each proposed model are discussed below.

a. International Civil Air Organization (ICAO)

Proponents of ICAO as a model noted that the "top-down" approach to managing space traffic was useful to achieve harmonization and standardization of national regulations. An ICAO-like entity for STM could develop standards and policies that States could implement through their national laws and regulations. However, ICAO has limited enforcement mechanisms. Additionally, the suitability of this model may be limited, particularly for on-orbit activities which are significantly different from aviation related activities. See Nightingale, Lal et al. (2016) regarding strengths and weaknesses of the ICAO model.

b. International Telecommunications Union (ITU)

Proponents of ITU as a model reference the fact that this body already engages in STM, given that it manages radio frequency spectrum and coordinates the use of GEO to minimize harmful interference between satellites. It is an example of the "bottom-up" approach where States come together to develop a specialized body to manage a limited resource. Another interviewee noted that "ITU is the best model because it is the only model, but ITU has limited authority" and is therefore not the best option. Additionally, the ITU primarily focuses on pre-launch coordination and not active management on orbit.

c. International GNSS Service (IGS)

Proponents of this model highlighted the data sharing aspect of the IGS. IGS has an open, transparent network with redundant data centers. This "data lake" system fosters collaboration between governments, commercial, academic, and other entities and could provide a similar function for STM. However, the IGS is a voluntary federation that does not have enforcement mechanisms.

3. National Governments Will Likely Focus on Domestic Regime-Building to Address Organization, Coordination, and Management Issues

As space is increasingly seen as a strategic sector, beneficial to national security, economic, and societal activities, efforts to revise existing or establish new legal and regulatory mechanisms for space activities will likely intensify. Given slow progress at the global level to develop an overarching and binding coordination regime, it is likely that countries will increasingly focus on domestic regime-building to address challenges of expanding activity in space. In our assessment, individual countries would continue to streamline existing licensing processes and develop new processes and policies, in particular for industry growth and national security. As more non-governmental entities become involved in space and challenge existing international liability and enforcement mechanisms, there will be growing national effort to oversee activities.

Key emerging challenges would be related to liability and enforcement. Governments would likely face growing challenges of balancing the need to implement sufficient national regulatory mechanisms to oversee space activity while not stifling or otherwise adversely impacting their efforts to promote economic growth of their own domestic space sector. Deterring the use of "flags of convenience" will likely be a key issue in the next decade. It is likely that to address these issues, domestic policies will need to establish mechanisms with more descriptive and prescriptive means of overseeing and managing non-governmental space activities. This need was highlighted by the recent case of the U.S. company that was able to launch its satellites using an Indian launcher despite having been denied a spectrum license by a U.S. Government agency.

For a variety of reasons (e.g., supporting industry, national security, liability), domestic-regime building will continue to focus on addressing issues of expanding space activity, especially if international forums continue to focus on developing non-binding and voluntary mechanisms. As national governments continue to revise and develop their policy frameworks to address expanding space activities, these individual efforts could serve as the building blocks for implementation of an overarching global regime.

4. Military Interests Likely to Remain Dominant

Most governments see SSA first and foremost as a critical national security function, and military organization interests are likely to remain dominant in this area. In the countries that were reviewed as part of this study, SSA is typically led by military entities with civil entities assisting by providing technical expertise, offering operational support, or conducting research and development to improve SSA capabilities (see Table 4-2). Several countries have space operation centers that are run by the military (e.g., Canada, France, Germany, and the United Kingdom). Interviewees generally noted that the military leads SSA efforts due to both the national security component and because the military is typically the entity with the hardware (e.g., sensors, radars) to conduct SSA. However, as technologies and capabilities increasingly become dual-use, the roles and responsibilities for SSA may evolve over time.

The military's involvement in SSA may pose challenges to developing an overarching organization and coordination regime and underscores a broader trend that was raised by nearly all interviewees: that issues of lack of transparency and trust can be barriers to both SSA data sharing and developing institutions to govern space activities globally.

Table 4-2. Roles and Responsibilities for SSA

Country Name	Military	Civil
Australia	Operations lead	Technical support
Brazil	Operations lead	Technical support
Canada	Operations lead	Technical support
Chile	Unknown	Unknown
China	Operations lead	Unknown/Supporting
France	Lead	Supporting
Germany	Operations lead	Technical support
India	Unknown	Currently lead but responsibilities evolving
Italy	Lead	Supporting
Japan	Gaining more lead responsibilities	Moving into a technical support position
Poland	Responsibilities evolving but likely that military will lead	Responsibility evolving
Russia	Operations lead	Technical support
South Africa	Unknown	Lead
South Korea	Supporting but responsibilities evolving	Lead
Spain	Unknown	Lead
Thailand	Responsibilities evolving but likely that military will lead	Responsibilities evolving
UAE	Responsibilities evolving	Responsibilities evolving
United Kingdom	Operations lead	Technical support

Increasing dual-use of space technology could potentially mean more defense capabilities built up in space, straining existing policy mechanisms that call for non-militarization of space. From a data sharing perspective, governments, industry, academia, and others want more access to more data to be able to do their own analysis (or want greater understanding of how data was processed) to support timely predictions. As discussed above, this lack of trust in the fidelity and accuracy of the data is a contributing factor for why some countries want to develop their own SSA systems independent of the United States.

Almost every interviewee highlighted the need for trust and transparency to build a global effort. Interviewees seemed generally optimistic that if all space actors can continue to collaborate, these barriers can be reduced (though perhaps not fully removed), though this will take time. One interviewee compared SSA to GPS and made the point that the SSA system could follow a similar path: GPS started as a military system that some countries were initially wary of using, and now it is ubiquitous. While several countries have developed their own systems to complement or supplement GPS, the ultimate (at least stated) goal is for the systems to be interoperable with each other, allowing for a more holistic and redundant system.

5. Summary and Conclusions

Given the world's growing dependence on space for critical national security, economic and societal services, and infrastructure (and the resultant growing vulnerabilities to any disruptions), there is mounting concern globally to ensure that space assets perform as planned. Additionally, capabilities to track objects in space have not grown at the same rate as the increased use of space. Accurate and precise awareness of the location of satellites and spacecraft and the environment around them, as well as ensuring radiofrequency interference-free operation, are key components of this interest.

Up until recently, the United States Department of Defense (DoD) was the only organization in the world—perhaps together with those in Russia—to develop high-quality space situational awareness (SSA) information. Today, DoD shares some of its SSA information freely with the world, and has agreements to share more with 15 governments and other international organizations and 66 private organizations that operate assets in space. Given a legacy architecture that originated in missile warning and in the era where there were few objects in space, and its overarching national security mission, the DoD SSA system today does not provide the kind of information needed for safe operations in space. Emerging trends in the space environment—where there is growth in the number of objects in space, growth in the number and diversity of operators, diversity of the types of activities in space, and changing satellite technology—will increasingly strain DoD's ability to provide actionable SSA services.

As a result of these changes, there is increasingly an expectation on the part of operators—to include other governments as well as private operators—that the SSA information they receive be better (more precise, more information) and more transparent. Governments of other countries would also like to be more self-reliant with respect to a critical capability that must be sustained (given their own growing dependence and vulnerability on space) if U.S. capabilities become unexpectedly unavailable or no longer offered free of charge. There is also a desire amongst some countries to be a more equal partner with the United States and make more substantive contributions to the U.S. SSA enterprise. As a result, there is growing demand for SSA sensors, software, products and services, and country-level funding for SSA is increasing, dramatically in some countries such as Australia and Japan, and gradually in others such as Poland and Thailand.

Concurrent with this growing demand, technological developments, especially in information technology (IT), have enabled the SSA "system" (that comprises data collection, processing, and creation of products such as conjunction warnings) to be segmented in a way that different organizations can service each part. Unlike the integrated DoD SSA system, organizations providing sensor data need not process it, organizations processing the data into a "catalog" need not collect it, and organizations developing value-added SSA products need neither collect data nor develop a catalog. Each segment in this "functionally modularized" system is also less expensive, which means that the private sector can step in and operate in each segment independently. This trend is visible already with private sector firms especially in the United States and Europe focusing on one or more elements of the SSA system. Experience in other industries (e.g., computing) has shown that entrance of the private sector is a precursor to falling cost and greater innovation. While the field of SSA is more driven by national security concerns (and therefore will likely be slower to "democratize"), it likely will follow the trajectory other fields that were born for government use with government investment and evolved in the private sector for broader societal use. Our case studies show that given its role in national security, at least internationally, the field will remain dominated by defense organizations, even as they collaborate with their civil and commercial space counterparts, domestically and internationally, to develop indigenous capabilities.

Breaking up of the system has enabled each segment to evolve somewhat independently. On the data collection front, there is already an explosion of new sensors through the development of new sites. Countries and companies are also looking for "signals of opportunity" to repurpose existing sensors such as those used for astronomy and atmospheric science research, and for a small investment, utilize them for SSA. Newly added sensors include all types—optical, radar, and radiofrequency—though most are optical, at least in the near-term. Expecting a growing market for SSA, many private companies have plans to add more radar and space-based sensors. The fact that the costs of these sensors (especially optical ones but potentially also radar) is falling is beneficial for the private sector, which has to raise funds in private markets. However, the trade-off between cost and performance of radar may continue. More sensors, even if they are not as precise, allow for more persistence—ability to see assets more of the time. Over time, the plethora of sensors would allow data to become more of a commodity (the need for exquisite data for certain applications will always remain). This trend is similar to that seen in the satellite sector, where small platforms are largely becoming commoditized even as there are highly exquisite high-cost platforms designed to support targeted activities. It also reflects trends in the Earth observation sector where imagery itself is fast becoming a commodity with the value-added services in data analytics.

On the processing front, there is growth of software for creating catalogs and producing more actionable SSA products. Some of the software is open source with the potential to enable faster rates of innovation, although most appears to be proprietary and owned by governments and individual private companies. Most activity is in the United States; however there are pockets of excellence in France and Spain, among other countries

(Figure 5-1 is a color-coded summary of country capabilities discussed in Chapters 3 and 4).

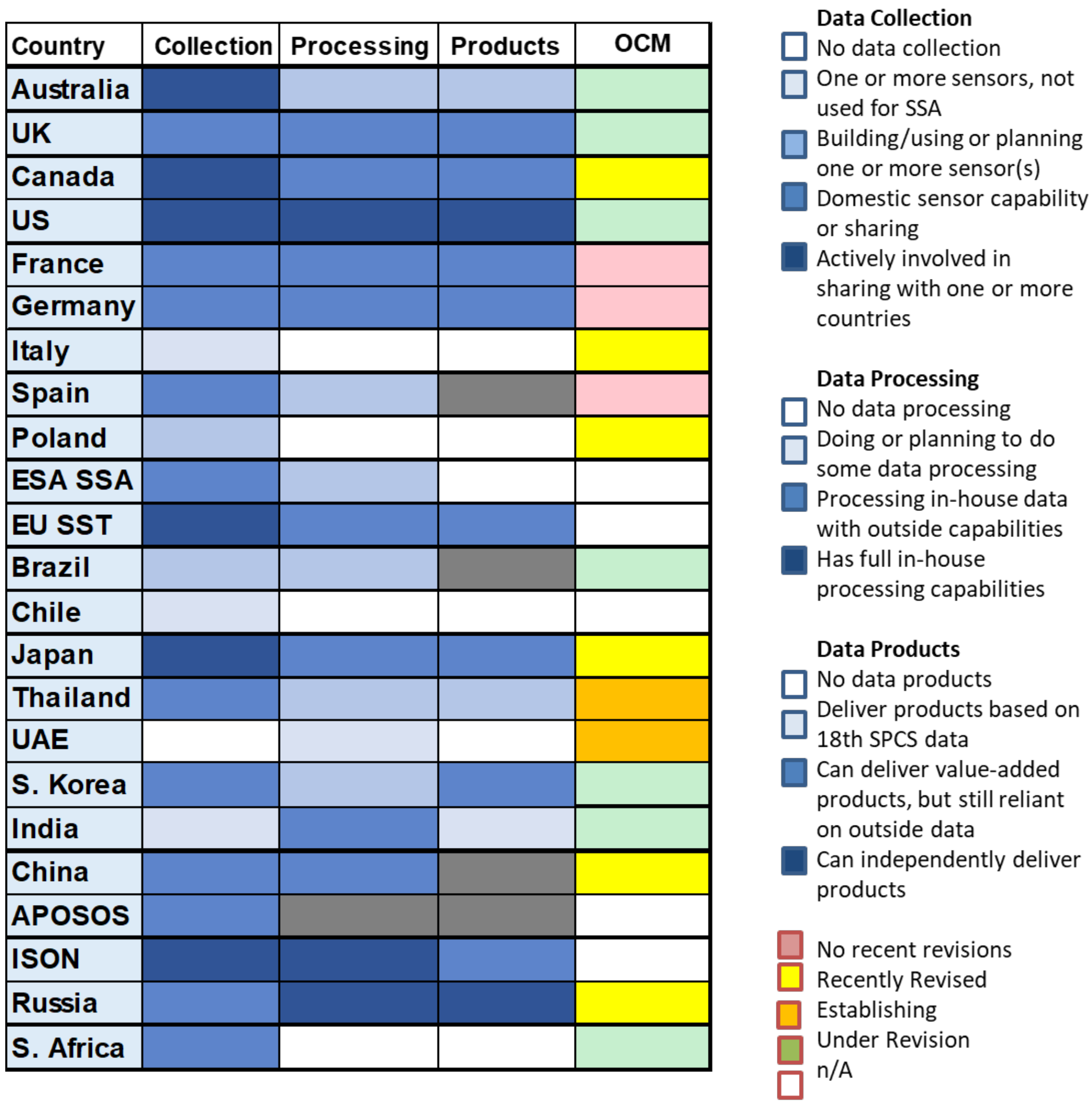


Figure 5-1. Color Coded Chart of Country-Level Capabilities Organized by Blocs

Innovation is not limited just to the counts of sensors or software. There are qualitative changes underway that are likely to improve SSA capabilities. For example, on the sensor front, there are efforts to examine if optical sensors, which are cheaper, easier to install, and more abundant, can be used to track objects in LEO, where most of the growth of space traffic is expected to be. On the processing front, machine learning and other techniques in the mainstream IT community are increasingly being applied to process data expected to come from the growing number and diverse types of sensors. There is also effort to use large amounts of data to compensate for physics-based models in algorithms (e.g., effect of solar weather) and predict at similar levels of accuracy as with more sophisticated models. As a result both countries and companies are increasing their capabilities.

In the coming years, this innovation—both on the quantity and quality front—would allow for increasingly better SSA information. Given growing capabilities in the private sector, it is also likely that the cost of SSA products could substantially decrease. This innovation would allow other countries to follow different pathways (for example, by leveraging the private sector or developing partnerships), and leap-frog closer to the expertise level of the United States without the same investment of time and funding. This in turn would allow them to become more equal partners as well as obtain capabilities that are closer to being on par with the United States, whether they collaborate and cooperate with the United States, or begin to become independent producers of SSA information. The end result is that the United States would likely not be the only source of SSA in the world, even if it remains the best system in the world.

Since space shares many features of a free resource with its concomitant tragedy-of-the-commons implication, there is agreement on part of all stakeholders interviewed including those in the United States that to ensure safe operations in space, there is greater need to share SSA information. As a result, in addition to the data sharing agreements many countries have with the United States, there is increasing collaboration between other countries as well, both bi- and multilateral. In some cases, the partnerships, such as the European Union-Space Surveillance and Tracking project (EU SST), do not involve the United States. Often the partnership/agreement involves sharing of sensor data, and less so algorithms, which more often than not tend to remain proprietary. Many countries are also placing sensors in other parts of the world, particularly in southern hemisphere countries, in exchange for capacity building in the broader space sector.

There is also growing agreement in the SSA community that data sharing alone across countries and organizations is not enough, and there is a need to collaborate to ensure the safety and sustainability of space activities (for example, ensuring that there is no radiofrequency interference across satellites, or that objects move out of each other’s way if there is risk of collision) that is both domestically and internationally coordinated. As a result, efforts to oversee, manage, and coordinate space traffic (i.e., space traffic management or STM) have been increasing. There is growing interest across all spacefaring countries, including emerging ones such as Brazil and South Africa, to contribute to the development of multilateral approaches that serve their interests in space and not simply those of the traditional spacefaring nations. At the same time, participants in international forums recognize that with increasing numbers of players, technologies and activities in space, this will be complex. Issues related to lack of trust in existing institutions, organizations and systems pose challenges to efforts to develop more binding and formal institutions for STM. For these and other reasons, unless some “wildcards” (an example being a significant collision event in space) come into play or until there is significant political will to restructure existing mechanisms, there is likely to be no international agreement on an international STM regime in the next decade. We also expect that governmental efforts would likely focus on domestic STM regime-building. Though global efforts to develop an STM regime may remain slow, there is activity in global forums such as UN Committee on the Peaceful Uses of Outer Space (COPUOS) to lay the foundation of an overarching regime.

Table 5-1 summarizes the global trends and their implications discussed in this report. We end this report with the claim that in the next decade, while U.S. Government capabilities in SSA would continue to be seen as the gold standard, many other countries would likely develop capabilities that would allow them to become independent of the United States, or at least not completely rely on the United States for their SSA needs. This growing independence—combined with their growing dependence on space--would also make countries around the world more vocal participants in discussions related to STM. The world is on a path-of-no-return for the proliferation of SSA capabilities and views on STM, a trend that has significant implications for the United States’ freedom of movement and leadership in space.

Table 5-1:Summary of Trends in SSA and STM and their Principal Implications

	Observations and Emerging Trends	Implications
External Drivers	1. There are emerging changes in the space environment—growth in the number of objects in space, growth in the number of operators, diversity of activities, changing satellite technology—all factors that make existing approaches to SSA more challenging.	1. These changes will necessitate changes in the way SSA (designed for a time when there were few assets doing a small number of things using known technology) would need to be conducted—there will likely be more data from more sources and better fusion capabilities to provide more timely and precise SSA services.
	2. USG provided data and services are viewed as not being transparent enough, and countries and private sector organizations are increasingly more motivated to aim for greater self-sufficiency or to make more substantial contributions to current efforts.	2. As a result of growing interest to participate, there is and will continue to be growing investment both in the private sector and other countries to supplement (and supplant) USG data and services..
	3. Technology changes and other factors have allowed the SSA value chain to undergo "functional modularization“ breaking up the SSA value chain, and allowing more players (including more private firms and academia) to enter the individual links.	3. A greater number of stakeholders in the system and especially the presence of the private sector can create more innovation in the individual segments; it may also require more coordination and interoperability across segments of the system.
Sensors, Data Processing, Creation of Products	4. There is a growing number of sensors of all types—primarily optical, but also radar, and active and passive RF (both ground- and space-based). The growth is driven both by new investment and repurposing of old assets used for science applications.	4. Growth in the amount of data available, together with other advancements such as ability to fuse data from disparate sources, will likely lead to more sophisticated SSA products, with fewer false negatives and positives, more confidence in CAs, lower covariance, etc.
	5. The sensors are increasingly more capable at comparable costs, and R&D is underway to minimize the limitations of optical systems including daytime imaging, mobile sensing platforms, and space-based sensing.	5. While exquisite data will always be needed and be available, growth in the amount of data available would likely lead to the commoditization of most SSA data, with value added services in data processing and creation of value-added services. This trend mirrors that seen in EO community.
	6. There is growth in the number and diversity (e.g., open source) of software/algorithms for processing data and creating SSA products as well as more efficiently operating sensors.	6. Increased data sharing would likely push for and lead to international standards. 7. The proliferation of sensors has already made it possible for more non USG organizations (including countries) to have independent access to data. As they grow capabilities in data processing, countries would increasingly achieve self-sufficiency, and able to be partners with the United States and each other on a more equal footing.

	Observations and Emerging Trends	Implications
	7. Software is increasingly more capable [through the use of tools that enable data fusion, faster processing for large amounts of data, automation]. One particular **emerging capability in the open source** is combining multiple phenomenologies or sensor types to improve the quality of assessment.	8. Given growing capabilities both in sensors and software, countries would increasingly achieve self-sufficiency, and be partners with the United States and each other on a more equal footing. 9. (without agreements in place) Assets would be harder to conceal by both governments around the world as well as private operators.
Private Sector	8. There are a growing number of private sector companies in the United States, but also in Europe, Japan and Australia (with global investors).	10. As a result of private sector approaches, both end-use (e.g., SSA products) and derived services and products (e.g., sensor data) would continue to improve and get less expensive.
	9. Their capabilities are improving at a faster rate especially when compared with government-owned sensors and publicly-released government data.	11. SSA would increasingly be able to be offered as a service (or a hybrid service ownership model).
	10. Companies are experimenting with mainstream business models (e.g., subscription, value-added risk management), turning SSA into a service rather than a technology capability to acquire.	12. With expectations of growth in space, SSA is likely to continue to attract investment. However, in other countries, it is unlikely to be led by the commercial sector. Given national security imperatives, most governments would leverage the private sector, but not outsource service provision to the private sector.
	11. Given national security constraints, many governments are leveraging the private sector (e.g., partnerships, software acquisition) but do not seem willing to outsource service provision to the private sector (see it as an inherently governmental function).	13. In other sectors, typically the emergence of a private sector has led to the globalization of that sector (e.g., computing). Unclear if that will happen here. However, U.S. companies, having already had a head-start, could dominate global markets.
Oversight and Management (O&M)	12.There is growing agreement on part of all countries (including the United States) and non-State actors that to ensure proper functioning of space assets and sustainability of space activities, not only is there need to share data but to oversee, manage, and coordinate space activities both domestically and internationally.	14. SSA is seen especially by governments as a critical national security function first, and military organizations and interests are likely to dominate especially the operational part of SSA, presenting additional challenges to collaborating with civil agencies or creating a global OCM regime.

	Observations and Emerging Trends	Implications
	13. There is growing collaboration on space activities and a growing number of data sharing agreements (including for SSA data). In some cases, the partnerships do not involve the United States.	15. Given lack of trust in international institutions, in the absence of any "wildcards" (such as a major collision in space), will further increase the likelihood that there is no international agreement on an international STM regime in the next decade.
	14. There is growing recognition that with increasing numbers of players, technologies and activities in space, creating a new or revising the existing international O&M regime will be complex.	16. National governments will likely focus on domestic regime-building (with some countries using measures such as incentives to develop bottom-up safety measures).
Overall Observations and Implications	1. Because of national security constraints, the field will likely "democratize" slower than analogous domains such as computing, Earth Observation or small satellites have.	
	2, Private sector capabilities in sensors and software systems will accelerate improvements in the quality of SSA, globally.	
	3. While there are many different reasons countries are pursuing self-reliance, the world is on a path-of-no-return for the proliferation of SSA capabilities, with support from the private sector; the US government will increasingly be one of many information providers to the world.	
	4. While U.S. capabilities are likely to be seen as the "gold standard" and will continue to have exquisite capabilities for SSA, using partnerships and engaging the private sector, other countries' will likely be able to produce "good enough" capability.	

Appendix A.
Current U.S. SSA System

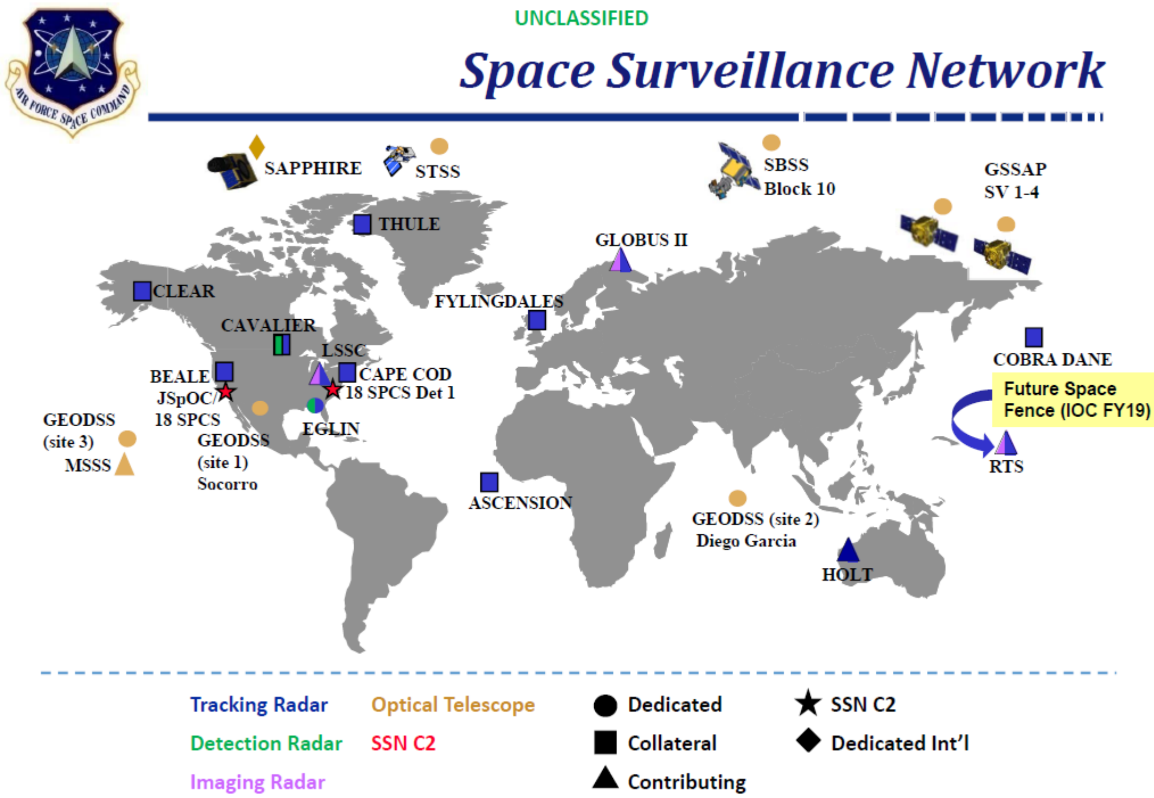
Data Collection

In the United States, metric space situational awareness (SSA) data generally comes from three main sources: the Space Surveillance Network (SSN) of sensors operated by DoD, non-DoD tracking networks, and the satellite owners/operators themselves.

The SSN is a global network of ground and space-based telescopes and radars (see Figure A.1). It includes the following sensors:

- Optical:
  - Ground-based Electro-Optical Deep Space Surveillance (GEODSS) sites
  - Maui Space Surveillance System and Advanced Electro-Optical System
  - Space Based Space Surveillance (SBSS)
  - Sapphire
  - Geosynchronous Space Situational Awareness Program (GSSAP)
  - Space Tracking and Surveillance System (STSS)
- Radar
  - GLOBUS II
  - AN/FPS-85 Space Track Radar (Eglin)
  - Space Fence (coming in 2019)
  - Haystack Ultra-wideband Satellite Imaging Radar, Haystack Auxiliary Radar, and Millstone Hill Radar (MIT/LL)
  - ALTAIR, ALCOR, MMW, Tradex (Reagan Test Site)
  - AN/FPQ-15 (Ascension Range Radar)
  - AN/FPS-123 Solid State Phased Array Radar System (Clear, Cape Cod)
  - AN/FPS-132 Upgraded Early Warning Radar (Beale, Fylingdales, Thule)
  - AN/FPS-108 Cobra Dane
  - AN/FPQ-16 Perimeter Acquisition Radar Characterization System (Cavalier)
  - Harold E. Holt (HEH)[109]

[109] This is a C-Band radar that was moved from Antigua to Australia



Source: US DoD

Figure A.1: Global distribution of SSN sensors.

Figure A.1 shows that most of the SSN sensors are in the northern hemisphere (though Harold Holt is now online in Australia, and the SST will soon be there as well), and the majority are ground-based. Altogether, the SSN takes between 380,000 to 420,000 observations per day.

Space weather data is also relevant for SSA—there are many separate sensors dedicated to collecting this information. The NOAA Space Weather Prediction Center monitors space weather phenomena and provides forecasts, alerts, watches, and warnings about their potential impact on technological systems on Earth's surface or in orbit.

Besides the government enterprise, several private companies such as ExoAnalytic Solutions, Rincon, and SRI International have also gotten involved in SSA data collection. They can operate their own sensors or "rent" time on telescopes from scientific organizations to collect their data.

The final primary source of SSA data comes from the satellite owners and operators themselves. They are the entities that will know of their planned and ongoing maneuvers the soonest, which is important for increasing the validity of future projections (rather than relying on sensors to detect maneuvers as they occur). They can also collect tracking information from their own satellites, including from onboard GPS, ground-based laser-ranging, and telemetry signal analysis. They also would have information on satellite metadata, including launch information, object type, and operator information.

Data Processing

The 18th Space Control Squadron is the tactical unit under the Air Force's 21st Space Wing (21 SW) responsible for maintaining and providing foundational SSA for the U.S. Department of Defense, as well as interagency, commercial and international partners around the globe. It does so on behalf of Air Force Space Command (AFSPC), in support of U.S. Strategic Command's Joint Force Space Component Command (JFSCC), which is charged with executing USSTRATCOM's presidentially-assigned space operations mission. The core functions of 18 SPCS include maintaining the space catalog through space surveillance and tracking data received from the U.S. Space Surveillance Network (SSN), generating spaceflight safety data, and processing high-interest events such as launches, reentries, and breakups. In years past, this role was accomplished successively by the Space Control Center (SCC), 1st Space Control Squadron (1 SPCS), and most recently the 614th Air Operations Center (614 AOC), also referred to as the Joint Space Operations Center (JSpOC). Currently, 18 SPCS is collocated with the JSpOC, which remains the command and control center for JFSCC,[110] and tasks 18 SPCS to perform the SSA mission.

In addition to providing SSA for the DoD and interagency partners, JFSCC, under the auspices of Title 10 U.S.C. § 2274, is also authorized to provide SSA data and information to domestic, international, and commercial entities, to the extent that it is consistent with the national security interests of the United States. JFSCC maintains classified and unclassified versions of SSA data sets and shares information in accordance with SSA sharing agreements with both foreign governments and commercial entities. It also shares the majority of unclassified data with the general public through the website www.space-track.org. This website allows anyone in the world to access current positional data, satellite catalog information, and decay/reentry predictions for over 16,000 on-orbit objects. Through 18 SPCS, JFSCC also provides tailored spaceflight safety support through the lifetime of a satellite, including pre-launch planning, launch and early orbit support, on-orbit conjunction assessment and collision avoidance, disposal/deorbit support, and reentry assessment, all at no cost to the recipient. Through the JSpOC, JFSCC may provide EMI resolution. 18 SPCS consists of approximately 90 military and civilian personnel who are directly involved with management of the satellite catalog. Of these, approximately 20 perform the conjunction assessment and SSA sharing functions and have constant interaction with global satellite operators. Separating the foundational SSA mission from the JSpOC has allowed JSpOC personnel to focus on national security functions, such as providing command and control of military space capabilities and providing space effects to warfighters in theater.

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[110] JFSCC is an all-encompassing entity that covers JSpOC, NSDC, and 18 SPCS, though 18 SPCS does the vast majority of SSA activities.

18 SPCS processes the data from the SSN and maintains catalogs at several levels. The high accuracy catalog (HAC) is a compilation of special perturbation element sets that are stored in state vector format with associated covariance, generated from SSN observations and used as the basis for further analysis by 18 SPCS. These analyses include the generation of special perturbation ephemerides, which are the predicted future positions of space objects created by running the HAC state vectors and covariance through a special perturbation propagator. 18 SPCS also compiles the two-line element (TLE) catalog, which consists of extrapolated general perturbation (eGP) element sets that are stored in TLE set format without covariance, generated from the HAC.[111] The TLE catalog is provided publicly on Space-Track.org. Because they do not have covariance, they may not be optimal for advanced analysis and risk assessment; however, they are accurate for fairly long periods of time and allow satellite operators and the space community to maintain knowledge of the general location of an object.[112]

JFSCC currently relies on two legacy systems to maintain its satellite catalog. The Space Defense Operations Center (SPADOC) began development in the early 1980s by the Ford Aerospace Corporation, with SPADOC version 4C being made operational in the 1990s. SPADOC is the system of record to provide SSA and many other space control functions. In 2000, analysts working within Cheyenne Mountain began development of a second system known as the Correlation, Analysis, and Verification of Ephemerides Network (CAVENet) to augment SPADOC 4C's limitations. CAVENet hosts a variety of applications, including the Astrodynamics Support Workstation (ASW) software suite, which performs key operational functions such as conjunction assessment and sensor tasking optimization. CAVENet is a stand-alone system that does not have direct connectivity to the SNN, so SPADOC 4C continues to be used for functions that require messaging to and from the sensor network, such as launch and reentry processing.[113]

DoD has launched multiple acquisitions efforts to replace SPADOC and CAVENet with more modern systems, all of which have faced significant challenges. In 2000, the Combatant Commanders' Integrated Command and Control System (CCIC2S) was created to replace and upgrade many of the critical systems in Cheyenne Mountain across air, missile, and space warning missions, including SPADOC. CCIC2S air and missile portions ran over budget, and the space portion was never delivered. In the mid-2000s, three new acquisitions programs were created to replace SPADOC and CAVENet: the Space C2 program, the Integrated SSA (ISSA) Program, and the Rapid Attack Identification and Reporting System (RAIDRS) Block 20. In 2009, all three were

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[111] eGP are TLEs based on SP (high-accuracy) data. ASW propagates the state vectors with covariance, converts the data to observations and creates TLEs, which are sent back into SPADOC for dissemination to the SSN and Space-Track. According to DoD, 96% of objects are maintained this way (high-area-to-mass objects are the exception).

[112] The DoD states on Space-Track that TLEs should not be used for conjunction assessment as this is not their primary purpose: TLEs are most useful for contacting a satellite, especially during the early post-launch phase of operations.

[113] This messaging requirement is a driver for the DoD's continued reliance on SPADOC.

merged into a new program called JSpOC Mission System (JMS), which was slated to be completed in 2018 and included three increments:

- Increment 1 provides the initial system infrastructure and data display capabilities.
- Increment 2 is "being developed to deliver most of the required mission functionality, including replacement of legacy data processing and analysis capabilities to directly task sensors, ingest sensor data, produce and sustain a high-accuracy space catalog, increase orbit determination and prediction accuracy, and improve capacity to support conjunction assessment (predicting orbit intersection and potential collision), orbital safety, threat modeling, and operational decisions."[114]
- Increment 3 "is expected to provide a battle management system. That program would help the Air Force prepare for threats to its satellites and bolster the Defense Department's space-event monitoring, planning, tasking, execution and post-event assessments."[115]

JFSCC is currently awaiting delivery of Increment 2, though a further delay was announced in April 2016—this one for 19 months, pushing the Phase 2 Delivery until 2018. JMS has faced many similar delays in the past, and stakeholders remain concerned about overrun budgets and delayed improvements. Between 2006 and 2010, an estimated $132 million was spent on the three predecessors to JMS. Since 2010, the U.S. Air Force has spent another $492 million on JMS, and plans to spend another $337 between 2017 and 2021.[116]

The Air Force has also developed the Non-traditional Data Pre-Processor (NDPP).[117] The purpose of the NDPP is to allow JFSCC to ingest and process a much wider range of data from sources such as commercial and foreign government satellite operators, research telescopes, and foreign government space surveillance systems, by converting them to a format acceptable by current mission systems, such as ASW and JMS. By ingesting and transforming a variety of data formats, NDPP will allow non-SSN data to be validated, verified, and used operationally in JFSCC missions. Information is securely exchanged across security classification levels using the Defense Information Systems Agency's Cross Domain Enterprise Services (CDES), which allows the

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[114] Office of the Director, Operational Test and Evaluation. 2013. "Joint Space Operations Center (JSpOC) Mission System (JMS)."

[115] Gruss, M. 2016. "House Panel Wants More Details on New Space Battle Management System." *SpaceNews*. http://spacenews.com/house-panel-wants-more-details-onnew-space-battle-management-system/. Some requirements of increment 3 have since been added to increment 2 or allocated to other acquisition efforts.

[116] Department of Defense. 2016. "Fiscal Year 2017 President's Budget Submission," 535.

[117] NDPP exists independently of JMS. According to the DoD, its primary purposes are cross domain solution and data conversion. It delivers data to both CAVENet for use in ASW and JMS; it is used daily to bring in ephemeris from satellite owner/operators. Within the year it will be the primary method to send data from JFSCC mission systems to Space-Track.org.

transfer of unclassified data to a classified network containing the government's satellite catalog and analysis tools. The CDES also permits the delivery of analytical results back to unclassified levels, primarily Space-Track.org.

Space-Track.org is a key enabler of NDPP; the public website is the main tool by which JFSCC currently communicates and exchanges data with any users outside the JSpOC, including DoD customers. Connectivity between Space-Track and NDPP will allow outside entities to upload data such as predictive ephemeris or observations to Space-Track.org and have those data automatically transmitted to JFSCC mission systems.[118] This will eliminate some of the current processes that require manual input of data or delivery via CD.

NASA's Conjunction Assessment Risk Analysis (CARA) mission at Goddard Space Flight Center also performs SSA data processing, in that they are responsible for the safety of NASA robotic missions along with selected robotic missions from other civil and commercial customers, and engages in conjunction assessment risk analyses for these missions.

NASA's Procedural Requirements for Limiting Orbital Debris requires NASA to use the HAC to conduct conjunction assessment analyses in NASA CARA for its maneuverable Earth-orbiting spacecraft with a perigee height of less than 2,000 kilometers in altitude or within 200 kilometers of GEO (NASA, Office of Safety and Mission Assurance 2009, Section 3.4). NASA reports its space events to JFSCC, including launches, maneuvers, and reentries. It also provides information on NASA operational missions to JFSCC for conjunction assessment purposes. NASA makes its project protection plans available to JFSCC to assist it in identifying vulnerabilities to NASA's robotic space systems. To serve the CARA mission, NASA Goddard funds a team of contractors who are embedded within JSpOC as CARA Orbital Safety Analysts (CARA OSAs). CARA OSAs provide dedicated and focused support, ensure mission safety and provide timeliness of required data streams to support NASA robotic space mission. Because CARA OSAs have access to appropriate CA systems and their time is paid by NASA, they can produce additional products for the benefit of NASA missions without taxing JFSCC resources. The CARA OSAs have the appropriate access and proficiencies to write scripts and tailor processes to quickly meet CARA mission needs and exigencies. NASA's agency requirements currently stipulate that all CARA-supported missions must use the CARA OSAs' capabilities.

There are also several private companies that are involved in SSA data processing. Some companies, including Analytical Graphics, Inc. (AGI), have developed full commercial Resident Space Object databases using commercial, scientific, and international data. Some companies also provide additional data analysis services to augment JFSCC's free set of conjunction data messages to satellite operators.

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[118] To protect the validity of the catalog, data enters into segregated locations of the DoD's information processing and are not entered straight into the catalog.

In addition to individual for- and non-profit firms, private non-profit associations such as the Space Data Association (SDA) also serve the commercial space sector. SDA is a membership-based organization of satellite owner/operators that wanted more accurate and up-to-date collision avoidance data. JFSCC currently does not ingest positional and maneuver data from satellite owner/operators into the space catalog in an automated fashion, which can sometimes create errors in conjunction predictions.[119] The analytical core of the SDA is the Space Data Center (SDC), run by AGI, and it provides the ability to ingest many different types of owner/operator positional data and maneuver plans. The SDC conducts in-depth analyses on collision warnings provided by JFSCC using DoD and owner/operator data. It also provides radio frequency interference mitigation tools, definitive contacts for collision avoidance, and radio frequency interference coordination to all 22 members of the SDA.[120] In exchange for these services, all members pay fees. The SDA does not collect data of its own—it relies on JFSCC's data for non-member space objects in addition to members' owner/operator data.

Data Sharing

The SSA information and spaceflight safety services currently provided to all operators of active spacecraft by the U.S. military are the result of several decades of evolution.[121] In 1958, NASA's Orbital Information Group (OIG) began sharing SSA data collected by the North American Aerospace Defense Command (NORAD). In 2004, the U.S. Congress modified Title 10 of the U.S. Code to give the DoD authority to carry out a "a pilot program to determine the feasibility and desirability of providing to non-United States Government entities space surveillance." This became the Commercial and Foreign Entities (CFE) Pilot Program. The Secretary of Defense delegated the authority to run the program to Air Force Space Command (AFSPC), which took over from NASA OIG and created Space-Track.org as the primary mechanism. In 2009, the delegated authority shifted to USSTRATCOM with the creation of the Joint Force Component Commander for Space. The CFE Pilot Program was renamed the SSA Sharing Program, and USSTRATCOM was designated the lead entity for negotiating SSA sharing agreements with commercial and foreign entities (Chow 2011). In 2010, the program's pilot phase was completed.

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[119] According to the DoD, though they are able to ingest data directly from satellite owner/operators, the decision is made not to because this data is not always superior, and it takes significant work to validate owner/operator data against the catalog. This is why, for CA, three sets of results are provided: catalog only (does not account for future maneuvers), O/O ephemeris vs. catalog (accounts for maneuvers), and O/O ephemeris vs. O/O ephemeris (accounts for maneuvers)

[120] Space Data Association (SDA). 2013. SDA Users Meeting: General Forum. http://www.space-data.org/sda/wpcontent/uploads/downloads/2013/03/20130318_SDA_Users_Mtg_p.m._Session_FINAL.pdf.

[121] It should be noted that the DoD does not offer Space Traffic Management services. Rather, it helps with spaceflight safety by providing data to empower owner/operators to make responsible decisions (contributing to potential self-imposed STM actions)

The services and data offered by USSTRATCOM through the SSA Sharing Program are broken into three levels: basic, emergency, and advanced. The basic level is available to anyone who registers for a user account on Space-Track.org and allows access to the satellite catalog, positional data in the form of two-line element sets (TLEs), and decay/reentry predictions. Emergency services are provided to mitigate unacceptable risk of: human casualty or damage to property on the surface of the earth or in the air; human casualty in outer space; mission degradation, failure, or damage to any active on-orbit space asset; or degradation to U.S. national security. Emergency Services are intended to provide a minimum level of space flight safety support, regardless of whether an SSA Sharing Agreement has been signed. Conjunction predictions make up the vast majority of emergency services, though JFSCC also provides anomaly support and reentry assessment under the same guidance. Advanced services are available to entities who sign an SSA Sharing Agreement with USSTRATCOM, and include but are not limited to, spaceflight safety support through all phases of operations, as well as specialized data products not available to the general public, such as state vectors and propagated ephemeris for the full unclassified catalog.

Currently, nearly all satellite operators, both domestic and international, rely on the SSA information and spaceflight safety services provided by USSTRATCOM to protect their satellites from collisions with other space objects. These relationships have been built slowly over a number of years, as both USSTRATCOM and the satellite operators developed an understanding of the risk of on-orbit collisions and the value of sharing data.

As of April 2018, USSTRATCOM has signed SSA sharing agreements with over 60 commercial entities,[122] as well as 13 foreign governments: Germany, the United Kingdom, South Korea, France, Canada, Italy, Japan, Israel, Germany, Australia, Spain, Belgium, and the United Arab Emirates.[123] The United States has also signed agreements with two intergovernmental organizations, the European Space Agency (ESA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).

As discussed above, there are also several private companies (and the non-profit SDA) that disseminate SSA data products to their paying customers and/or members.

Action

In general, satellite owners/operators make their own decisions based on the processed SSA data they receive—there is no actively managed space traffic management system in the United States. However, there is some form of space traffic management in that there are several licensing requirements in place for space operations. Four U.S. Government agencies are involved:

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[122] United States Strategic Command. 2014, 2016. SSA TTX After Action Report.

[123] United States Strategic Command. 2014, 2016. SSA TTX After Action Report.

- NASA: NASA operates its own fleet of robotic spacecraft in orbit around the Earth. In conjunction with other national space agencies, NASA actively controls the movements and activities of human space flight objects that are involved in rendezvous and docking operations with the ISS (i.e., it performs STM services for its own assets). NASA has developed a rigorous set of management practices to ensure the safety of the ISS and other spacecraft carrying humans.
- FAA: FAA is a regulator of space launch and reentry transportation carried out within the United States or by U.S. citizens. FAA/AST exercises this responsibility consistent with public health and safety, safety of property, and the national security and foreign policy interests of the United States. In determining whether to issue a license, FAA/AST conducts an interagency policy review, a safety review and approval, a payload review and determination, an environmental review, and sets financial responsibility requirements.
- FCC: FCC is responsible for efficient and effective use of non-Federal radiofrequency spectrum domestically. Internationally it promotes the growth and rapid development of innovative and efficient communication technologies and services. It regulates satellite communications through the licensing of radio transmitters in outer space. FCC licenses may contain conditions regarding end-of-life disposal and debris-mitigation practices.
- NOAA: NOAA is responsible for licensing private remote-sensing space systems. NOAA’s regulations require licensees to provide and operate their systems within certain orbits, submit a plan for post-mission disposition of remote-sensing satellites, and provide a casualty risk assessment for planned post-mission disposals involving atmospheric reentry of the spacecraft.

Appendix B.
Definitions of SSA and STM

There is little commonality in the definitions of SSA and STM across different entities and stakeholders. SSA and STM are often used interchangeably within the community. When entities define SSA and STM, the decision-making and maneuvering processes are often not included. After surveying the definitions of the two terms from the organizations below, STPI chose to use its own framework for the space traffic system in this report (Chapter 1). Below are the selected definitions.

SSA

United States Department of Defense

The DoD defines SSA as cognizance of the requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend.

USSTRATCOM

The requisite current and predictive knowledge of space events, threats, activities, conditions and space system (space, ground, link) status capabilities, constraints and employment—to current and future, friendly and hostile—to enable commanders, decision makers, planners, and operators to gain and maintain space superiority across the spectrum of conflict.

United States Air Force[124]

SSA involves characterizing, as completely as possible, the space capabilities operating within the terrestrial and space environments. SSA information enables defensive and offensive counterspace operations and forms the foundation for all space activities. It includes space surveillance, detailed reconnaissance of specific space assets, collection and processing of intelligence data on space systems, and monitoring the space environment. It also involves the use of traditional intelligence sources to provide insight into adversary space and counterspace operations. The components of SSA are intelligence, surveillance, reconnaissance, environmental monitoring and command and control. The tasks of SSA include find, fix, track, target, engage,

[124] Counterspace Operations. Air Force Doctrine Document 2-2.1. August, 2004

and assess. Accomplishing these tasks ensures coherent battlespace awareness for planners, operators, and commanders.

FAA/AST

SSA focuses on near term safety issues of the space environment, including location of all space objects, and actions of all objects in the environment, regardless of ownership.

NASA

The requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend as well as all factors, activities, and events of friendly and adversary space forces across the spectrum of conflict.

Joint Publication (3-14): Departments of the Army, Marine Corps, Navy, Air Force (JP)

The requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend as well as all factors, activities, and events of friendly and adversary space forces across the spectrum of conflict.

Cosmic Study 2018

The technical capacity to "detect, track, identify, and catalogue objects in outer space, such as space debris and active or defunct satellites, as well as to observe space weather and monitor spacecraft and payloads for maneuvers and other events."

Space Security Index (SSI)

The technical ability of different spacefaring actors, […] to detect, track, identify, and catalogue objects in outer space, such as space debris and active or defunct satellites, as well as observe space weather and monitor spacecraft and payloads for maneuvers and other events.

Science Applications International Corporation

Requisite decision-making knowledge to deter, predict, avoid, operate through, recover from, or attribute cause to the loss, disruption, or degradation of space services, capabilities, or activities, including traffic safety hazards.

Space Foundation

Ability to view, understand and predict the physical location of natural and manmade objects in orbit around the Earth, with the objective of avoiding collisions. Military and national security SSA applications also include characterizing objects in space, their capabilities and limitations, and potential threats.

Secure World Foundation

Ability to accurately characterize the space environment and activities in space. Civil SA combines positional information on the trajectory of objects in orbit (mainly using optical telescopes and radars) with information on space weather. Military and national security SSA applications also include characterizing objects in space, their capabilities and limitations, and potential threats. SSA is an inherently international and cooperative venture. It requires a network of globally distributed sensors as well as data sharing between owner-operators and sensed networks. SSA is also the foundation of space sustainability as it enables safe and efficient space operations and promotes stability by reducing mishaps, misperceptions, and mistrust.

Australian Space Academy

Knowledge of the energy and particle fluxes in near-Earth space, natural and artificial objects passing through or orbiting within this space, including the past, present, and future state of these components. The realm of near-Earth space may be left rather vague at this stage. It is definitely within cis-lunar space, but extends to an Earth-radius of at least 100,000 km to include nearly all man-made objects currently in orbit.

European Space Agency

For ESA, SSA comprises three segments of knowledge:

- SST - Space surveillance and tracking of objects in Earth orbit (Watching for active and inactive satellites, discarded launch stages and fragmentation debris that orbit the Earth)
- SWE - Space weather (Monitoring conditions at the Sun and in the solar wind, and in Earth's magnetosphere, ionosphere and thermosphere, that can affect space-borne and ground-based infrastructure or endanger human life or health)
- NEO - Near-Earth objects (Detecting natural objects that can potentially impact Earth and cause damage)

European Space Policy Institute

Comprehensive knowledge of the population of space objects, of the space environment, and of the existing risks and threats to the space domain. It is within the technical ability of different spacefaring actors to detect, track, identify and catalogue objects in outer space. SSA activities aim to recognize the situation and threats related to space and maintain the robustness of any space operation by commercial, civil, and military actors. Monitoring the space environment needs to be conducted world-wide and it is difficult to tackle the issue with each country acting separately. In this sense, the building of a new framework for international cooperation among the U.S., Europe, Japan and other countries in SSA activities is required.

STM

FAA/AST

STM focuses on making decisions before and during space operations for those operations within a nation's responsibility, such as near and long term safety issues, and actions for which you have authority and responsibility.

Cosmic Study 2018

Space Traffic Management means the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space, and return from outer space to Earth free from physical or radiofrequency interference.

International Academy of Astronautics

Set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space, and return from outer space to Earth free from physical or radiofrequency interference. It is to provide appropriate means for conducting space activities without harmful interference. It supports the universal freedom to use outer space as articulated in the Outer Space Treaty of 1967. It should also be clear that for the purpose of achieving a common good, actors have to follow specific rules, which are also in their self-interest.

Legal Subcommittee of the UN Committee on Peaceful Uses of Outer Space

A concept sometimes defined as the development and implementation of a set of technical and regulatory provisions for promoting safe access to and from outer space, and for maintaining secure operations in space, free from physical or radiofrequency interference.

Science Applications International Corporation

Most notable is whether "space traffic management" includes both policy AND the tools and processes used for Space Situational Awareness (SSA). In a report by the organization, they assumed the two cannot be separated in the context of the goal or space traffic safety, which requires a holistic policy, technology, and operations solution. Also important to note is that policy will dictate SSA technical and operational solutions, and it is paying for those SSA solutions where most of the resources will be expended.

Appendix C.
Case Study Protocol

1. List motivations for doing SSA. What external factors are affecting SSA (e.g., changing technologies)?
2. How do they define SSA? What is included?
3. What are current goals of SSA? What are future goals of SSA? Why are these future goals? What are some challenges to achieving these goals?
4. If known, what is the approximate level of investment in space activities? How has investment changed over time and how, if known, might this investment change in the future? Why?
5. If known, what is the approximate level of investment in SSA? How has investment changed over time and how, if known, might this investment change in the future? Why?
6. Who is funding SSA? (e.g., civil agency or ministry of defense?) Does the level of funding correspond to level of responsibilities? What, if any, distinction is made between civil and defense responsibilities for SSA? Have the responsibilities for SSA changed over time? How might it change in the future?
7. If known, is their preference to build in-house or buy, and why? (develop in-house, augment existing capabilities, or utilize all commercial) If developing in-house capabilities, what are the goals of developing in-house capabilities?
8. Do they get SSA products from outside or produce in-house? If in-house, how is the collection and analysis organized? If from others, where? What are the current and future SSA products and, if known, what are the details they include? What types of SSA products do you use? What current (or emerging) trends do they see as occurring with respect to SSA products (e.g., more reliable, more accurate, more customizable, etc.)? In what other ways are products changing? How will this change, if at all, in the future?
9. Describe level of government reliance on external providers including other governments or commercial products for SSA. Are they purchasing SSA products/services from U.S. or local commercial companies? In what ways do they use commercial? (E.g. are they buying just the software and using it with their own data?

Are they buying data and fusing it with their own data)? Is the commercial SSA market in that country nascent, robust, or nonexistent?)

10. What are sensors and sensor capabilities, currently and in the future? Other data sources used, currently and in the future? Are sensor capabilities (ground- and space-based) improving? Are sensors getting more affordable? Is sensor network becoming more persistent? How will this change, if at all, in the future?
11. What are software and processing capabilities (e.g., new algorithms), currently and in the future? Are processing capabilities getting better? In what ways (software, computing speed, algorithms, etc.)? Is software getting more affordable? How will this change, if at all, in the future?
12. What are the planned technical capabilities or improvements (actual or ideal)?
13. List the major policies, laws, or directives that describe the country's plans to oversee and coordinate space activities. How have these changed over time?
14. What are future plans and why?
15. Provide brief overview or examples of international collaboration on space activities in particular SSA.
16. Provide a brief overview of whether this country participates or invests in any international or regional consortia, specifically for SSA. How active are they in participating and what is their role and how might this change over time? (for example, in the EU SST you can be a provider or a consumer) Do they plan to participate in more groups in the future? (e.g., other regional consortia, SDA, others?)
17. Does this country have a data sharing agreement with the United States?
18. List what, if any, data sharing or MOUs exist and with which countries. Who are the agreements with and why? (e.g., military to military, military to civilian, civilian to civilian) When were they signed? If possible, also discuss what information is shared; is data becoming more accessible to all stakeholders?
19. Are there plans to sign more data sharing agreements in the future? If so, with which countries and why? What is the status of the agreement? (e.g., signed, in discussion)
20. What are views on the future global SSA/oversight and coordination regime? What are perspectives on STM? What models could be used to develop a global space governance system and why? (e.g., ITU, IGS, ICAO, others?) What do they see as limitations or challenges to implementing this model? What will and should international cooperation look like going forward?
21. What are key challenges or threats facing a future global SSA and oversight and coordination regime? How might they be addressed?

Appendix D.
Case Study Summary

	Asia					
Case Study Question	**Japan**	**S. Korea**	**China**	**India**	**Thailand**	**UAE**
Primary motivation to do SSA	National security	National security	National security	Launch conjunctions	Protect space assets	International Collaboration
Definition of SSA (in addition to SST)	NEO, Space Weather	NEO	Unknown	NEO, Space Weather	Unknown	Unknown
Approximate level of investment in SSA	MOD requested 1 billion yen for FY 2018 SSA program	Unknown	Unknown	Unknown	1.5M USE; if SSA approved would be 30 million USD; 1 million on SSA R&D	Unknown
Role of military in SSA	Gaining more lead responsibilities	Supporting, but evolving	Operations lead	Unknown	Evolving, but likely lead	Evolving
Role of civil government in SSA	Moving toward technical support	Lead	Unknown/supporting	Currently lead, but evolving	Evolving	Evolving
Current/planned SSA system development	Preference is not clear; considering using private sector	Preference for domestic capabilities. Currently only government; would consider domestic commercial	Unknown	Preference for domestic capabilities	Preference is not yet clear; SSA is likely to remain government-dominated	Preference is not yet clear, though source indicates likely preference for domestic capabilities
Data sharing agreement with US DoD	MOU (MOD, JAXA, Others)	Ministry of National Defense	None	In discussion	None	Space Agency

	Asia					
Case Study Question	**Japan**	**S. Korea**	**China**	**India**	**Thailand**	**UAE**
Sensor capabilities	1 radar sensor and 1 optical sensor	5 optical sensors	At least 2 optical sensors, 4 tracking ships; global network of sensors through APOSOS	2 radar sensors	1 optical sensor	None
Software/processing capabilities	JAXA does some analysis; also relies on NASA, 18th SPCS, and AGI	Some processing capabilities; reliant on outside data	Unknown; sources indicate maneuvers in response to DoD conjunction warning emails	Software for radar developed in-house; unk how reliant on 18th SPCS	Some processing capabilities; mostly reliant on 18th SPCS	Unknown processing capabilities; reliant on outside data
Planned technical improvements	Developing 1 additional radar and refurbishing optical telescopes; interested in making more observations automated	Developing 1 optical telescope and planning to upgrade 2 of their satellite tracking facilities; plan to deploy optical sensors to high latitude areas, install a radar, and start a space operations center	Conducting R&D on forecasting space environments; considering developing space-based lasers for debris removal	Potentially interested in developing technology similar to or imitating a partnership with Europe	Developing 1 optical sensor and interested in funding space-based sensor	Unknown
Current global/regional partnerships	APRSAF	APRSAF	APRSAF, APOSOS, APSCO	APRSAF	APRSAF, APOSOS, APSCO	APRSAF

	Europe					
Case Study Question	**UK**	**Spain**	**Poland**	**Germany**	**France**	**Italy**
Primary motivation to do SSA	National security and/or protect space assets	International Collaboration	International collaboration	National security and/or protect space assets	Protect space assets and territory	International collaboration
Definition of SSA (in addition to SST)	NEO, Space Weather	NEO, Space Weather	NEO, Space Weather	NEO, Space Weather	NEO, Space Weather	NEO, Space Weather
Approximate level of investment in SSA	22M Euro over 4 years to ESA's SSA programme	Contributed 1,720,000 Euro to the third segment of the EU SST	Contributes unknown amount to regional efforts	Contributes unknown amount to regional efforts	Contributes unknown amount to regional efforts	Contributes unknown amount to regional efforts
Role of military in SSA	Operations lead	Unknown	Evolving, but likely lead	Operations lead	Lead	Lead
Role of civil government in SSA	Technical support	Lead	Evolving	Technical support	Supporting	Supporting
Current/planned SSA system development	Preference for domestic capabilities. Working to improve UKSpOC	Unknown	Unknown	Interested in in-house orbit surveillance sensors	Unknown	Unknown
Data sharing agreement with US DoD	Ministry of Defence	Ministry of Defense	None	Federal Ministry of Defense	Ministry of Defense	Ministry of Defense
Sensor capabilities	1 radar sensor and 2 optical sensors (1 with laser ranging)	1 radar sensor	None	2 radar sensors	1 radar sensor and 1 optical sensor	2 optical sensors
Software/processing capabilities	Developing in-house capabilities; rely on ESA, 18th SPCS	Unknown	Developing in-house capabilities; unk how reliant on 18th SPCS	BACARDI processes sensor data; developing additional capabilities	CAESAR and JAC provide value-added software; fuse 18th SPCS data with French data	Unknown
Planned technical improvements	Interested in revamping UKSpOC	Unknown	Interested in having space-based optical sensor; interested in improving automation of systems	Interested in improving sensors and hardware	Interested in satellite ranging; upgrade GRAVES	Unknown

	Europe					
Case Study Question	**UK**	**Spain**	**Poland**	**Germany**	**France**	**Italy**
Current global/regional partnerships	APRSAF, ESA SSA, EU SST	ESA SSA, EU SST, ISON	ESA SSA, Pursuing membership in EU SST	APRSAF, ESA SSA, EU SST	APRSAF, ESA SSA, EU SST	APRSAF, ESA SSA, EU SST, ISON

	South America		Africa	North America	Australia	Russia
Case Study Question	**Brazil**	**Chile**	**S. Africa**	**Canada**	**Australia**	**Russia**
Primary motivation to do SSA	Protect space assets	Protect space assets	Protect territory	Protect space assets	International collaboration	National security and/or protect space assets
Definition of SSA (in addition to SST)	Unknown	Unknown	NEO, Space Weather	NEO, Space Weather	Neither NEO nor Space weather	NEO, Space Weather
Approximate level of investment in SSA	Unknown	Unknown	Unknown	Unknown	Plan for $1-2 billion on SSA from 2018-2035	Unknown
Role of military in SSA	Operations lead	Unknown	Unknown	Operations lead	Operations lead	Operations lead
Role of civil government in SSA	Technical support	Unknown	Lead	Technical support	Technical support	Technical support
Current/planned SSA system development	Preference for domestic capabilities	Unknown	Preference is not yet clear; improving domestic industry suggests possible commercial involvement	Preference for domestic capabilities. Currently only government; would consider integrating domestic commercial	Currently only government; would consider integrating domestic commercial	Unknown
Data sharing agreement with US DoD	None	None	None	Department of National Defense	Department of Defence	None
Sensor capabilities	None	1 optical sensor	1 optical telescope	1 space-based optical sensor, 1 satellite to track NEOs,; had 1 ground-based optical sensor (2010-2013)	1 optical sensor, 1 RF sensor, 1 laser-ranging sensor	Global network of sensors through ISON
Software/processing capabilities	Interest in developing in-house capabilities; unk how reliant on 18th SPCS	Unknown	Unknown	Analysis done at CanSpOC; also rely on 18th SPCS	Analysis done at AUSSpOC; also rely on 18th SPCS	Have in-house processing capabilities

	South America		Africa	North America	Australia	Russia
Case Study Question	**Brazil**	**Chile**	**S. Africa**	**Canada**	**Australia**	**Russia**
Planned technical improvements	Developing 1 optical sensor in partnership with Russia	Unknown	Partnership with Australia to develop an optical sensor	Developing future ground-based optical sensor	Transferring 1 radar sensor in partnership with U.S.; interested in automating AUSSpOC functions; potential upgrades to current sensors; continuing to conduct R&D research	Unknown
Current global/regional partnerships	ISON	N/A	ISON	N/A	APRSAF, ISON	APRSAF, ISON

Appendix E.
List of Interviewees

First	Last	Affiliation	Country	Category
Greg	Cohen	Western Sydney University	Australia	Academic
Anthony	Wicht	Alliance 21 Fellow at the Centre for a New American Security	Australia	Government
Andre	Rypl	Embassy of Brazil in Vienna	Brazil	Government
Alessandro	D'Amato	MoD, Brazilian Air Force	Brazil	Government
Michel	Doyon	Canadian Space Agency	Canada	Government
Charity	Weeden	Lquinox Consulting LLC	Canada	Government (former)
Stewart	Bain	NorStar Space Data Inc.	Canada	Industry
Guoyu	Wang	China Academy of Sciences	China	Academic
Igor	Portillo	GomSpace	Denmark	Industry
Jean-Luc	Bald	Delegation of EU to USA (First Secretary, Space)	EU	Government
Sebastien	Moranta	European Space Policy Institute (ESPI)	Europe	Academic
Tim	Flohrer	ESA	Europe	Government
Holger	Krag	ESA	Europe	Government
Andy	Williams	European Southern Observatory	Europe	Government
Pascal	Faucher	CNES	France	Government
Francoise	Laporte	CNES	France	Government
Monique	Moury	CNES	France	Government
Sofie	Gauthier	Ministry of Foreign Affairs	France	Government
Stephen	Huland	Air Force	Germany	Government
Tobias	Schmitt	Air Force	Germany	Government
Jurgen	Drescher	DLR	Germany	Government
Karsten	Hess	DLR	Germany	Government
Uwe	Wirt	DLR	Germany	Government
Lars	Wilhelmy	German AF/DLR (Liaison officer from AF to DLR)	Germany	Government
Lt. Col. Walter	Villadei	Italy MoD (Space Policy Office)	Italy	Government
Colonel Shinichiro	Tsui	Japan Cabinet Office	Japan	Government

First	Last	Affiliation	Country	Category
Hiro	Iwamoto	JAXA	Japan	Government
Hiroshi	Yamakawa	Kyoto University AND committee on national space policy, cabinet office, GoJ	Japan	Government
Michiru	Nishida	Ministry of Defense	Japan	Government
Igor	Molotov	Keldysh Institute of Applied Mathematics	Russia	Academic
Viktor	Voropaev	Keldysh Institute of Applied Mathematics	Russia	Academic
Vladimir	Agapov	Russian Academy of Science	Russia	Government
Mark	Reynhardt	Department of International Relations and Cooperation	South Africa	Government
Itumeleng	Makoloi	South African Space Agency (SANSA)	South Africa	Government
Sangwoo	Shin	Korea Aerospace Research Institute	South Korea	Academic
Javier	Cuesta	GMV	Spain	Vendor
Jose	Lozano	GMV	Spain	Vendor
Thomas	Schildknecht	University of Bern	Switzerland	Academic
Thagoon	Kirdkao	LESA	Thailand	Government
Sumaya	Husain Hamad Al-Hajeri	UAE Space Agency	UAE	Government
Moriba	Jah	University of Texas	US	Academic
Diana	McKissock	18th SPC	US	Government
Richard	Buenneke	Department of State	US	Government
Steph	Earle	FAA	US	Government
Marissa	Heron	NASA	US	Government
Scottie	Van Sant	US STRATCOM	US	Government
Doug	Loverro	Department of Defense	US	Government (former)
Mark	Skinner	Boeing (former)	US	Industry
-	-	Lockheed Martin	US	Industry
Patricia	Cooper	SpaceX	US	Industry
David	Williamson	Tyvak Nanosatellite Systems	US	Industry
Chris	Kunstadter	XL Catlin	US	Insurance
Dylan	Taylor	Colliers International	US	Investor
Andrew	D'Uva	SDA	US	Non Profit
Jim	Cooper	AGI	US	Vendor
TS	Kelso	AGI	US	Vendor
Travis	Langster	AGI	US	Vendor

First	Last	Affiliation	Country	Category
Dan	Oltrogge	AGI	US	Vendor
Paul	Welsh	AGI	US	Vendor
Tom	Kubancik	Applied Defense Solutions	US	Vendor
John	Carrico	Astrogator (Google)	US	Vendor
Helen	Reed	Chandah	US	Vendor
Clint	Clark	ExoAnalytic Solutions	US	Vendor
Phil	Cunio	ExoAnalytic Solutions	US	Vendor
Doug	Hendrix	ExoAnalytic Solutions	US	Vendor
Chris	Ingram	ExoAnalytic Solutions	US	Vendor
Bill	Therien	ExoAnalytic Solutions	US	Vendor
Darren	McKnight	Integrity Applications, Inc.	US	Vendor
Phil	Carrai	Kratos Defense and Security Solutions	US	Vendor
Dan	Seperly	LeoLabs	US	Vendor
Cyrus	Foster	PlanetLabs	US	Vendor
Matt	Duncan	SpaceNav	US	Vendor

Appendix F. Scenarios for the Future

This Appendix describes four scenarios for SSA that may come to fruition in the coming decade. The scenarios are extreme archetypes created to generate dialogue, and may ultimately not be realistic, but are helpful to conceptualize a possible framework for SSA. The scenarios are derived from variations on two dimensions—degree of government control (government vs private), and degree of internationalization (domestic vs international) (see Figure F-1).

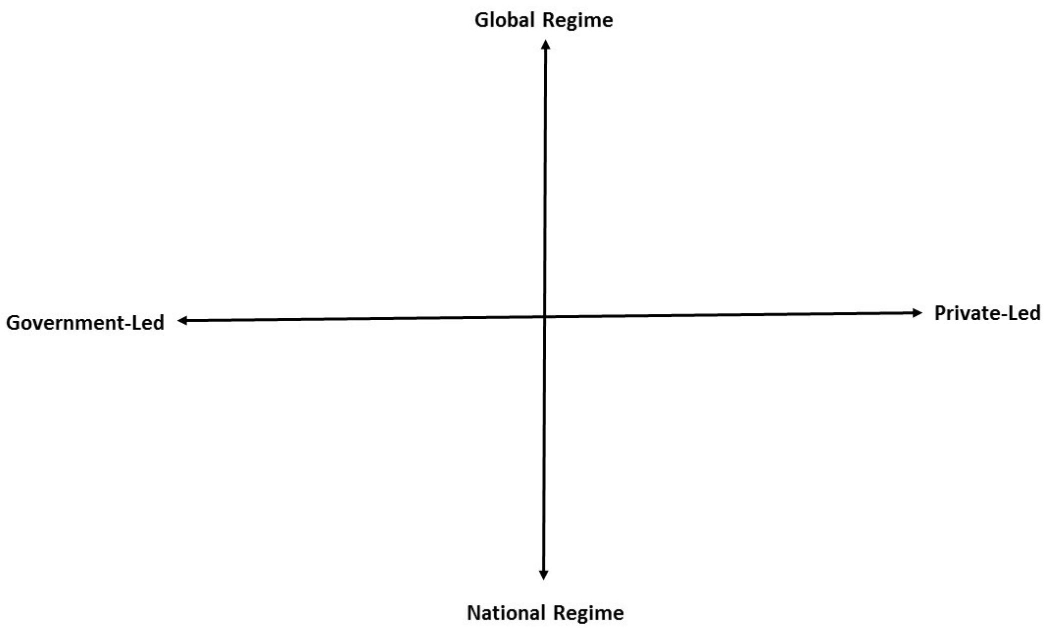

Figure F-1 - Framework for the Scenarios - Two Dimensions

The four scenarios can be found overlaid on the framework in Figure F-2. Scenario 1 is very similar to the current global SSA system, and will extend into the future. The U.S. private sector would lead the SSA system in Scenario 2. Scenario 3 describes a future system where governments work together to share data and there is an international body that coordinates the global SSA system. Finally, Scenario 4 describes a future where each country develops their own systems – they may share data with partners, but they are not reliant on partners for their SSA products and services.

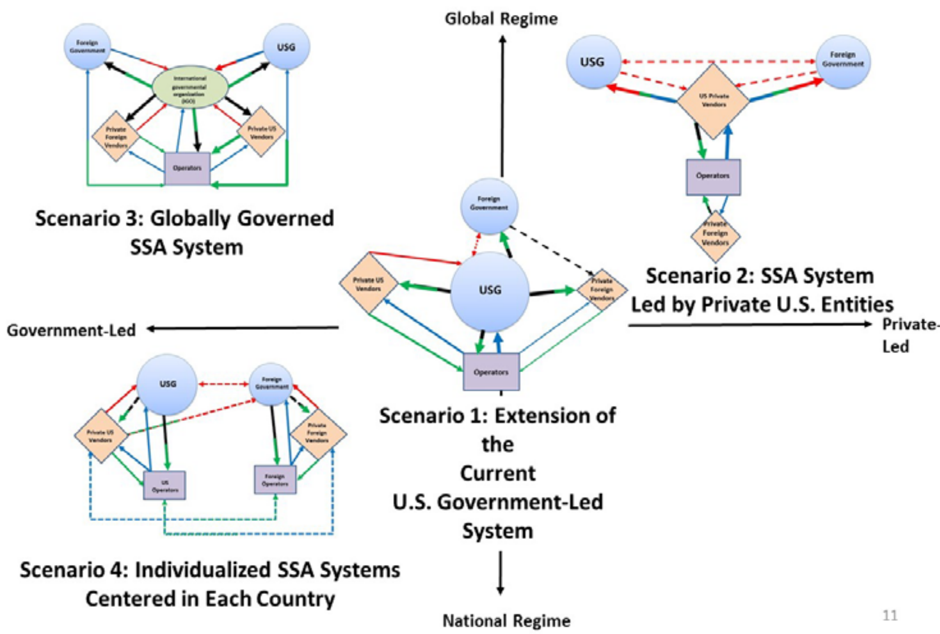

Figure F-2 –Scenarios Overlaid on the Framework

Scenario 1: Extension of the Current U.S. Government-Led System

Description

In this scenario, the United States Government (USG), through either a military or civilian lead agency, remains the primary source of space situational awareness (SSA) data and services for the global space community. The USG would follow the model used by the Global Positioning System (GPS) to provide “gold standard” SSA data and services to the world at little or no cost. Private and international owner-operators would continue using USG data as their principal input, supplemented as needed from other sources such as private companies that provide data to operators for a fee. The USG would continue issuing conjunction and collision warnings for free, as it does today.

USG-owned sensors would remain the primary source of data for the USG catalog, supplemented with data from private and foreign government sensors. To this end, the USG would expand the number of data sharing agreements it has with foreign governments. As part of the data sharing agreements, the USG would continue to decide on the terms of the agreements. In addition, the USG would also expand the number of data sharing agreements with private companies, and the number of private domestic and private foreign vendor organizations with which it works. Those operators who have data sharing agreements with the USG, would continue to share ephemeris and maneuvers with them.

The figure below provides a high-level visual summary of the scenario. The circles represent organizations, their sizes, and their relative positions, and the arrows represent flows of data and information. Arrow colors represent the type of data (sensor, database, SSA products such as conjunction data messages [CDM], and maneuver information). Solid arrows are primary relationships.

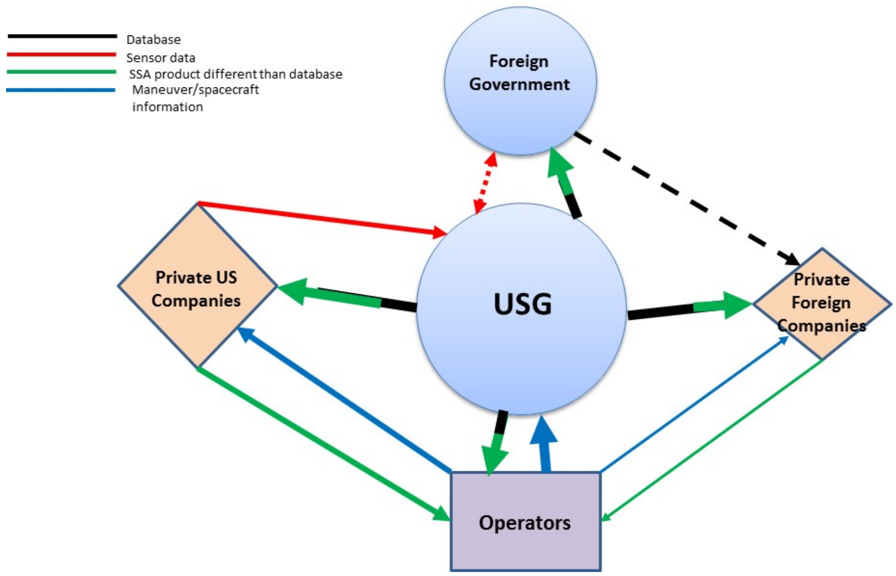

Figure F-3 –Scenario 1: Extension of Current USG-Led System

Implications for the United States

An implication of this scenario is that USG (whether military or civil) remains in control of all data and data products and can control transparency to a level it deems appropriate. It also implies that USG would likely lead global rules on STM.

Drivers

Drivers of this scenario are as follows:

- USG data and algorithms are so much better than the rest of the world that everyone wants to use U.S. systems
- USG provides the service at high quality to the rest of the world at essentially no cost.

Feasibility

Feasibility of this scenario coming to fruition is low, partly because USG does not seem as open to private and international data systems (it would prefer to internalize all innovation).

Scenario 2: Private Sector SSA System Led by U.S. Entities

Description

In this scenario, a consortium of companies predominantly from the United States would serve as the primary source of SSA data. The U.S. consortium collects and processes data and provides SSA data and services to operators and governments that are either members of the consortium or otherwise pay for information services (similar to the Space Data Association [SDA] today). The consortium would get SSA information at all levels from mainly non-governmental providers, but also may incorporate data from governments of all participating countries. The consortium would build an in-house database and sell products and services to entities willing and able to purchase them (similar to the way other multinational entities in the United States and other global enterprises do now). Because of the prominent role of US private companies on SSA, it is expected that the US would have a primary role on the development on an STM regime. However, not to the large extent of scenario 1 as US private companies could easily move to other countries. The USG would have some (but not complete) influence over entities with which they do business.

Sensor data might still be shared between the USG and foreign governments, and between foreign governments and foreign companies; however, the consortium would likely have the best ephemeris, maneuver data and operator database, and would therefore dominate the market. USG agencies as well as foreign governments would likely be members of the consortium and supplement their databases as needed. In this scenario, there is no supervisory entity with an oversight or coordination role.

Innovation for industry comes in the form of data collection (provide extra observations to operators on secondary object), data processing, and data products. Innovation could include development of new sensors, fusing sensor data and developing new algorithms.

Figure F-4 below provides a high-level visual summary of the scenario. The circles represent organizations, their sizes, and their relative positions, and the arrows represent flows of data and information. Arrow colors represent the type of data (sensor, database, SSA products such as CDM, and maneuver information). Solid arrows are primary relationships.

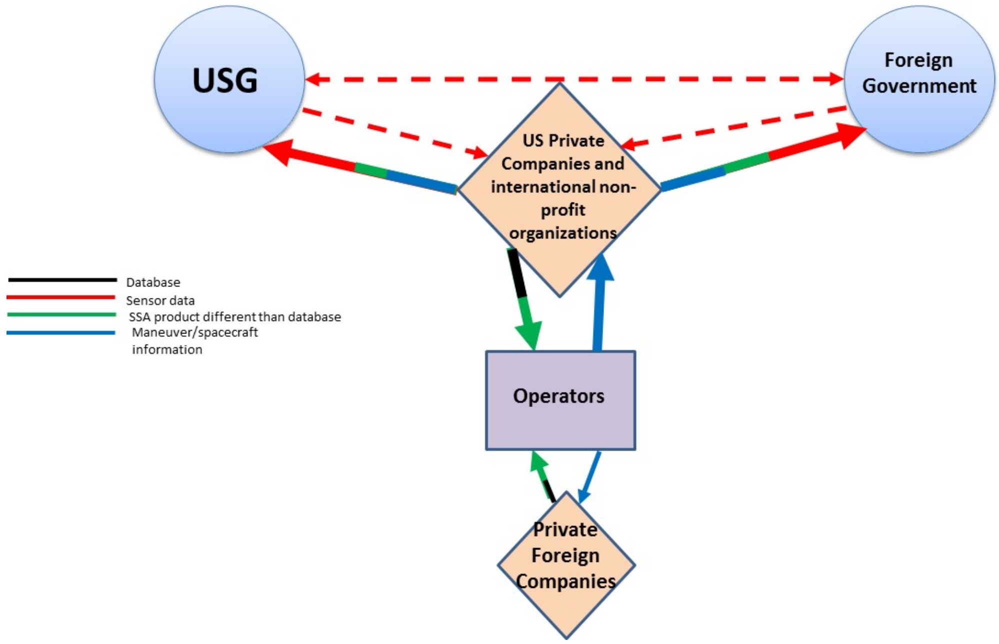

Figure F-4 –Scenario 2: Private Sector SSA System Led by U.S. Entities

Implications for the United States

An implication of this scenario is that now there is an independent external database, which will likely conflict with the USG database.

Drivers

Drivers of this scenario are as follows:

- Growing operator needs—government interest prevents operators from having the information they require so private companies need to step up (e.g., operators need more data to act on a more complex space ecosystem, operators need more transparency to be sure data is actionable, etc.)
- Continued growth in capabilities especially in the U.S. private sector, which are driven in turn by need and the potential for profitability, leading to the private sector investing in new and better capabilities
- Continued reduction in cost of data collection and processing.

Feasibility

Feasibility of this scenario coming to fruition is high because U.S.-led organizations such as SDA are already showing signs of success. Although the dominance will be from U.S. companies in the beginning, private companies will emerge in other countries following the U.S. example. In any case, in the next 10 years, U.S. private companies would dominate.

Scenario 3: Globally Governed SSA System

Description

In this scenario, the main source of SSA data is a global, government-led SSA system with centralized operations fed by government and private nodes spread worldwide; this differs from the SSA system in Scenario 2, which is privately led. Data collection, fusion, and global database generation in this scenario would be led by an international intergovernmental organization (IGO), such as the United Nations or International Telecommunication Union.

The IGO would be open for international participation, but may also include regional nodes that provide data to the central node as deemed appropriate. The data at each of the nodes would come from both government sensors and privately owned sensors. Operators would be mandated to share data (ephemeris and maneuvers) with the IGO. As a result, the IGO would collect data from each of the nodes to create the database. This data sharing would be governed by data sharing agreements administered through member countries. This database would be open and transparent and all participating stakeholders would have access to the data. Because of the number of participating organizations sharing data, this database would likely be the best possible database of space objects. As a result, the IGO supervises space activities, knows about country capabilities, has a list of all RSOs with all the necessary information about them.

Analysis and communication of warnings could be done by the IGO but would most likely be accomplished privately or by individual governments. In other words, operators around the world would develop their own processing and decision-making tools, or they would be supported by other private entities dedicated to interpreting data on behalf of operators. The main contribution of the private sector is the provision of other SSA services different than a database.

The figure below provides a high-level visual summary of the scenario. The circles represent organizations, their sizes, and their relative positions, and the arrows represent flows of data and information. Arrow colors represent the type of data (sensor, database, SSA products such as CDM, and maneuver information). Solid arrows are primary relationships.

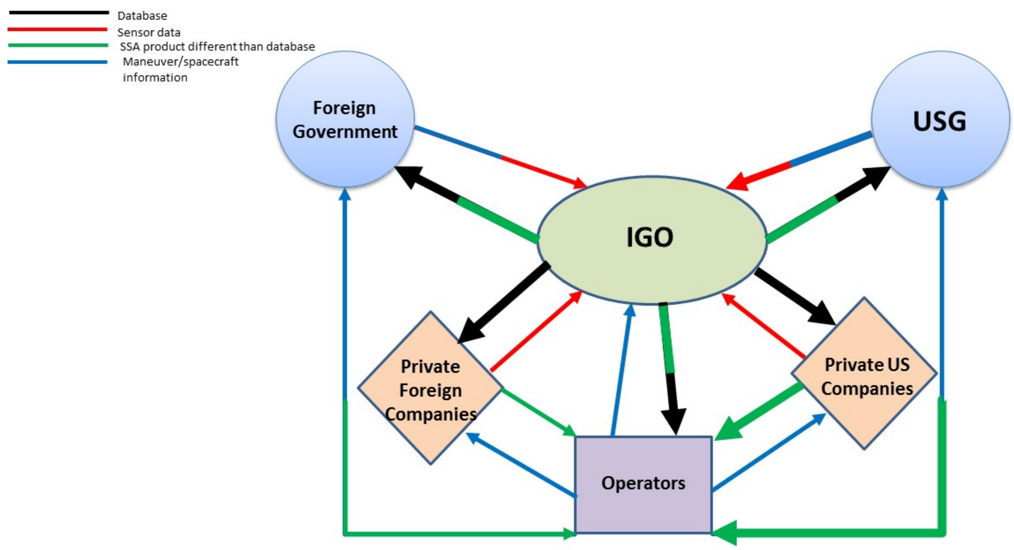

Figure F-5 –Scenario 3: Globally Governed SSA System

Implications for the United States

An implication of Scenario 3 is that USG loses its control over SSA, despite potentially being the largest contributor to the common database. The need for STM may be lessened because of greater global access to SSA.

Drivers

Drivers of this scenario are as follows:

- Growing capabilities in data collection and analysis outside USG
- USG interest in participating in a global system, and sharing more data to make common database superior
- There is a mishap that includes destroying an important government asset or that leads to a significant increase of space debris (similar to 2007 or 2009 events)
- The number of space actors and the large variety of space activities is such that there are orbits (e.g., LEO) where it is difficult to operate in. There is a need to impose restriction on where and how to operate so governments come together to tackle the issue.

Feasibility

The likelihood of this scenario coming to fruition is low due to national security issues, though it is technically feasible.

Scenario 4: Individualized SSA systems centered in each country

Description

In this scenario, each space-faring government owns and runs their own SSA and STM systems, sharing data as they see fit. SSA would be inexpensive enough that each country could have its own system without depending on the USG or other international private or public databases. Private operators and governments would be able to purchase data from any private sector entity. Private vendors would play whatever role governments decide, but in general, governments would significantly restrict what private actors could share—and with whom—for reasons of national security.

The USG catalog would contain data mostly from USG sensors, supplemented with data from U.S. private vendors. Similarly, foreign governments would use data from their own sensors or from domestic or international private vendors. Data could be shared between the USG and foreign governments; however, such sharing would be optional and limited (because governments would no longer depend on information services from the USG). The USG might still provide free services to the world similar to what it currently does; however, other countries would no longer depend on the services.

Operators share data (ephemeris and maneuvers) with the governments and private companies they collaborate with. They could also share data with others for a fee. As each individual country has developed their own SSA system, operators receive support from either their governments or private companies established on their countries for a fee.

Figure F-6 provides a high-level visual summary of the scenario. The circles represent organizations, their sizes, and their relative positions, and the arrows represent flows of data and information. Arrow colors represent the type of data (sensor, database, SSA products such as CDMs, and maneuver information). Solid arrows are primary relationships.

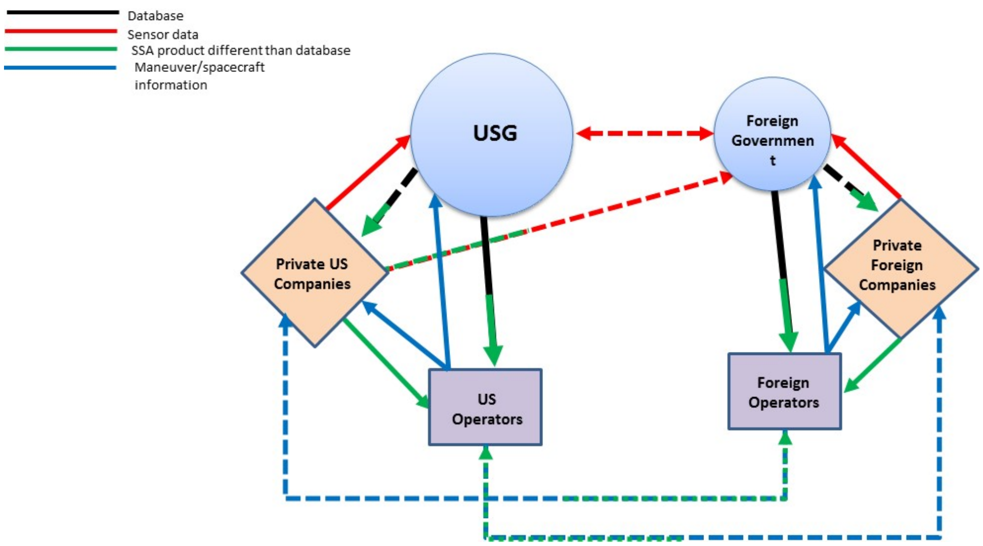

Figure F-6 –Scenario 4: Globally Governed SSA System

Implications for the United States

An implication of this scenario is that more governments would want to have a say in establishing a global STM regime now that they have independent SSA capabilities.

Drivers

Drivers of this scenario are as follows:

- Continued growth in capabilities, especially in the private sector
- Continued reduction in cost of data collection and processing
- Governments investing in developing domestic capabilities to become independent of the USG.

Feasibility

Feasibility of this scenario coming to fruition is high. More countries are becoming dependent on space, and would prefer to have more control over the fate of their space assets.

Appendix G.
Summary of AMOS Dialogue

The IDA Science and Technology Policy Institute co-hosted a dialogue with Secure World Foundation (SWF) and the Maui Economic Development Board (MEDB) at the 2017 Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference in Maui, Hawaii Sept. 19–22, 2017. The topic of the 2017 AMOS Dialogue was the future of SSA, and how it might support future STM regimes. The invite-only event was attended by representatives from government, industry, and academia. The discussion was non-attributional. A summary of the discussion was prepared by SWF and is available https://swfound.org/media/206083/2017-amos-dialogue-report.pdf

To generate and guide the discussion, STPI researchers presented four notional scenarios they developed to identify current and future trends for SSA, the implications for governments and commercial operators, and policy considerations especially with respect to STM. The scenarios are listed below.

- Scenario 1: Extension of the USG-led system
- Scenario 2: SSA System led by U.S. private entities
- Scenario 3: Globally governed SSA system
- Scenario 4: Individualized SSA systems centered in each country

Participants were asked to describe which scenario was the most realistic and which one was the most desirable. While there was significant debate regarding whether there was one "right" scenario that accurately reflected the future SSA and STM environment or whether the future would include elements of each scenario, most participants identified Scenarios 1 and 4 as the most realistic. Scenario 1 was recognized as the least desirable, whereas Scenario 3 was identified as the most desirable, but least likely. Table 1 and Table 2 reflect a call for votes by the moderator to get a better sense of what participants perceived to be the most realistic versus the most desirable SSA scenario.[125]

[125] Note: Not everyone who participated in the discussion voted

Table 1: Votes for Most Realistic versus Most Desirable Scenario (Participants get two votes)

Scenario	Most Realistic	Most Desirable
Scenario 1	15	1
Scenario 2	4	4
Scenario 3	0	14
Scenario 4	15	9

Table 2: Votes for Most Realistic versus Most Desirable (Participants get one vote)

Scenario	Most Realistic	Most Desirable
Scenario 1	14	0
Scenario 2	0	2
Scenario 3	0	10
Scenario 4	6	8

Participants provided various examples of why Scenario 1 seemed more realistic, which included the existing U.S. SSA infrastructure and capabilities, and the U.S. role in providing SSA data and services to the world. However, it was viewed by participants as the least desirable because it is not able to keep pace with the future role of SSA. Participants also saw Scenario 4 as realistic, or at least likely, because some countries may want to have their own system, though some continuation of Scenario 1 where the U.S. Government provides data would still exist for those countries that do not want their own system.

Scenario 3 was seen by most participants as the most desirable but the least likely because international agreements can take considerable time to negotiate. Participants also viewed this as unlikely due to limited resources of other countries and potential hesitance by United States to be directed by an international governmental organization. However, Scenario 3 was seen as the most desirable and the way the system "ought to be" given the collaborative nature of SSA, STM, and space activities more broadly. It should be noted that some participants suggested that the future system could be one that evolves from Scenario 1 to 4, and skips Scenario 3 as countries opt to focus on developing their own capabilities.

A key takeaway from the discussion was that the desired end state depends on what the goals and needs are—if national security is the focus then Scenarios 1 and 4 may develop, whereas if it is safety of spaceflight or SSA for the preservation of the space environment then Scenario 3 may be more likely. Issues of trust and transparency were frequently raised during the discussion as many participants noted that governments, especially the United States, would not want to give up complete control of SSA data or sources to either commercial or international entities. With respect to SSA, participants raised the point that there needs to be a reassessment of how SSA capabilities are categorized. Participants noted that "less sophisticated" SSA capabilities can be sufficient for SSA (e.g., one does not need an entire network, rather a single telescope can be valuable). Finally, with respect to STM, several participants noted that guidance at the international level is important but enforcement of rules and standards will likely be implemented through domestic regimes.

Attendees

(in addition to representatives from STPI and Secure World Foundation)

1. Andrew D’Uva, SDA
2. Tim Flohrer, ESA
3. Gary Henry, Boeing
4. Cyrus Foster, Planet
5. Diana McKissock, 18^{th} SPCS
6. Brian Weeden, Secure World Foundation
7. Ed Lu, LeoLabs
8. Doug Hendrix, ExoAnalytic Solutions
9. Tom Kubancik, Applied Defense Solutions
10. Paul Graziani, AGI
11. Stewart Bain, NorthStar
12. Helen Reed, Chandah
13. Stuart Eves, SSTL
14. Col. Shinichiro Tsui, Japan Cabinet Office
15. Victoria Samson, Secure World Foundation
16. Steph Earle, FAA/AST
17. Uwe Wirt, DLR
18. Thagoon Kirdkao, Royal Thai Air Force

Appendix H.
Models for Oversight and Coordination

(Extracted from STPI report *Evaluating Options for Civil Space Situational Awareness*, available at: https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/P-8038.ashx)

There are four general approaches that can address the "oversight and coordination" category discussed in the space traffic model above: augmenting current licensing processes to include new on-orbit activities; supporting industry safety standards for preventing collisions; establishing government-set "rules of the road" for space traffic direction and collision avoidance; and, finally, establishing an authority with direct control over space traffic. The levels build on each other and are not mutually exclusive. They can be implemented at either/both national or international levels.

Licensing On-Orbit Activities

The United States already licenses space objects for launch and reentry of spacecraft, and regulates two space-based activities—remote sensing and communications. One option for creating an on-orbit STM regime is simply to expand the current licensing to include all on-orbit and deep space activities.

The idea has support. For example, in 2016, the White House Office of Science and Technology Policy submitted a report to Congress requesting that FAA receive regulatory authority to coordinate an interagency process to review proposed private sector space activities for safety and compliance with international law, and issue licenses (Holdren 2016). This report essentially asks Congress to provide FAA with authority to oversee on-orbit activities through pre-launch licensing but not necessarily active oversight during space activities.

Supporting Industry Best Practices and Standards

The Satellite Industry Association has published best practices for responsible space operations (Satellite Industries Association 2015). Such a set of standards could be further developed in collaboration with government and industry stakeholders in the United States in addition to international parties. The theory behind industry-set standards is that industry has the incentive to set safety standards that are high enough that the space environment is safe and usable in the long-term. The self-regulating approach could be very successful in GEO where most owner/operators have a strong profit-motive in keeping the environment safe; however, it is more likely to fail in more common and easily accessible orbits such as LEO.

The principal limitation of this option is that there may not be consequences or repercussions for actors that do not follow the rules, aside from peer or social pressure. This could become increasingly likely as more low-cost satellites are launched. These “free riding” entities are less likely to follow industry-set rules because they may believe that the adverse effects of bad behavior will not affect them in the long-term.

Government-Set Regulations for Preventing Collisions

Another way to implement an STM regime would be for the Federal Government to set “rules of the road” for space that dictate if and when a satellite must maneuver. This type of regulation will likely include rules that limit orbits for non-propulsive spacecraft such as cubesats. In this scenario the Federal Government, while it provides SSA services, will not actively instruct owner/operators to move. Instead, the onus will be on the owner/operators to understand the rules and self-enforce or face penalties, such as denial of a future license. This system will likely increase membership at organizations such as SDA or the need for services from SSA companies.

The practical rules for STM could be very similar under this option as they would be under Scenario 2. The primary difference is simply in who is setting the rules, which affects how the relevant authorities could penalize noncompliance.

Active Space Traffic Control

The final option discussed here for SSA provision is active space traffic management, akin to air traffic control, whether governmentally controlled as in the United States or privately controlled as in Canada and other countries. The controlling authority will be responsible for continuously knowing where all objects are in space, and also for instructing at least U.S. licensee satellites (and possibly others, depending on if other nations acquiesce to the controlling system) when and how to move. If properly created and managed, it could result in the safest space environment. It also has the most onerous regulatory regime as compared with the previous three options.

There are two major concerns with this approach. The first is that the U.S. Government only has authority over the activities of U.S. private sector entities. While this would include a significant proportion of current and planned future satellites, there would still be many satellites over which the U.S. Federal agency managing STM would not have control. If other countries created their own national regulators and gave them active control authority, then the U.S. entity could interface with these other entities, as is the case in air traffic management. However, the prospects of this happening in the near future are slim, given that most countries do not have even a basic space law in place.

The second major concern with this approach is liability. Commercial satellite operators may hold the U.S. Government liable for directing actions that result in damage or destruction to their assets, or for actions that turn out to be unnecessary.

Appendix I.
Scopus Analysis

Publication indexes can be a metric for R&D activity in a field of research. We conducted a Scopus review to look at trends in publications related to SSA around the world. The Scopus review looked at all publications that had "space situational awareness" include in the title, keyword list, or abstract. Exclusions were made for fields that yielded false-positive results—such as medicine, nursing, neurology, and health. Altogether, search results included 1,238 publications from 1987 to 2018.[126] In this report, we only use data form 2001 to 2017. 2018 was excluded because this data does not reflect a full year of publications in the field. In 2017, the number of SSA publications appears to decrease. This may be because publications for 2017 are still in review and are not yet published. Prior to 2001, SSA publications remained low; starting in 2001 SSA publications grow steadily.

Throughout the years, the United States has been a dominant contributor to SSA publications, contributing to well over half of the total publications indexed by Scopus. In recent years, the number of publications from the international community has increased. In 2001, three countries, not including the United States, had SSA publications. Since then, 50 other countries have published on SSA. Notably, Germany, the UK, France, China, Spain, Canada, and Australia all have 38 or more SSA publications since 2001. Germany is the most published country after the United States with 88 publications. The United Kingdom started publishing in 2002, and has since published 78 SSA-related papers or articles. Other countries, such as Italy, Netherlands, Belgium, Austria, Japan, Switzerland, and South Korea, have at least 10 publications. The analysis found that the number of countries publishing is increasing as is the number of publications from each country. Countries with at least 10 publications include India, Finland, Brazil, Poland, Russia, Norway, Turkey, New Zealand, and South Africa. With the exception of Russia, these countries have expressed some interest in SSA, though their capabilities are still nascent.

[126] Areas included in the search included: engineering (943), computer science (418), earth and planetary sciences (367), physics and astronomy (364), mathematics (230), materials science (167), social sciences (62), environmental science (24), energy (21), economics, econometrics, and finance (13), decision sciences (11), business, management, and accounting (6), chemistry (5), arts and humanities (4), biochemistry, genetics, and molecular biology (4), chemical engineering (4), chemical engineering (4), psychology (4), agricultural and biological sciences (3), and multidisciplinary (1). Types of documents included conference papers (862), articles (268), conference reviews (47), reviews (24), book chapters (20), short survey (10), article in press (3), editorial (2), book (1), and note (1). Language was predominately English (1,219) but also included Chinese (16), French (1), German (1), Persian (1), and Turkish (1).

There are some notable surprises in the dataset. Russia, for example, has mature capabilities in data collection, software, and SSA products. They may either not be publishing, or their publications may not be getting indexed by Scopus.

There are limitations to the bibliometric analysis discussed above. Scopus has an extensive number of publications in its database (over 30,000) but it is not comprehensive. Additionally, certain sectors, such as military or industry may be less likely to publish research—in particular classified, sensitive, or propriety research. Figures I-1–I-3 summarize the Scopus analysis.

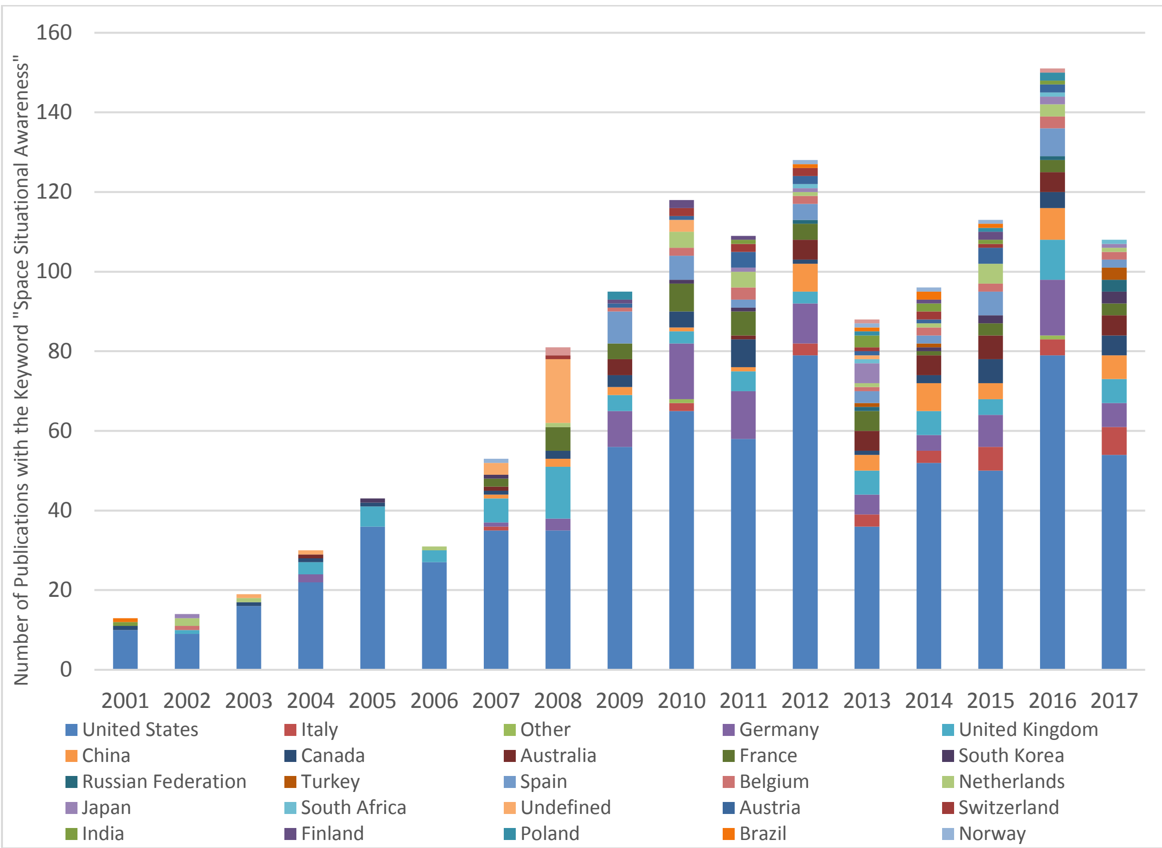

Figure I.1. Scopus-indexed publications by country (2001–2017) n = 1,238

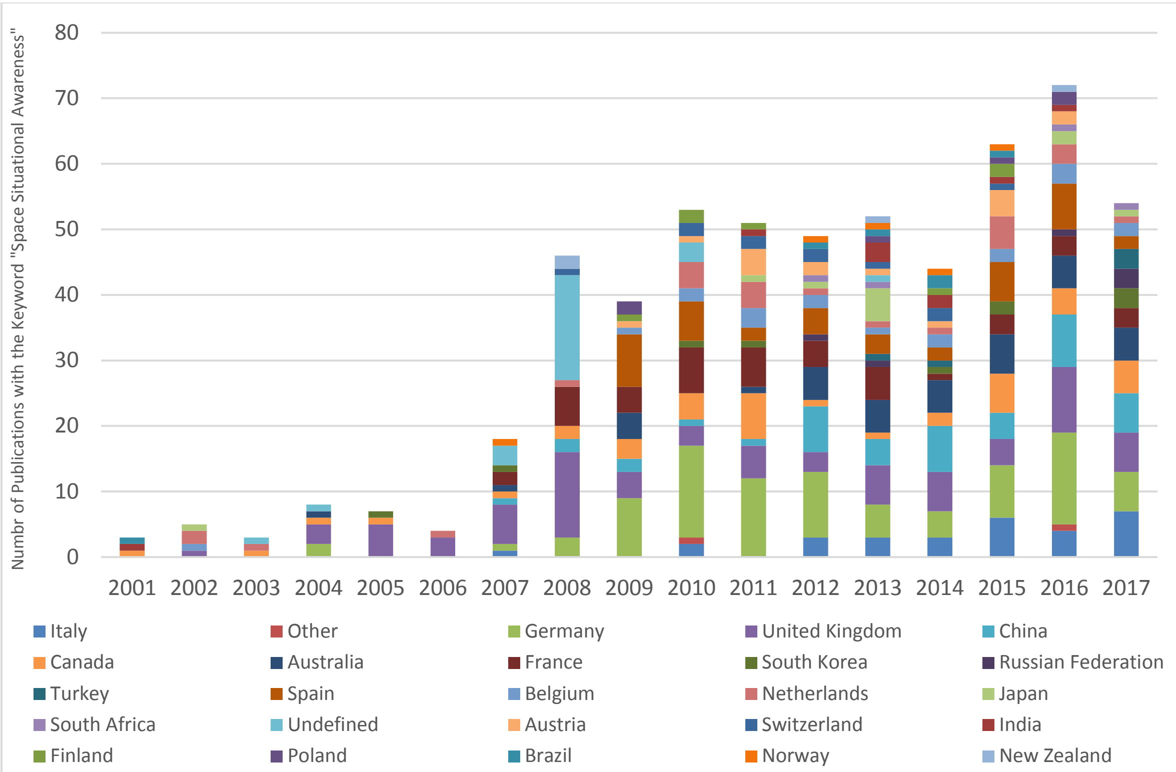

Figure I-2. Scopus-indexed publications by country, excluding the United States (2001–2017)

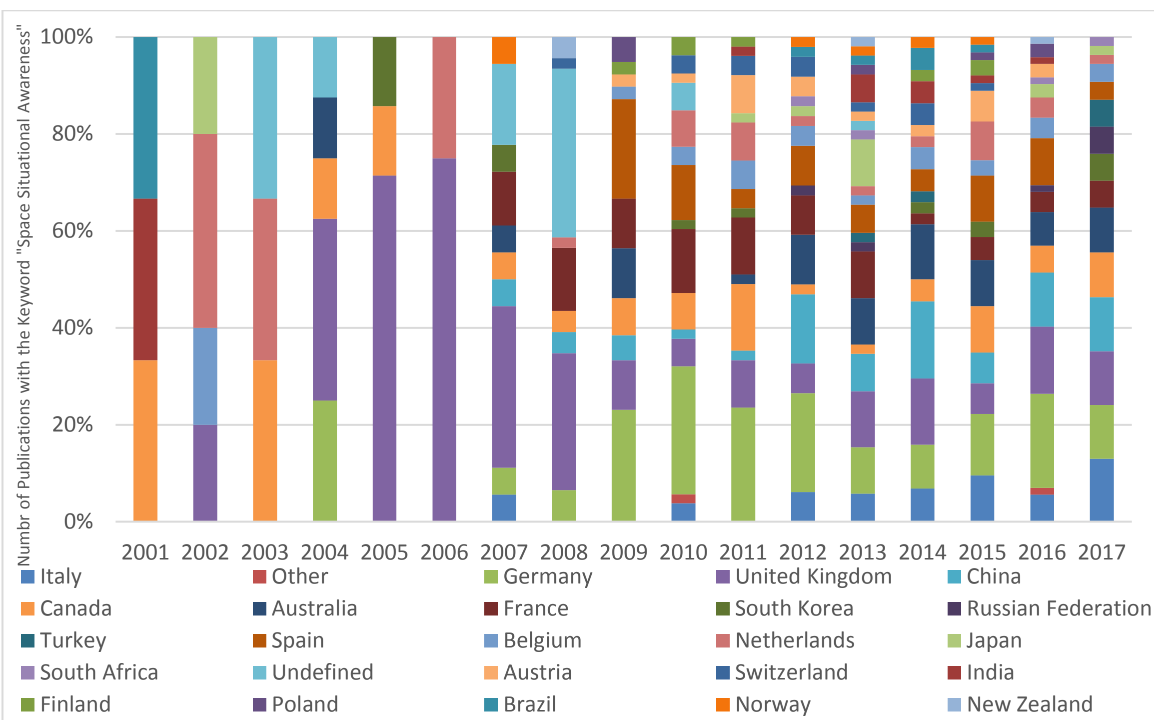

Figure I-3. Normalized Scopus-indexed publications by country, excluding the United States (2001–2017)

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