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THESIS

USING COMMERCIAL SPACE SITUATIONAL AWARENESS AS A VERIFICATION MECHANISM FOR ORBITAL DEBRIS MITIGATION

by

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June 2021

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Orbital debris is a space security problem, and the existing space debris mitigation framework is insufficient to achieve long-term space sustainability. Fortunately, recent developments in commercial space situational awareness (SSA) systems may provide an alternative solution. This thesis explores two research questions. First, could commercial SSA systems be used as a verification mechanism for space debris mitigation accountability? Second, how could such a verification regime lead to future enforceable space debris mitigation policy? To answer the first question, this thesis surveys the capabilities and limitations of the significant SSA technical infrastructures around the world. For the second research question, this thesis explores how commercial SSA systems could be used as a space debris verification mechanism in four possible future options. The four options are the status quo, international enforcement, domestic enforcement, and commercial best practices. This thesis concludes that commercial SSA systems could overcome the transparency concerns of existing government-run systems and that regulators should consider using commercial systems as the primary source of data for space debris mitigation verification. Policy and organizational changes will be needed to attain a verification regime that could enforce future legally binding space debris mitigation policies.

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ABSTRACT

Orbital debris is a space security problem, and the existing space debris mitigation framework is insufficient to achieve long-term space sustainability. Fortunately, recent developments in commercial space situational awareness (SSA) systems may provide an alternative solution. This thesis explores two research questions. First, could commercial SSA systems be used as a verification mechanism for space debris mitigation accountability? Second, how could such a verification regime lead to future enforceable space debris mitigation policy? To answer the first question, this thesis surveys the capabilities and limitations of the significant SSA technical infrastructures around the world. For the second research question, this thesis explores how commercial SSA systems could be used as a space debris verification mechanism in four possible future options. The four options are the status quo, international enforcement, domestic enforcement, and commercial best practices. This thesis concludes that commercial SSA systems could overcome the transparency concerns of existing government-run systems and that regulators should consider using commercial systems as the primary source of data for space debris mitigation verification. Policy and organizational changes will be needed to attain a verification regime that could enforce future legally binding space debris mitigation policies.

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TABLE OF CONTENTS

I. INTRODUCTION ... 1
- A. MAJOR RESEARCH QUESTIONS ... 1
- B. SIGNIFICANCE OF THE RESEARCH QUESTION ... 1
- C. LITERATURE REVIEW ... 3
- D. POTENTIAL EXPLANATIONS AND HYPOTHESES ... 6
- E. RESEARCH DESIGN ... 7

II. GOVERNMENT SSA TECHNICAL INFRASTRUCTURE ... 9
- A. INTRODUCTION ... 9
- B. OVERVIEW OF GOVERNMENT SSA SYSTEMS ... 9
  - 1. The United States: The Space Surveillance Network ... 9
  - 2. Foreign Government SSA Systems ... 15
- C. LIMITATIONS ... 19
- D. CONCLUSION ... 20

III. INTERNATIONAL AND SCIENTIFIC COMMUNITY TECHNICAL INFRASTRUCTURE ... 21
- A. INTRODUCTION ... 21
- B. OVERVIEW OF INTERNATIONAL AND SCIENTIFIC COMMUNITY SSA SYSTEMS ... 21
  - 1. International Scientific Optical Network (ISON) ... 21
  - 2. Europe ... 25
  - 3. Asia-Pacific Ground-Based Optical Space Object Observation System (APOSOS) ... 31
- C. LIMITATIONS ... 33
- D. CONCLUSION ... 34

IV. COMMERCIAL SSA TECHNICAL INFRASTRUCTURE ... 35
- A. INTRODUCTION ... 35
- B. OVERVIEW OF COMMERCIAL SSA SYSTEMS ... 35
  - 1. ExoAnalytic Solutions ... 35
  - 2. LeoLabs ... 38
  - 3. NorthStar Earth and Space ... 42
  - 4. Space Data Association (SDA) ... 43
  - 5. Space Safety Coalition (SSC) ... 45
- C. LIMITATIONS ... 47
- D. CONCLUSION ... 47

V. FUTURE OPTIONS FOR A SPACE DEBRIS VERIFICATION MECHANISM USING COMMERCIAL SSA SYSTEMS 49
A. INTRODUCTION 49
B. THE STATUS QUO AND EXISTING SPACE DEBRIS MITIGATION POLICIES 49
1. International Space Debris Mitigation Policy 50
2. United States Domestic Space Debris Mitigation Policy 52
3. Advantages 55
4. Disadvantages 55
C. WORKING AT THE INTERNATIONAL LEVEL: INTERNATIONAL ENFORCEMENT 56
1. Advantages 58
2. Disadvantages 59
D. WORKING WITH INDIVIDUAL GOVERNMENTS: DOMESTIC ENFORCEMENT 59
1. Advantages 62
2. Disadvantages 63
E. COMMERCIAL LED: COMMERCIAL BEST PRACTICES 63
1. Advantages 64
2. Disadvantages 64
F. CONCLUSION 65

VI. CONCLUSION 67
A. KEY POINTS 67
B. RECOMMENDATIONS 70
C. OPEN THE DOOR FOR SPACE TRAFFIC MANAGEMENT REFORM 72
D. AREAS TO CONDUCT FURTHER RESEARCH 74

LIST OF REFERENCES 77

INITIAL DISTRIBUTION LIST 85

LIST OF FIGURES

Figure 1. SSN Sensor Types and Locations. 11

Figure 2. Sharing Agreements with USSPACECOM by Organization Type. 14

Figure 3. Japan's SSA Concept of Operations. 16

Figure 4. ISON Telescopes and Observatories 23

Figure 5. EU SST Sensors Network 30

Figure 6. The ExoAnalytic Global Telescope Network 37

Figure 7. LeoLab's Interactive Visualization of LEO Objects 42

Figure 8. "Virtuous Cycle Interaction of Global Space Debris Mitigation Activities." 46

Figure 9. The interaction between SEM, SSA, and STM to achieve SOA 74

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LIST OF TABLES

Table 1. Country Technology Maturity Matrix. 18

Table 2. ESA Member States Participating in SSA 26

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LIST OF ACRONYMS AND ABBREVIATIONS

18th SCS	18th Space Control Squadron
APOSOS	Asia-Pacific Ground-Based Optical Space Object Observation System
APSCO	Asia-Pacific Space Cooperation Organization
ASAT	anti-satellite
ASPOS OKP	Automated System for Prediction and Warning on the hazardous situations in the near-Earth space
ASW	Astrodynamics Support Workstation
CARA	Conjunction Assessment and Risk Analysis
CAVENet	Correlation, Analysis, and Verification of Ephemerides Network
CCPAISD	Center on Collection, Processing, and Analysis of Information on Space Debris
COPUOS	Committee on the Peaceful Uses of Outer Space
CSpOC	Combined Space Operations Center
DBF	digital beam forming
DOD	Department of Defense
EGTN	ExoAnalytic Telescope Network
ESA	European Space Agency
ESOC	European Space Operations Center
ESPoC	ExoAnalytic Space Operations Center
EU	European Union
EU SST	European Union Space Surveillance and Tracking
FAA	Federal Aviation Administration
GEO	geosynchronous orbit
IADC	Inter-Agency Debris Coordination Committee
IADC	Inter-Agency Space Debris Coordination Committee
ICAO	International Civil Air Organization
ISON	International Scientific Optical Network
ITU	International Telecommunication union
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KIAM	Keldysh Institute of Applied Mathematics

LEO	low earth orbit
LIDAR	light detection and ranging
LTS	long-term sustainability
NAPA	National Academy of Public Administration
NASA	National Aeronautics and Space Administration
NDPP	Non-Traditional Data Pre-Processor
NEO	Near-Earth Objects
NOAA	National Oceanic and Atmospheric Administration
NSC	National Space Council
NZSA	New Zealand Space Agency
OADR	open architecture data repository
ODMSP	Orbital Debris Mitigation Standard Practices
OSC	Office of Space Commerce
SATCAT	Satellite Catalog
SDA	Space Data Association
SDA	Space Domain Awareness
SPADOC	Space Defense Operations Center
SPD	Space Policy Directive
SSA	space situational awareness
SSC	Space Safety Coalition
SSN	Space Surveillance Network
SSS	Space Surveillance System
SST	Space Surveillance and Tracking
STM	Space Traffic Management
SWE	Space Weather
TLE	Two Line Element
UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs
USSF	United States Space Force
USSPACECOM	United States Space Command

I. INTRODUCTION

A. MAJOR RESEARCH QUESTIONS

How can commercial space situational awareness (SSA) be used as a verification mechanism for space debris mitigation accountability? Furthermore, how can such a verification regime lead to future enforceable space debris mitigation policy?

Orbital debris is an urgent issue that threatens all users of space, and it will only get worse as space inevitably gets more congested. Despite this known challenge, current orbital debris restrictions remain voluntary. They are inadequate to solve future problems, and no systems or policies enforce orbital debris mitigation at either the national or international levels. One reason no such systems or policies exist is the lack of availability of high-fidelity SSA technology outside of the U.S. Department of Defense. However, the private sector is developing new capabilities and services that can possibly fill the technology gap of enforcing such a policy.

B. SIGNIFICANCE OF THE RESEARCH QUESTION

Orbital debris is a space security problem, and the current framework on orbital debris mitigation lacks a verification regime to deal with the challenge of achieving long-term space sustainability. Space policy expert James Clay Moltz defines space security as "the ability to place and operate assets outside the Earth's atmosphere without external interference, damage, or destruction."[1] The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) defines the long-term sustainability of outer space activities

> as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in

[1] James Clay Moltz, *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*, Third edition (Stanford, California: Stanford University Press, 2019), 11.

> order to meet the needs of the present generations while preserving the outer space environment for future generations.[2]

Unsurprisingly, orbital debris puts space security at risk. A 2004 study concludes, "Continued annual growth in orbital debris populations represents a clear threat to the sustainability of space security over the longer term."[3] Despite this clear threat to space security, the current international framework on long-term space sustainability has proven insufficient to hold violators accountable.

China's 2007 anti-satellite (ASAT) test and India's 2019 ASAT test both added a considerable amount of space debris without facing harsh consequences. Although applicable policy on orbital debris mitigation can be traced to the 1967 Outer Space Treaty and the 1972 Liability Convention, the first policy to specifically address orbital debris mitigation guidelines was NASA Management Instruction (NMI) 1700.8 in 1993 for the United States' civil space program. This led to the establishment of the U.S. Government Orbital Debris Mitigation Standard Practices in 2001 (recently updated in 2019), which is applicable to U.S. civil and military space. In 2007, the United Nations adopted the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space on a non-legally binding, voluntary basis. Despite the many orbital debris mitigation policies, there is no accountability, and space debris continues to grow. There remains much to be desired for future policy that is legally binding that could address the future challenges of orbital debris.

Even if an adequate policy that was legally binding was hypothetically created today, neither the United Nations, the United States, nor any other nation could realistically enforce such a policy. For many years, the only comprehensive SSA architecture was the United States Space Force's Space Surveillance Network. However, the U.S. military is not and should not be responsible for maintaining SSA for the whole world. This is where commercial SSA comes in. Today, the private sector can provide accurate and

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[2] Committee on the Peaceful Uses of Outer Space, *Report of the Committee on the Peaceful Uses of Outer Space*, A/74/20 (New York: United Nations, 2019), 50, https://www.unoosa.org/res/oosadoc/data/documents/2019/a/a7420_0_html/V1906077.pdf.

[3] Simon Collard-Wexler et al., *Space Security 2004* (Ontario: Spacesecurity.org, 2004), 6.

comprehensive SSA at low earth orbit (LEO). Governments that lack SSA architectures of their own can leverage commercial SSA services as a tool to enforce their policies.

Much, if not all, of the academic literature on this subject agrees that orbital debris is a growing challenge, yet does not offer actionable solutions on how to hold violators accountable. This research aims to help the global community reach a solution by seriously considering the use of commercial SSA services as a verification mechanism.

C. LITERATURE REVIEW

This literature review will focus on several schools of thought of how to solve the debris problem. These schools of thought are scientifically led approaches, single-nation approaches, international approaches, and public-private approaches toward debris mitigation. The order is chronological in how each approach came about. Once the schools of thought have been characterized, the capabilities of the current technical SSA architecture must be analyzed to determine how commercial SAA can be applied. However, literature on how to use commercial SSA as a verification mechanism is underdeveloped, and this thesis aims to contribute toward such research.

The scientific community plays an important role in influencing space debris mitigation policy, and it was the first to develop policy specific on debris mitigation. James Clay Moltz, who was introduced earlier, credits scientific cooperation between the United States and several other governments during the late 1980s for progressing orbital debris management in his work *The Politics of Space Security*. From the February 1989 "Report on Orbital Debris by Interagency Group (Space)" to the December U.S.-Soviet Orbital Debris Working Group, "this increasingly important environmental issue had finally emerged onto the international space agenda."[4] Although it would be more than a decade for international policy to drafted and approved, NASA continued to make progress on their end. Jer Chyi (J.-C.) Liou is NASA's Chief Scientist for Orbital Debris and serves as the Program Manager for the NASA Orbital Debris Program Office at the Johnson Space Center. In a 2017 presentation on orbital debris, Liou showed how the scientific community

[4] Moltz, *The Politics of Space Security*, 220.

can successfully influence policy. He noted, “NASA was the first organization in the world to develop orbital debris mitigation policy” with NASA Management Instruction 1700.8 “Policy for Limiting Orbital Debris Generation” in 1993.[5] NASA, with the Department of Defense, then established the U.S. Government (USG) Orbital Debris Mitigation Standard Practices, which was approved in 2001. Although the scientific community can successfully influence policy, it is a slow process.

The next school of thought for debris management is a single-nation approach, particularly by a spacefaring nation that can serve as a model for others. No one in particular is promoting this unilateral approach, but this is what is actually happening, so it should be discussed. The United States released its first mitigation guidelines in 2001. Although the United States’ policies on orbital debris mitigation are stricter and more quantitative than its international counterparts, a single-nation approach to the debris problem is ineffective for solving a global problem. In an M.A. thesis titled “Dodging Bullets: The Threat of Space Debris to U.S. National Security” from the U.S. Army Command and General Staff College, Susan Ireland states, “The current [domestic] space debris mitigation efforts operate in this disjointed system because there is no international enforceable standard.”[6] It would take every spacefaring nation to have and enforce its own strict debris mitigation policies for this approach to be successful.

Many prominent figures in space policy call for a stronger international approach to solve the debris problem, but little progress has been made since 2007. There is consensus within the space law literature that space law has not caught up with technological advancement, especially when it comes to matters such as commercial space activities, space traffic management, and orbital debris mitigation. As discussed earlier, the current space debris mitigation guidelines are voluntary and not legally binding. However, such an international approach will be an uphill battle. The disadvantages of the international approach in solving the debris problem can be tied to the disadvantages of

[5] Jer Chyi Liou, “Orbital Debris Briefing” (Presentation, EOP/OSTP Briefing, Washington, D.C., December 2017), 5, https://ntrs.nasa.gov/api/citations/20170011662/downloads/20170011662.pdf.

[6] Susan Ireland, “Dodging Bullets: The Threat of Space Debris to U.S. National Security” (Master’s Thesis, Fort Leavenworth, KS, U.S. Army Command and General Staff College, 2010), 40.

global institutionalism with regard to space security. Moltz states, "The disadvantages of the global institutionalist school are enforcement costs and the risk of free riders."[7] Just as the science community alone cannot establish nor enforce debris mitigation policy, the international community cannot enforce guidelines that are not legally binding. Getting nations to fund international organizations that will be required for space debris and traffic management will not be easy, and it will take a great deal of political will to do so. In an effort to provide a road map for developing future space policy, the University of Nebraska's Frans von der Dunk analyzed the 1967 Outer Space Treaty and the 1972 Liability Convention in the 2001 journal article "Space Debris and the Law." He proposed developing future law "firstly by means of 'soft', non-binding law such as resolutions, guidelines or codes of conduct which later on could develop, if of proven value and feasibility, into 'hard' law."[8] The softs laws of the 2007 UN mitigation guidelines have yet to evolve into hard law. In a separate analysis of the 1972 Liability Convention appearing in his book *Crowded Orbits*, Moltz assessed the guidelines as confusing and inadequate to deal with complex international liability issues.[9] Space debris mitigation policy needs to be clarified so enforcement can take place.

As far as what should happen next for an international approach, there are a variety of ideas from specific policies to calling for a stronger international regime. In the *Chicago Journal of International Law*, Chelsea Muñoz-Patchen suggests that the international community adopt a "market-share liability regime under which debris-creating nations fund the clean-up."[10] However, this requires strong buy-in that is not possible with current "soft" laws. Many experts call for a stronger international regulatory regime that could apply such policies. In both *Crowded Orbits* and *The Politics of Space Security,* Moltz calls for multilateral cooperation in space to control and eventually reduce orbital debris. Susan

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[7] Moltz, *The Politics of Space Security*, 357.

[8] Frans von der Dunk, "Space Debris and the Law," *Proceedings of the Third European Conference on Space Debris, 19 - 21 March 2001*, SP-473, 2 (March 2001): 867.

[9] James Clay Moltz, *Crowded Orbits: Conflict and Cooperation in Space* (New York: Columbia University Press, 2014), 84.

[10] Chelsea Munoz-Patchen, "Regulating the Space Commons: Treating Space Debris as Abandoned Property in Violation of the Outer Space Treaty," *Chicago Journal of International Law* 19, no. 1 (June 2018): 28.

Ireland prescribes that "a peer-monitored space debris mitigation compliance program implemented within the IADC would provide better protection of U.S. national security interests in space,"[11] and "the IADC has the necessary operational focus and expertise to implement a mutual evaluation compliance program for space debris mitigation."[12] This thesis will show how commercial SSA might be applied by international regulators to enforce space debris policies.

The fourth school of thought is an increased private-public led approach. Literature on this subject is limited, but it was captured in Moltz' *The Politics of Space Security* when he noted the establishment of the commercial-consortium Space Data Association in 2009.[13] Moltz also assessed that commercial SSA systems such as California-based LeoLabs could increase transparency, which might improve chances for collision avoidance, and provide data that can hold debris creating entities accountable. This thesis will explore this approach further.

In conclusion, there are four school of thought when it comes to solving the space debris problem: scientifically led approaches, single-nation approaches, international approaches, and public-private approaches. There is expert consensus that the lack of law and policy, not technology, is holding the world back from solving the orbital debris issue. Also, literature that details the use of commercial SSA by regulators as an enforcement mechanism for space debris mitigation is under-developed, so this thesis will contribute to this area. Lastly, the topics of Space Situational Awareness and Space Traffic Management are often tied together. For the scope of this thesis, I will have to be diligent in focusing on orbital debris mitigation because space traffic management is a separate problem set.

D. POTENTIAL EXPLANATIONS AND HYPOTHESES

There are four possible solutions that are worth exploring for how commercial SSA could be applied to be a verification mechanism for space debris mitigation. The four options are (1) continuation of the status quo, (2) international enforcement, (3) domestic

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[11] Ireland, "Dodging Bullets," 102.

[12] Ireland, 103.

[13] Moltz, *The Politics of Space Security*, 344–45.

enforcement, and (4) commercial best practices. The status quo is a weak international regulatory regime with the U.S. Department of Defense providing the bulk of SSA data to the world. The second and third possible solutions would involve governments moving away from the U.S. military's SSA system and contracting commercial SSA services. This could be done either by contracting individual commercial SSA systems or using international consortiums like the Space Data Association. Commercial best practices would require commercial sector applying strict guidelines on themselves with the interest of preserving space for future use.

E. RESEARCH DESIGN

Using a qualitative case study approach, this thesis focused on the capabilities of existing SSA systems and how commercial SSA can be used as a verification mechanism by regulators for space debris mitigation. This thesis intends to answer the research questions by discovering shortcomings in existing SSA systems and policy. It was impractical to analyze every SSA system. It was also impractical to analyze the domestic space debris mitigation policies of every spacefaring nation, so this thesis will only examine the United States' policies in detail. This thesis only used unclassified information when discussing DOD SSA capabilities. When literature fell short, I consulted space policy experts, technical space experts, and those in the private sector.

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II. GOVERNMENT SSA TECHNICAL INFRASTRUCTURE

A. INTRODUCTION

This chapter will explore the capabilities and limitations of the SSA infrastructures operated and maintained by individual governments. Governments use SSA for various purposes that range from national security applications to supporting civil and commercial endeavors. Governments also use SSA to further international cooperation, promote space sustainability, and ensure safety in space. The first section will cover the capabilities, and the second section will cover the limitations of government SSA systems. Although the SSA systems are vastly different from one another, government SSA systems' limitations are similar.

B. OVERVIEW OF GOVERNMENT SSA SYSTEMS

This section will first cover the United States Space Surveillance Network then foreign government SSA systems.

1. The United States: The Space Surveillance Network

The United States operates the largest and best overall SSA infrastructure globally known as the Space Surveillance Network (SSN), and the military runs it. Although the SSN is military in origin, the catalog of space objects maintained by the 18th Space Control Squadron is the most comprehensive to date. Other government agencies, foreign countries, the science community, academia, and commercial entities alike use the SSN as their primary source for SSA data. For example, NASA uses SSN data as the source for the Conjunction Assessment and Risk Analyses (CARA) program for monitoring potential collision threats for civil and participating commercial customers.[14] Many others in the space community have relied on this data since the DOD's data-sharing program began in 2010 in response to the 2009 debris-generating satellite collision between an active commercial Iridium satellite and a non-functional Russian satellite.

[14] "Satellite Safety," National Aeronautics and Space Administration, accessed January 18, 2021, https://satellitesafety.gsfc.nasa.gov/cara.html.

The 18th Space Control Squadron (18th SCS) operates the SSN in Vandenberg, California, which falls under the United States Space Force's (USSF) Space Delta 2 in Colorado Springs, Colorado. Headquartered at Peterson Air Force Base, the mission of Space Delta 2 is "to prepare, present and, if necessary, fight to protect and defend the U.S. and our allies from attack in, through and from space."[15] Headquartered at Vandenberg Air Force Base, the 18th Space Control Squadron's stated mission is to "defend freedom of action in space for the Joint Force, multinational partners and humanity."[16] The 18th SCS

> is tasked with providing 24/7 support to the space surveillance network (SSN), maintaining the space catalog, and managing United States Space Command's (USSPACECOM) space situational awareness (SSA) sharing program to the United States, foreign government, and commercial entities.[17]

The 18th SCS is co-located with the Combined Space Operations Center (CSpOC,) which falls under Space Delta 5. The CSpOC hosts international exchange officers and "a Commercial Integration Cell representative to enhance cooperation" and information exchange with allies and commercial partners.[18]

The SSN is a global network comprised of various sensors to include more than 30 radar, optical, and space-based assets that detect, track, and characterize space objects larger than 10 cm from LEO to GEO. Figure 1 shows the layout of SSN sensors by location and type. The sensor categories are further divided into three categories: dedicated, collateral, and contributing.[19] Dedicated sensors' primary mission, such as the Space Fence, is SSA. International partners also contribute dedicated sensors as well. For

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[15] "Space Delta 2 Fact Sheet" (United States Space Force, 2020), https://www.peterson.spaceforce.mil/Units/SPACE-DELTA-2/.

[16] United States Space Force, "18th Space Control Squadron Fact Sheet" (United States Space Force, 2021), https://www.peterson.spaceforce.mil/About/Fact-Sheets/Display/Article/2356622/18th-space-control-squadron/.

[17] United States Space Force.

[18] "Combined Space Operations Center / Space Delta 5 Fact Sheet" (United States Space Force), accessed January 14, 2021, https://www.vandenberg.spaceforce.mil/Portals/18/documents/CFSCC/CSpOC-Delta5-FactSheet.pdf?ver=2020-07-23-181257-343.

[19] Craig Boucher, "Lesson 5- Space Situational Awareness" (Presentation, lecture, Naval Postgraduate School, Monterey, California, October 19, 2020), 10.

example, the United Kingdom contributes ground-based radars, and Canada operates the space-based Sapphire, which both are part of the SSN. Collateral sensors such as COBRA DANE primarily conduct missile warning but can also be used for SSA. Contributing sensors are typically non-DOD R&D assets under contract with the USSF. An additional SSA data source comes from civil and commercial satellite operators themselves. In summary, not every asset part of the SSN primarily conducts SSA all the time. The architecture as a whole takes between 380,000 to 420,000 observations a day,[20] and it maintains a catalog of over 22,000 objects over 10 cm at various orbits, 13,000 of which are debris.[21] However, these statistics do not yet include the newest addition of the Space Fence nor the Space Surveillance Telescope (SST), which will add a significant overall architecture capability.

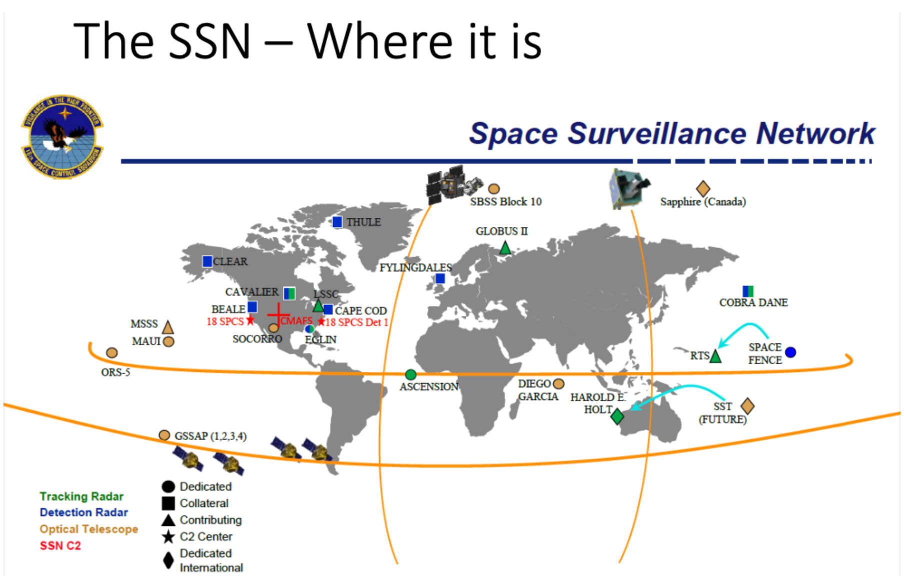

Figure 1. SSN Sensor Types and Locations.[22]

[20] Bhavya Lal et al., *Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)*, D-9074 (Science and Technology Policy Institute, 2018), A-2, https://www.ida.org/-/media/feature/publications/g/gl/global-trends-in-space-situational-awareness-ssa-and-space-traffic-management-stm/d-9074.ashx.

[21] "Box Score," 18th Space Control Squadron, accessed January 15, 2021, https://www.space-track.org/#boxscore.

[22] Source: Boucher, "SSA," 9.

To date, it is not clear the Space Fence is contributing to the public catalog, so its capabilities will be examined to see how it will likely enhance the SSN. Located on Kwajalein Atoll, the AN/FSY-3 Space Fence Radar was declared operational in March 2020,[23] but little information has been made public. The Space Fence uses a solid-state S-band phased array radar designed to provide unqueued assured coverage in LEO and provide queued support of GEO.[24] The higher S-band frequency will allow the Space Fence to achieve higher resolutions than the current SSN radars, which use lower frequencies. More specifically, unclassified acquisition documents from 2016 show that both the threshold and objective requirements for the Space Fence for minimal detection size was 10 cm at orbital altitudes between 250 km - 2000 km and 20 cm between 2000 km - 3000 km.[25] However, the USSF reports the Space Fence can detect and track nano-satellites and debris less than 10 cm at unspecified orbits.[26] Space operations expert Brian Weeden expects that the Space Fence will track objects as small as 5 cm at GEO.[27] The Space Fence will also use a technique called Digital Beam Forming (DBF) that is capable of maintaining persistent surveillance while tracking hundreds of objects simultaneously within the radar's field of view.[28] Once relevant technical details are made public, further analysis can be made on the Space Fence's specific capabilities. Until then, it is reasonable to assume, based on the available information, that the Space Fence will significantly enhance the SSN's capability to detect, track, and characterize space objects and orbital debris, which will be invaluable for the future of space safety and sustainability.

[23] Sandra Erwin, "Space Fence Surveillance Radar Site Declared Operational," SpaceNews, March 28, 2020, https://spacenews.com/space-fence-surveillance-radar-site-declared-operational/.

[24] G. Fonder et al., "Space Fence Radar Overview," in *2019 International Applied Computational Electromagnetics Society Symposium (ACES)* (Miami, 2019), 1–3.

[25] Dana Whalley, *Space Fence Ground-Based Radar System Increment 1 (Space Fence Inc 1)*, DD-A&T(Q&A)823-438 (Hanscom Air Force Base, MA: United States Air Force, 2015).

[26] Erica Blanton, "Swinging for the Space Fence," United States Space Force, April 7, 2020, https://www.spaceforce.mil/News/Article/2142648/swinging-for-the-space-fence.

[27] Brian Weeden, "US Policy and Capabilities on SSA" (Presentation, Seoul, South Korea, January 24, 2019), 5.

[28] Fonder et al., "Space Fence Radar Overview," 1.

Just as important as having the sensors to collect data, the capability to process the data is crucial to getting the right information to the right decision-maker at the right time. The 18th Space Control Squadron uses the catalog maintenance cycle to collect, validate, and update observations to task appropriate sensors for follow-on observations.[29] There are three systems that process collected data and maintain the catalog. First, the Space Defense Operations Center (SPADOC) uses a 1980s era IBM 3090 mainframe to maintain the catalog. SPADOC maintains the current general perturbations (G.P.) and extrapolated general perturbations (eGP) catalog for all objects with a calculation precision of up to seven significant digits.[30] The second system is from the year 2000, and it is called the Correlation, Analysis, and Verification of Ephemerides Network (CAVENet), which includes the Astrodynamics Support Workstation (ASW). More simply, known as CAVENet/ASW, it maintains the historical continuity files of space objects and has a calculation precision of up to 16 significant digits. It uses special perturbations (S.P.), which consider higher-order force models for more accurate processing.[31] Both SPADOC and CAVENet/ASW only process organic SSN data, and both use batch weighted least squares as the processing method. This method requires that the data be processed in batches, which is generally more timely than other processing methods such as Kalman filtering, which relies on timely updates. The third system is Non-traditional Data Pre-Processor (NDPP), which allows the 18th SCS to incorporate data from commercial and foreign government entities. The public users' result is the Satellite Catalog (SATCAT), which is available to all on www.space-track.org. However, this catalog only includes two-line elements (TLE) for space objects' positional data. The covariance data required for higher levels of analysis are not included, which may not be helpful in the space community.

In addition to providing data supporting the DOD and other U.S. government applications, the DOD offers services and products that promote spaceflight safety and debris mitigation to the public at no cost. There are three categories that are part of the SSA

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[29] Boucher, "SSA," 7.

[30] Boucher, 19.

[31] Boucher, 19.

Sharing Program: Basic Services, Emergency Services, and Advanced Services.[32] Basic Services are available to the public through www.space-track.org, where registered users have access to the SATCAT, general perturbation positional data for the unclassified space catalog, satellite decay, and reentry predictions. The second category, Emergency Services, is offered to satellite operators or customers with specific needs. These users have access to anomaly resolution, basic emergency conjunction assessments, and basic emergency collision avoidance services. Access to Emergency Services requires customers to register their satellite or payload with the 18th SCS. The final category, Advanced Services, requires an SSA Sharing Agreement with USSPACECOM. Those with an SSA Sharing Agreement have access to various additional services such as launch support, end-of-life/disposal, and reentry. Figure 2 shows the number of Sharing Agreements increase over time. Access to Advanced Services requires a more formal application process. However, it is still available for all domestic and foreign space community members to include satellite operators, commercial entities, and even research/academic institutions.

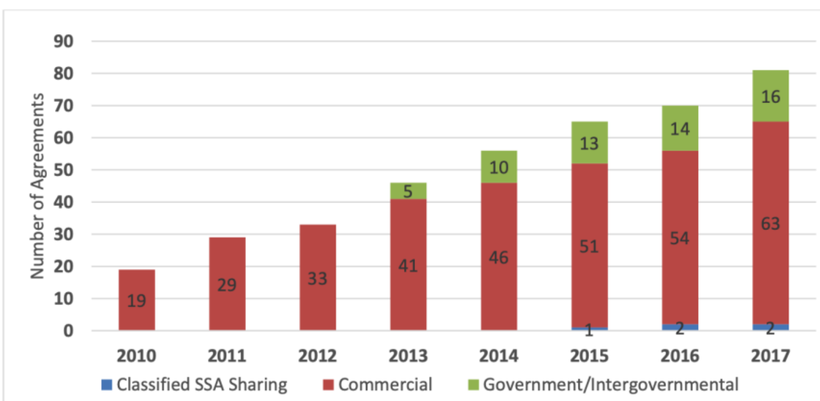

Figure 2. Sharing Agreements with USSPACECOM by Organization Type.[33]

[32] Clinton Crosier, "United States Strategic Command Space Situational Awareness Sharing Program Update" (Presentation, Vienna, Austria, February 3, 2016), 4.

[33] Source: Lal et al., *Global Trends*, 49.

2. Foreign Government SSA Systems

No other individual government SSA system comes close to the capabilities and public data sharing products offered by the United States. Even foreign militaries with SSA sensors use their data to augment data from the United States. This section will give a brief overview of foreign systems and emerging trends in Russia, Asia, and Europe since these regions have the next most mature SSA infrastructures.

Russia's Space Surveillance System (SSS) is the second-largest network of SSA sensors globally, and it is primarily used for national security purposes, which is not helpful for space debris mitigation efforts. Technical information on the SSS is scarce, but it consists of traditional radars, phased array radars, electro-optical sensors, and LIDAR (light detection and ranging) sensors.[34] Operated by the Russian military, the sensors are located throughout Russia and the former Soviet republics through bilateral agreements.[35] Although Russia maintains a catalog that competes with that of the United States concerning its completeness, the SSS is primarily used for national security purposes. It does not share data as openly as the United States. This is not to say Russia does not share data with the international community. Russia collaborates with the international community through the International Scientific Optical Network (ISON), which will be covered in the next section.

In Asia, Japan is increasing its investment in SSA. Japan's existing SSA architecture is less capable than that of the United States. Still, it is actively involved in independently maintaining a space catalog and analyzing TLE data from the SSN through a Sharing Agreement. Japan is in the process of upgrading its sensor network as part of its 2018 Space Act. The Japan Aerospace Exploration Agency (JAXA) plans to develop a new radar to increase the resolution of 1.6 m at LEO of the current system to 10 cm at LEO and refurbish existing ground-based electro-optical sensors and restructure its analysis system

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[34] "Russian Space Surveillance System (RSSS)," Global Security, accessed January 12, 2021, https://www.globalsecurity.org/space/world/russia/space-surveillance.htm.

[35] Brian Weeden, "Space Situational Awareness Fact Sheet" (Secure World Foundation, 2017), https://swfound.org/media/205874/swf_ssa_fact_sheet.pdf.

to enhance data processing and conjunction assessments.[36] This new system will integrate with the Ministry of Defense's operating system per the concept of operations in Figure 3. Despite these upgrades, Japan will still need to rely on the SSN or other SSA sources because of its lack of global coverage.

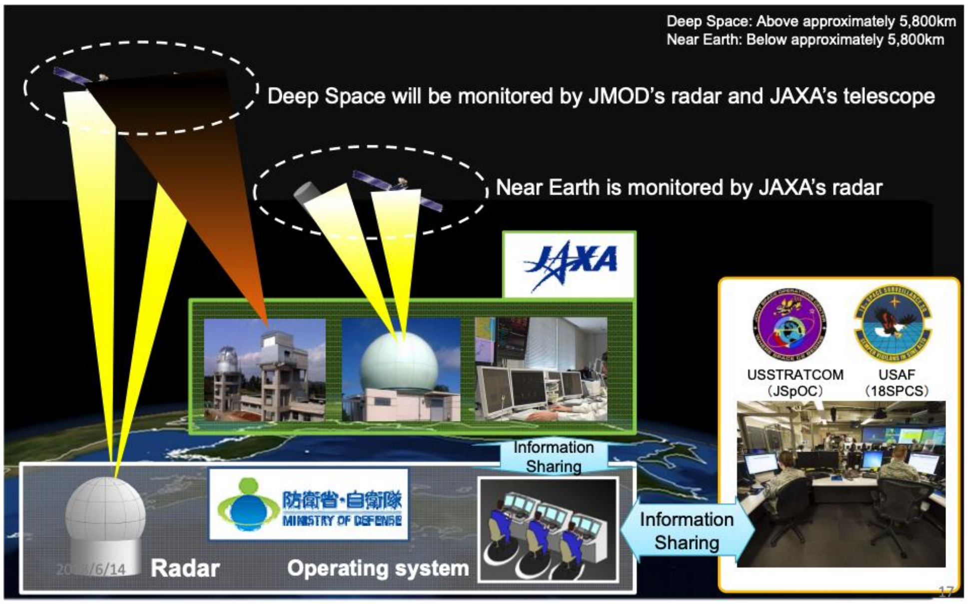

Figure 3. Japan's SSA Concept of Operations.[37]

Other key countries with SSA capabilities in the Asia and Pacific include China, South Korea, Australia, and India. China's "Purple Mountain Observatory is operating telescopes in at least four locations" across China, and they have ship-based SSA used during new satellite launches and military purposes.[38] Not much else is publicly known about the Chinese government's SSA capabilities. However, China is heavily involved with the international scientific community as the leader of the Asia-Pacific Ground-Based optical Space Objects Observation System (APOSOS). Since this is an international

[36] Susumu Yoshitimi, "SSA Capabilities and Policies in Japan" (Presentation, The K Hotel, Seoul, South Korea, January 24, 2019), 10, https://swfound.org/media/206349/susumu-yoshitomi-ssa-workshop-in-seoul-20190124.pdf.

[37] Source: Yoshitimi, 18.

[38] Lal et al., *Global Trends*, 29.

scientific architecture, APOSOS will be discussed in the next chapter. China does not have a Sharing Agreement with the United States, whereas South Korea, Australia, and India do. South Korea primarily uses its five optical sensors for national security purposes, but they are still reliant on outside data.[39] Australia uses SSA mostly for international collaboration, but they have an extensive partnership with the U.S. military. Australia operates one optical sensor, one radar, and one laser-ranging sensor. Australia's military processes SSA data at its Australian Space Operations Center in addition to using data from the U.S. The Australian military will also operate the United States' Space Surveillance Telescope, which is expected to enter service in 2022.[40] Lastly, India operates two SSA radars to support domestic space launches and recently signed a Data Sharing agreement with the United States on October 27, 2020.[41]

In Europe, several countries operate individual SSA sensors. The "United Kingdom and Norway operate radar systems that are part of the United States' SSN."[42] France and Germany have radar SSA systems primarily for national security. Spain operates a radar sensor, and Italy operates two optical sensors primarily for international cooperation.[43] Individual European countries do not operate SSA systems that are as robust as the United States because it is not economical. Instead, there is either a reliance on SSN data or European countries form a multinational SSA system such as the European Space Agency's SSA Program.

For other countries around the world, Table 1 summarizes where foreign government SSA systems "stand in terms of data collection, data processing, and data products," as assessed by the 2018 "Global Trends" report.[44]

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[39] Lal et al., D-2.

[40] Sandra Erwin, "U.S. Space Force Deploying Surveillance Telescope in Australia," SpaceNews, April 23, 2020, https://spacenews.com/u-s-space-force-deploying-surveillance-telescope-in-australia/.

[41] Vivek Raghuvanshi, "India, U.S. Sign Intel-Sharing Agreement Amid Tension with Neighboring China," DefenseNews, October 28, 2020, https://www.defensenews.com/space/2020/10/28/india-us-sign-intel-sharing-agreement-amid-tension-with-neighboring-china/.

[42] Lal et al., *Global Trends*, 33.

[43] Lal et al., D-3.

[44] Lal et al., 52.

Table 1. Country Technology Maturity Matrix.[45]

	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
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

Table 1 con’t on next page

[45] Source: Lal et al., 52.

Table 1 con't from previous page

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

C. LIMITATIONS

Even though individual governments' SSA capabilities differ, they share many of the same limitations, such as lack of coverage, lack of transparency, and not meeting the needs of regulators and the commercial sector. The SSN, with its ground sensors spread across the globe and sensors in space, still has gaps in coverage. The coverage gaps are especially apparent in parts of Asia, Africa, and South America.[46] The second limitation is transparency. Many government SSA systems are tied to national security, and their leaders are reluctant to share their data. The lack of transparency unavoidably leads to some level of distrust, which has caused some countries to pursue self-reliance. Third, governments cannot meet all of the needs of the space community. For example, the DOD's services are a one-size-fits-all approach that cannot meet everyone's needs. Related to the transparency issue, the DOD's TLE-based catalog is not useful for higher levels of analysis because covariance data is not made public. Not meeting the space community's needs is partly because the primary purpose of the SSN is for national security, not civil and commercial space traffic management and sustainability. It is impractical and doubtful that an individual government's SSA system will be everything for everyone, regulators included.

[46] Weeden, "US Policy and Capabilities on SSA," 7.

These limitations have paved the way for nations forming multinational SSA organizations like the International Scientific Optical Network (ISON) or created an industry for commercial SSA.

D. CONCLUSION

As far as individual governments, the United States and Russia have the most capable SSA systems in the world. However, individual government SSA systems are generally limited by coverage gaps, lack transparency, and are unable to meet the global space community's needs. Therefore, government SSA systems may not be the best answer for serving as a verification mechanism for orbital debris mitigation. As we will see in the next two chapters, multinational and commercial SSA may be better suited to overcome these limitations.

III. INTERNATIONAL AND SCIENTIFIC COMMUNITY TECHNICAL INFRASTRUCTURE

A. INTRODUCTION

In an effort to either establish independence from the United States or increase international cooperation, many countries have formed bilateral and multilateral partnerships to create their own SSA networks. Some of these partnerships come in the form of the international scientific community banding together. Others come in the form of regional political relationships. The clear advantage of both international political and scientific partnerships is burden-sharing, which overcomes the limitation of individual-government SSA architectures that do not find it practical or affordable to create their own global systems.

B. OVERVIEW OF INTERNATIONAL AND SCIENTIFIC COMMUNITY SSA SYSTEMS

This section will discuss major non-commercial international and scientific community SSA systems. Some SSA systems are global and some are regional.

1. International Scientific Optical Network (ISON)

While the Russian military's Space Surveillance System is secretive, Russia is a leader in international cooperation through the International Scientific Optical Network (ISON). ISON started in 2004 as a voluntary international project for scientific and academic institutions to develop "an independent open source of data for scientific analysis and spacecraft operators."[47] As its name suggests, it operates a network of optical sensors only. As of 2019, ISON collected measurements from 43 observation facilities with access to more than 100 telescopes in 17 countries across the globe.[48]

[47] I. Molotov et al., "ISON Network Tracking of Space Debris: Current Status and Achievements," in *Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias*, vol. 51 (Huelva, 2017), 145, https://doi.org/10.22201/ia.14052059p.2019.51.25.

[48] Molotov et al., 144.

ISON is organized by the Russian Academy of Sciences (RAS) in Moscow, and it is organized into three segments. Each segment has its own scheduling center and sources of finance. First, the Keldysh Institute of Applied Mathematics (KIAM)[49] coordinates ISON's activities, processes collected measurements, and provides various space operations services. The second segment is called Roscosmos. More accurately, the second segment is KIAM's support to Roscosmos. The KIAM supports Roscosmos with its daily operations and conjunction warnings. The third is Vimpel, which is commercial-oriented. Altogether, these three segments make up ISON.

ISON has partners across the globe with varying levels of cooperation. According to a February 2020 presentation from the KIAM RAS' Igor Molotov to COPUOS, there are three broad levels of cooperation with ISON: international cooperation, informal collaboration, and cooperation of observatories.[50] Organizations part of the international cooperation include the Zimmerwald Observatory in Switzerland, the Barcelona Observatory in Spain, and the Cosala Observatory in Mexico. ISON also collaborates informally with NASA's Jet Propulsion Laboratory (JPL) in the United States. The cooperation of observatories category included observatories from Georgia, Bulgaria, and Kazakhstan. Figure 4 depicts the locations of ISON's telescopes and observatories around the world.

International cooperation is expected to grow through the UN's access to Space for All Initiative, a partnership between ISON and the United Nations Office for Outer Space Affairs (UNOOSA). Announced in January 2020, UNOOSA and KIAM RAS planned to offer select academic and research institutions in developing countries 20 cm aperture telescopes and training on using them.[51] The Access to Space for All Initiative aims to share technology and grow ISON. The applications for these two opportunities to receive

[49] The KIAM is also often referred to as KIAM RAS.

[50] Igor Molotov, "International Cooperation in Field of Observations of the Near-Earth Objects Within ISON Project" (Presentation, Fifty-seventh session of Scientific and Technical Subcommittee COPUOS, Vienna, February 3, 2020), 4.

[51] United Nations Office for Outer Space Affairs, "Access to Space for All ISONscope," https://www.unoosa.org/documents/pdf/psa/bssi/KIAM/Detailed_explanation_of_Announcement_of_Opportunity_and_Application_Form.pdf.

the telescopes and training are open until July 2021. The winners will be selected in October 2021.

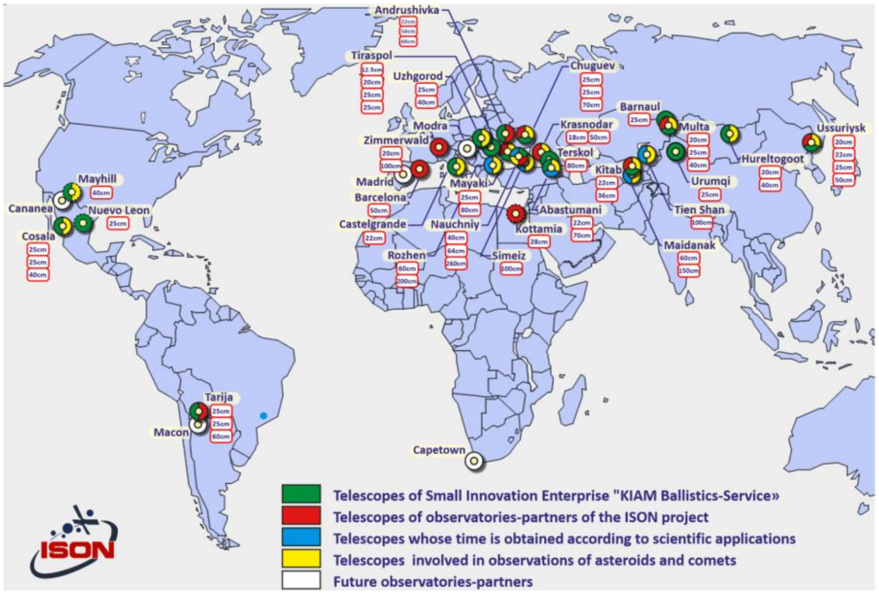

Figure 4. ISON Telescopes and Observatories[52]

A variety of telescopes contribute SSA data to ISON. Of the over 100 telescopes that are part of ISON, details for only about half are publicly available. ISON's sensors include: 30 telescopes with 20 cm to 40 cm apertures, 12 telescopes with 50 cm to 80 cm apertures, and 10 telescopes with 60 cm to 2.6 m apertures.[53] ISON conducts six types of observations:

1. Standard GEO survey with 22 to 25 cm telescopes
2. Extended GEO survey with 18 to 19.2 cm telescopes
3. Deep GEO survey with 50 to 75 cm telescopes
4. Bright GEO and HEO objects with 25 cm telescopes
5. Faint space debris at GEO with 40 to 80 cm telescopes

[52] Source: Molotov, "International Cooperation in Field of Observations of the Near-Earth Objects Within ISON Project," 3.

[53] Molotov, 2.

6. Photometry observations of asteroids with 40 cm to 2.6 m telescopes[54]

In 2017, the telescope network collected 20.048 million measurements and cataloged 6,740 objects.[55] This catalog is much smaller than the United States' SATCAT because ISON's catalog primarily accounts for GEO and HEO orbits. However, ISON collected data on 2,863 objects that are not in the SATCAT and do not have TLE information.[56] The numbers of measurements and objects are expected to grow as ISON continues to mature and add new sensors.

While data is collected globally, it is processed and analyzed by the KIAM. The RAS established the Center on Collection, Processing, and Analysis of Information on Space Debris (CCPAISD) at the KIAM. The CCPAISD schedules ISON's sensors, processes raw measurements, and maintains ISON's master database of space objects. As mentioned, the CCPAISD's catalog focuses its analysis primarily on objects in GEO and HEO.[57] The catalog is available on the website spacedata.vimpel.ru. The KIAM provides products in the following fields:

1. Estimation of real population of space debris at high geocentric orbits
2. Determination of physical properties of discovered space debris objects
3. Determination of probable sources of newly discovered space debris fragments
4. Verification of existing evolution models of space debris distribution
5. High orbit space debris risk assessment
6. Improvement of technologies of studying of space debris population using optical instruments
7. Improvement of motion models for space debris objects with complex physical properties[58]

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[54] "ISON Network Tracking of Space Debris," 147.; Molotov, "International Cooperation in Field of Observations of the Near-Earth Objects Within ISON Project."

[55] Molotov et al., "ISON Network Tracking of Space Debris," 147.

[56] Molotov et al., 147.

[57] Molotov et al., 145.

[58] Molotov et al., 147.

The KIAM also provides services dedicated to Roscosmos. Using ISON data, the joint Roscosmos and KIAM project "Automated System for Prediction and Warning on the hazardous situations in the near-Earth space" (ASPOS OKP) provides conjunction analysis and support for daily operations for Russian satellite operators.[59]

For future development, ISON intends to increase international cooperation through its partnership with the United Nations. As for data processing, ISON plans to improve its software.[60] In 2017, the Secure World Foundation determined that ISON had grown closer to the Russian government.[61] Russia's skeptics may be concerned about transparency with the Russian government's growing involvement in ISON.

2. Europe

Europe has two major international SSA systems. The European Space Agency Space Situational Awareness Program (ESA SSA) and the European Union Space and Surveillance and Tracking Framework (EU SST) are distinct regional efforts in coordinating SSA. They are distinctive because the members of ESA and the EU are not the same, and their systems serve different purposes. ESA SSA primarily focuses on science and research, while the EU SST focuses on security.

a. European Space Agency SSA Program (ESA SSA)

ESA SSA Program's organization is spread across Europe, and its SSA is organized by function. ESA SSA was established in 2009 as an independent SSA capability. While ESA is headquartered in Paris, France, the SSA Program Office is located at the European Space Operations Center (ESOC) in Darmstadt, Germany. Teams across ESA conduct technology research and development, project planning, and industrial contracting.[62] As shown in Table 2, 19 states participate in ESA SSA as of 2021. Participation by country varies over time and ranges from contributing financially to contributing SSA sensors. ESA

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[59] Molotov et al., 145.

[60] Molotov et al., 149.

[61] Weeden, "Space Situational Awareness Fact Sheet," 3.

[62] "SSA Programme Overview," The European Space Agency, accessed February 7, 2021, https://www.esa.int/Safety_Security/SSA_Programme_overview.

practices geo-return as an equitable means of return on investment from member states. Space policy researcher Patricia McCormick stated, “Geo-return is a central component in the relationship and exchange between ESA and its member states.”[63] Functionally, ESA SSA is organized into “three main areas: Space Weather (SWE), Near-Earth Objects (NEO), and Space Surveillance and Tracking (SST).”[64] The SST segment is most relevant to orbital debris, and it is not to be confused with the EU SST.

Table 2. ESA Member States Participating in SSA[65]

Austria	France	Sweden	Portugal
Belgium	Germany	Netherlands	Romania
Czech Republic	Greece	Norway	United Kingdom
Denmark	Italy	Poland	Switzerland
Finland	Luxembourg	Spain	

While ESA SSA’s sensors are regional, ESA has partners across the globe. Some of ESA’s major partners in SSA data sharing and international cooperation are:

- The United States (2014 SSA Sharing Agreement with the DOD)
- South Korea
- The European Union
- Inter-Agency Debris Coordination Committee (IADC)
- European Organization for Astronomical Research in the Southern Hemisphere (ESO)

[63] Patricia McCormick, “Space Situational Awareness in Europe: The Fractures and the Federative Aspects of European Space Efforts,” *Astropolitics* 13, no. 1 (March 2015): 49, https://doi.org/10.1080/14777622.2015.1012002.

[64] The European Space Agency, “SSA Programme Overview.”

[65] Source: The European Space Agency.

- United Nations Committee on the Peaceful Uses of Outer Space – Scientific and Technical Subcommittee (UNCOPUOS-STSC)[66]

ESA SSA's sensors fall under Space Surveillance and Tracking (SST) segment, but the sensors' technical specifications are vague. ESA defines its SST segment as "watching for active and inactive satellites, discarded launch stages, and fragmentation debris orbiting Earth" and "the ability to detect and predict the movement of space debris in orbit around Earth."[67] The sensors are comprised of radar, laser, and optical capabilities. However, details on the capabilities and how each sensor contributes to the network are lacking, likely due to the sensors' close ties to national security. Even in ESA's 2020 Annual Space Environment Report, the primary data sources were from the United States SSN and Russia's KIAM.[68] Not one organic ESA sensor was listed as a data source for the report. Sensor sources are likely protected due to connections to the sensors being tied to systems used for national security purposes. This is likely why ESA focuses its endeavors more on the space weather and near-earth objects segments.

ESA maintains the Database and Information System Characterizing Objects in Space (DISCOS) to catalog space objects. The ESOC in Darmstadt, Germany, oversees DISCOS' operations. The database "is a single-source reference" for all unclassified trackable objects that allows ESA to provide support in collision avoidance, re-entry analysis, and contingency support.[69] Over 40,000 objects are cataloged.[70] DISCOSweb is a web-based catalog that can be accessed by space operators at discosweb.esoc.esa.int. A 2017 upgrade allowed DISCOS to link fragments and debris to parent objects, which could

[66] The European Space Agency.

[67] The European Space Agency.

[68] European Space Agency, *ESA's Annual Space Environment Report*, GEN-DB-LOG-00288-OPS-SD (Germany: European Space Agency, 2020), 6, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

[69] "DISCOSweb," European Space Agency, 2021, https://discosweb.esoc.esa.int/.

[70] European Space Agency.

be useful for enforcing future orbital debris mitigation regulations.[71] The upgrade also promises that new data sources can be incorporated with ease in a coherent interface.[72] One of the most significant products of DISCOS is ESA's Annual Space Environment Report. This report describes the space environment and details trends in compliance and non-compliance with the United Nations' Long-term Sustainability of Outer Space Activities.[73] While ESA lacks enforcement mechanisms, ESA can provide the appropriate data to regulatory bodies.

b. European Union Space Surveillance and Tracking (EU SST)

The European Union Space Surveillance and Tracking (EU SST) was established by the European Union in 2014 and became operational in 2016. "The EU SST framework is built on a unique, member state-led governance model" where EU member states cooperate with the EU Satellite Center to network existing SSA sensors, operations centers, and data processing capabilities.[74] The original members include France, Germany, Italy, Spain, and the United Kingdom. In 2018, the EU SST added Poland, Portugal, and Romania.

While ESA focuses on science and research, the EU's goal was "to develop a European capability to protect European space assets."[75] Although the "EU SST is a civilian framework, it systematically integrates and leverages military, civil, and civil-military contributions" to preserve EU security interests.[76] In a 2013 decision, the European Commission concluded, "The European [Union] SST service has a security dimension

[71] F. McLean, S. Lemmens, and V. Braun, "DISCOS 3: An Improved Data Model for Esa's Database and Information System Characterising Objects in Space," in *7th European Conference on Space Debris*, vol. 11 (Darmstadt: ESA Space Debris Office, 2017), 1, https://doi.org/10.1016/0273-1177(91)90541-Q.

[72] McLean, Lemmens, and Braun, 4.

[73] European Space Agency, *Nnual Space Environment Report*, 4.

[74] Marc Peldszus and Pascal Faucher, "Recent Developments in the Implementation of European Space Surveillance & Tracking (EU SST) – Security and Data Policy," in *71st International Astronautical Congress (IAC) – The CyberSpace Edition* (International Astronautical Federation (IAF), 2020), 1–2, https://doi.org/10.1007/978-3-030-22786-9_104-1.

[75] Lal et al., *Global Trends*, 72.

[76] Peldszus and Faucher, "Implementation of European Space Surveillance & Tracking (EU SST)," 1.

which the EU, unlike ESA, has the competence and [equipment] to deal with."[77] The European Commission went on to say, "The EU does not seek to supplant SSA initiatives undertaken by individual member states or collectively by ESA, but to complement such actions and reinforce coordination were deemed essential to secure common objectives."[78] The EU SST model allows its members to balance national security and data sharing in ways international scientific SSA organizations inherently cannot.

A variety of sensors around the globe contribute toward the EU SST. The sensors are provided, operated, and maintained by individual member states. The sensors track space objects at LEO, MEO, GEO, and HEO. The sensor network includes 51 sensors, of which 13 are radars, 34 are telescopes, and four are laser-ranging stations.[79] Figure 5 is a map of existing EU SST sensors. The sensor variety and geographic diversity give the EU SST advantages of general global coverage. Still, the radars are concentrated only in Europe, which leads to gaps in timeliness if the EU were to rely on organic sensors alone. Information on specific sensor capabilities is scarce, and there is no evidence to suggest the EU SST is more capable than the United States SSN. Unfortunately, per the EU, "The SST Support Program shall not provide support for the development of new SST sensors." Therefore, there is little financial incentive to upgrade or add new sensors.[80]

[77] McCormick, "Space Situational Awareness in Europe," 56.

[78] McCormick, 57.

[79] European Commission, *EU Space Surveillance and Tracking Service Portfolio* (SST Cooperation, 2020), 6.

[80] McCormick, "Space Situational Awareness in Europe," 57.

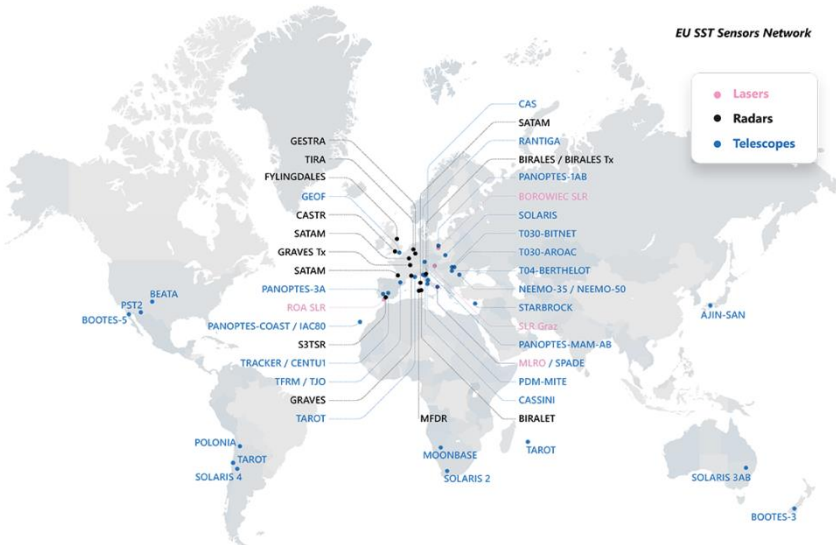

Figure 5. EU SST Sensors Network[81]

EU member states process and feed data into the EU SST Database. The EU SST Database came into operation in 2019, and Germany is responsible for hosting the database. Under the EU SST framework, member states operate sensors and process data at the national level through various national operations centers before data reaches the EU SST Database.[82] The EU SST Database can be accessed by creating an account for the EU SST Service Provision Portal, which can be found at sst.satcen.europa.eu. The online portal manages sensor tasking and service requests. In addition to the EU SST Database, the EU SST is developing the European SST Catalog. Once online, the future SST Catalog will process data independently from the national operations centers and be the basis for SST services.[83]

The EU SST provides three distinct SSA services for its approved users. First, the "Collision Avoidance service provides risk assessment of collision between spacecraft and between spacecraft and debris."[84] Second, "the Re-entry Analysis (RE) service provides

[81] Source: European Commission, *EU Space Surveillance and Tracking Service Portfolio*, 6.

[82] Peldszus and Faucher, "Implementation of European Space Surveillance & Tracking (EU SST)," 3.

[83] European Commission, *EU Space Surveillance and Tracking Service Portfolio*, 7.

[84] European Commission, 9.

risk assessment of the uncontrolled re-entry of manmade space objects into the atmosphere that may constitute a potential risk to the safety of EU citizens and to terrestrial infrastructure."[85] Third, "the Fragmentation Analysis (FG) service provides detection and characterization of in-orbit fragmentations."[86] France and Spain are responsible for the Collision Avoidance service, and Italy is responsible for the Re-entry Analysis and Fragmentation Analysis services. Over 90 organizations are receiving these services, and the EU SST safeguards over 140 European satellites through these services.[87]

The EU SST is well equipped to be an enforcement mechanism for space debris mitigation. In January 2020, EU Commissioner Thierry Breton stated the EU SST should explicitly be understood as the "precursor of a European Space Traffic Management [STM] system."[88] With this, European space policy experts Marc Becker and Pascal Faucher suggest this approach resonates with the United States handing over STM services from the U.S. Department of Defense to the Department of Commerce via the 2018 Space Policy Directive 3. Becker and Pascal also suggest that the "EU SST provides the operational capabilities and services needed to underpin future STM efforts," such as "verifying compliance with norms and regulations."[89]

3. Asia-Pacific Ground-Based Optical Space Object Observation System (APOSOS)

The Chinese-led Asia-Pacific Space Cooperation Organization (APSCO) initiated the Asia-Pacific Ground-Based Optical Space Object Observation System (APOSOS) in 2016. APSCO is an international cooperative project, and APOSOS is a multinational electro-optical based SSA system. APSCO is headquartered in Beijing, China, and includes eight members. The member states are Bangladesh, China, Iran, Mongolia, Pakistan, Peru, Thailand, and Turkey. Indonesia and Mexico are listed separately as a signatory state and

[85] European Commission, 16.

[86] European Commission, 19.

[87] European Commission, 7.

[88] Peldszus and Faucher, "Implementation of European Space Surveillance & Tracking (EU SST)," 4.

[89] Peldszus and Faucher, 4.

an observer state, respectively.[90] The member states believe international "collaboration and cooperation are effective approaches to promote science and technology."[91] APSCO "has formal rules and requires that its members pay dues."[92] Additionally, APSCO has a cooperative relationship with the United Nations Office for Outer Space Affairs. APSCO's goals with APOSOS are to build a cost-effective telescope observation network, "acquire accurate astrometric measurements of space objects, and encourage scientific exchanges in space debris research."[93]

APOSOS' primary sensor is a 15 cm aperture electro-optical telescope. Although there are eight member states, only three of the member states host telescopes so far. The member states with telescopes are Pakistan, Peru, and Iran. APSCO chose the sites based on environment and infrastructure assessments.[94] The 15 cm aperture was chosen as a balance of cost and performance. The electro-optical telescopes are custom designed to meet APSCO's needs, and they are integrated and built by the Chinese Academy of Sciences.[95] "Each APOSOS telescope, as an integrated system of hardware and software, costs $180,000," and is capable of detecting 10 cm objects at LEO and 1 m objects in GEO.[96] The telescopes are also capable of tracking space objects at MEO and HEO at unspecified resolutions. The goal of APOSOS is to build more observation nodes with telescopes around the world for global coverage.

Data processing occurs at the Data and Operation Management Center located at the National Astronomical Observatory, Chinese Academy of Sciences in Beijing, China. The Data and Operation Management Center is responsible for network coordination,

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[90] "APSCO," Asia-Pacific Space Cooperation Organization, accessed February 15, 2021, http://dssp.apsco.int:9191/#/APSCODetail.

[91] Xiaozhong Guo et al., "Introduction to APOSOS Project: 15 Cm Aperture Electro-Optical Telescopes to Track Space Objects," *Advances in Space Research*, Introduction to APOSOS Project, 65, no. 8 (January 2020): 1990, https://doi.org/10.1016/j.asr.2020.01.024.

[92] Lal et al., *Global Trends*, 73.

[93] Guo et al., "Introduction to APOSOS Project: 15 Cm Aperture Electro-Optical Telescopes to Track Space Objects," 1990–91.

[94] Guo et al., 1994.

[95] Guo et al., 1994.

[96] Guo et al., 1994.

observation schedules, data processing, and orbit determination.[97]APOSOS primarily uses TLE data for processing “because of its commons usage in the scientific community and public accessibility.”[98] APOSOS is mainly in a training and experimentation phase, and it is unclear exactly what SSA services and products are offered to APSCO members.[99]

C. LIMITATIONS

In general, the limitations of international and scientific community SSA systems are due to the regional nature of the architecture, technical challenges, and lack of transparency. Some of the major international SSA systems, such as the EU SST, are regionally focused on the services and products provided. Some, like ESA SSA, are regional in sensor placement. APOSOS, on the other hand, only has three electro-optical sensors around the world but is regionally focused, with the exception of Peru.

All of the international SSA systems discussed face some sort of technical limitation that prevent them from achieving comprehensive coverage. ISON and APOSOS only use electro-optical sensors. The EU SST’s radars are only in Europe. ESA SSA’s organic sensors are located in Europe. These technical challenges prevent these SSA systems from being independent SSA architectures. There is still a heavy reliance on the United States SSN.

Despite efforts in international collaboration and burden sharing, some international and scientific community SSA systems still suffer from a lack of transparency, and some even suffer from mistrust. A few interviewees in the study titled “Global Trends in Space Situational Awareness and Space Traffic Management” compared the EU SST’s lack of transparency of data to the United States SSN.[100] In the same study, interviewees cited geopolitical issues between China and Japan that will likely limit the extent of regional SSA efforts in the case of APOSOS.[101] Altogether, the limitations of

[97] Guo et al., 1990.

[98] Guo et al., 1992.

[99] Lal et al., *Global Trends*, 50.

[100] Lal et al., 73.

[101] Lal et al., 73.

international and scientific community SSA systems give plenty of opportunities for commercial SSA.

D. CONCLUSION

International and scientific community SSA systems do not quite overcome the limitations of individual-government SSA systems, but they may be better suited to serve as a verification mechanism for orbital debris. Cooperation and burden-sharing prevent the need for individual countries to create their own global SSA systems and builds mutual trust between participating members. In particular, the EU SST may be a model for serving as a verification mechanism for orbital debris mitigation because the technical infrastructure is tied to a regulatory body that could both verify and enforce compliance.

IV. COMMERCIAL SSA TECHNICAL INFRASTRUCTURE

A. INTRODUCTION

Various factors have led to the rise of commercial SSA in the last ten or so years. In general, the limitations of existing SSA systems, the advancement of technology, and the increase of commercial space activities have created opportunities for the private sector to establish SSA systems and services. Commercial SSA also generally offers higher levels of transparency and more customized SSA services that simply cannot be provided by many non-commercial SSA systems. More specifically, the 2018 report “Global Trends in Space Situational Awareness and Space Traffic Management” noted that while the “private sector has always been a significant part of the SSA enterprise,” the functional modularization of SSA is allowing more private sector players to participate.[102] The report describes functional modularization as breaking up SSA into individual components such as data collection, processing, software, and product generation.[103] Functional modularization allows commercial companies to sell piecemeal information that contributes to SSA as a whole rather than the need to create an entire end-to-end SSA system.[104]

B. OVERVIEW OF COMMERCIAL SSA SYSTEMS

This section will cover several major commercial SSA systems. Each company focuses on a different aspect of SSA. The companies range from Silicon Valley startups to international commercial partnerships. This section will also introduce two commercial entities without SSA sensors but still contribute significantly toward SSA.

1. ExoAnalytic Solutions

ExoAnalytic Solutions is a U.S.-based company that specializes in GEO SSA, operates a global network of ground-based optical sensors, and offers customers multiple

[102] Lal et al., 53–54.

[103] Lal et al., 54.

[104] Lal et al., 54.

web-based platforms. Three career physicists founded ExoAnalytics in 2008. The headquarters is in Foothill Ranch, California, and there are several other offices located across the United States.[105] With the first sensors deployed in 2013, ExoAnalytics currently operates the largest network of ground-based optical sensors in the world.[106] ExoAnalytics categorizes its business into three "solutions": Space Domain Awareness, Missile Defense Technology, and Systems Analysis.[107] This section will cover Space Domain Awareness since it is most applicable to space debris mitigation. Although the company works closely with the defense and intelligence sector, the sensor network is 100% privately funded and provides services to customers worldwide with transparency.[108]

ExoAnalytics owns and operates the ExoAalytic Global Telescope Network (EGTN). The EGTN includes more than 30 observatories and 300 telescopes worldwide that collect angle and brightness measurements of space objects.[109] Figure 6 shows the locations of EGTN's sites. The sensors' diverse placement around the world allows the EGTN to monitor 100% of both the GEO belt and the graveyard region at 99% availability, pending weather and lighting conditions.[110] The sensors also regularly detect and track objects in MEO and HEO.[111] The EGTN can detect a 10 cm object and achieve an accuracy of about 0.1 to 0.25 arcseconds in GEO.[112] In comparison, the EGTN is 4 – 10 times more accurate than the SSN's ground-based optical sensors for tracking objects in GEO.[113] Additionally, the EGTN collected over 200 million observations in 2018, whereas ISON

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[105] "Who We Are – ExoAnalytic Solutions," ExoAnalytic Solutions, accessed March 8, 2021, https://exoanalytic.com/about/.

[106] Lal et al., *Global Trends*, 28.

[107] ExoAnalytic Solutions, "Who We Are – ExoAnalytic Solutions."

[108] ExoAnalytic Solutions.

[109] ExoAnalytic Solutions.

[110] ExoAnalytic Solutions.

[111] ExoAnalytic Solutions.

[112] Mark Jeffries, "ExoAnalytic Solutions Capabilities Overview," 2, https://www.satelliteconfers.org/wp-content/uploads/2018/12/Mark-Jeffries-ExoAnalytic-Solutions.pdf.

[113] Lal et al., *Global Trends*, 36.

collected just 20 million observations in 2017.[114] ExoAnalytics plans to continue leasing sites and placing telescopes around the world.[115]

Figure 6. The ExoAnalytic Global Telescope Network[116]

In addition to hardware, ExoAnalytics offers extensive software and automated processing products to its customers. The ExoAnalytic Space Operations Center (ESpOC) software suite encompasses the ESpOC Command Center and ExoMaps. From the company's website, "the ESpOC Command Center enables remote command and control of all ExoAnalytic sensors, automatically integrates and fuses data from multiple sensors in real-time, and overlays all collected data in real-time on a full-sky common operational picture."[117] It goes on to describe ExoMaps as "a browsable interface into ExoAnalytic's historical and near-real-time observation archive, with integrated analyst tools such as orbit

[114] Jeffries, "ExoAnalytic Solutions Capabilities Overview," 4; Molotov et al., "ISON Network Tracking of Space Debris," 49.

[115] Lal et al., *Global Trends*, 29.

[116] Source: ExoAnalytic Solutions, "Who We Are – ExoAnalytic Solutions."

[117] "Space Domain Awareness – ExoAnalytic Solutions," ExoAnalytic Solutions, accessed March 8, 2021, https://exoanalytic.com/space-domain-awareness/.

determination."[118] These products can be acquired by purchasing a license and installing them on a computer or a virtual machine.[119]

ExoAnalytics offers additional products and services useful to the space community, which can be found on their publicly available Multiple Award Schedule (MAS)[120] and commercial pricing list.[121] The ESpOC Catalog, which is separate from Exomaps, has tools that autonomously correlate known tracked objects, perform orbit determination with less than 10 m of error at GEO, and produce timely alerts such as conjunction warnings.[122] Customers can also purchase observation data from a historical archive or even from dedicated telescopes. Customers can even request ExoAnalytic subject matter experts to provide real-time support through the Event Support Service.[123] Altogether, ExoAnalytics could help regulators maintain SSA in MEO, GEO, and HEO orbits.

2. LeoLabs

LeoLabs is a U.S.-based company that focuses on LEO SSA, operates a global network of phased-array radars, and offers customers a cloud-based data platform. In 2016, a team of scientists and space industry veterans founded LeoLabs in Menlo Park, California. Originally a spinoff of Stanford Research Institute (SRI) International, "LeoLabs is built on 30+ years of R&D [research and development] in radar systems and satellite-tracking algorithms."[124] LeoLabs provides SSA services to satellite operators, regulators, defense applications, and insurance companies alike.[125]

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[118] "Multiple Award Schedule (MAS)" (ExoAnalytic Solutions, 2020), 11, https://www.gsaadvantage.gov/ref_text/47QTCA21D000D/0VR7A8.3RHK8Z_47QTCA21D000D_MASPRICELISTEXOANALYTICSOLUTIONS.PDF.

[119] ExoAnalytic Solutions, 11.

[120] ExoAnalytic Solutions, 11.

[121] "Commercial Price List," ExoAnalytic Solutions, accessed March 9, 2021, https://exoanalytic.com/space-domain-awareness/commercial-price-list/.

[122] "Space Domain Awareness – ExoAnalytic Solutions."

[123] ExoAnalytic Solutions, "Multiple Award Schedule (MAS)," 10.

[124] "About LeoLabs," LeoLabs, accessed March 10, 2021, https://www.leolabs.space/company/.

[125] LeoLabs

LeoLabs operates three unique phased-array radars around the world. Two are ultra-high frequency (UHF), and their newest radar is S-band.[126] The first UHF radar is the Poker Flat Incoherent Scatter Radar (PFISR) near Fairbanks, Alaska. This location allows for coverage in the Northern Hemisphere and satellites with higher inclinations.[127] Operational since 2007, the radar was initially built by SRI International and the National Science Foundation before LeoLabs purchased it.[128] The PFISR is a two-dimensional phased array radar that consists of 4,096 transmitting and receiving elements.[129] It detects objects 10 cm or greater in LEO with a range uncertainty of about 15 m and a doppler uncertainty of about 3 m/s.[130] On average, the PFISR makes about 6.5 million measurements and tracks about 10 million unique space objects a month based on data from March 2020 to February 2021.[131]

The second UHF radar is the Midland Space Radar (MSR) near Midland, Texas. This location is better suited to track satellites with equatorial to middle inclinations. Commissioned by LeoLabs in 2017, the MSR uses a proprietary one-dimensional design.[132] Like the PFISR, the MSR detects 10 cm objects or larger in LEO with a range uncertainty of 15 m.[133] Different from the PFISR, the MSR has a more sensitive doppler uncertainty of 25 cm/s.[134] On average, the MSR makes about 1.6 million measurements and tracks about 6.5 thousand unique space objects per month.[135] Together, both the PFISR and the MSR achieve global LEO coverage with multiple satellite revisits a day.

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[126] S-band is in the upper bound of UHF and the lower bounds of super high frequency (SHF).

[127] "Radars," LeoLabs, accessed March 10, 2021, https://www.leolabs.space/radars/.

[128] LeoLabs.

[129] LeoLabs.

[130] Nathan Griffith et al., *Commercial Space Tracking Services for Small Satellites,* SSC19-WKVI-03 (Menlo Park, CA: LeoLabs, Inc., 2019), 2.

[131] LeoLabs, "Radars."

[132] Griffith et al., *Commercial Space Tracking Services for Small Satellites*, 2.

[133] Griffith et al., 2.

[134] Griffith et al., 2.

[135] LeoLabs, "Radars."

LeoLab's third and newest radar is the Kiwi Space Radar (KSR),[136] which went operational in late 2019. Located in the Central Otago region of New Zealand, the KSR is LeoLab's first radar in the Southern Hemisphere, covering mid-inclination orbits.[137] The KSR uses LeoLab's proprietary S-band technology that reliably detects LEO objects as small as 2 cm, which is a significant leap in capability compared to many existing SSA radars in the world today.[138] Based on the same time period of PFISR's and MSR's data, KSR makes about 5 million measurements and tracks about 12.2 thousand unique space objects a month.[139]

Moving onto LeoLab's data services platform, the company handles all data processing for its customers. LeoLabs process all data by utilizing machine learning algorithms to deliver information to customers in real time.[140] Furthermore, LeoLabs streamlines the information flow from radars to users via edge processing, cloud processing, and automation.[141] Edge processing at each radar minimizes the need for follow-on processing after data from all radars are aggregated. Cloud processing minimizes the hardware processing requirements that LeoLabs must operate and maintain. Automation minimizes human delays when processing massive amounts of data. By handling all of the radar operations and data processing, LeoLabs is able to provide end-to-end SSA services to its customers for LEO.

LeoLab's data has advantages over the free TLE data provided by the U.S. government's SSN. The SSN's use of TLE's represent only approximations of a space object's actual "orbit and may have errors of several kilometers."[142] On the other hand, LeoLabs delivers more accurate orbital state vectors and uses higher fidelity force models,

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[136] The KSR is made up of two redundant radars KSR1 and KSR2

[137] LeoLabs, "Radars."

[138] LeoLabs.

[139] LeoLabs.

[140] "Data Analytics," LeoLabs, accessed March 10, 2021, https://www.leolabs.space/data-analytics/.

[141] LeoLabs.

[142] Griffith et al., *Commercial Space Tracking Services for Small Satellites*, 1.

which results in uncertainties of about 15 meters.[143] Additionally, LeoLabs uses a Kalman filter algorithm for orbital state estimations.[144] This algorithm type takes advantage of LeoLab's timely phased array radars to process accurate orbital state vectors during a single satellite pass. In contrast, the SSN uses batch filtering that requires more data over time, as discussed in Chapter 2. Lastly, LeoLabs uses the International Laser Ranging Service as an independent third party to fully characterize LeoLab's sensors' performance, thus ensuring high fidelity data from the beginning.[145] LeoLab's calculated sensor bias and uncertainty are publicly available on their website as measures of transparency.

In addition to handling 100% of the radar operations and processing, LeoLabs offers a web-based platform for customers to access its services. The "platform is accessible through two primary interfaces: A web-based API[146] (suitable for custom analysis scripts and automation tasks), and a graphically oriented web application (focused on intuitive plots and visualizations of the available data)."[147] Figure 7 shows an example of the web-based visualization of LEO objects and LeoLab's radars' locations. Some of LeoLabs' services include tracking and monitoring, regulatory reporting, space domain awareness, and collision avoidance, all without the need to install local software packages.[148] The company markets toward satellite operators, regulators, national defense stakeholders, and the insurance industry.[149]

[143] "FAQs," LeoLabs, accessed March 10, 2021, https://www.leolabs.space/faqs/.

[144] Griffith et al., *Commercial Space Tracking Services for Small Satellites*, 3.

[145] Griffith et al., 2.

[146] API - application programming interface

[147] Griffith et al., *Commercial Space Tracking Services for Small Satellites*, 2.

[148] "LeoLabs," LeoLabs, accessed March 10, 2021, https://www.leolabs.space/.

[149] "LeoLabs."

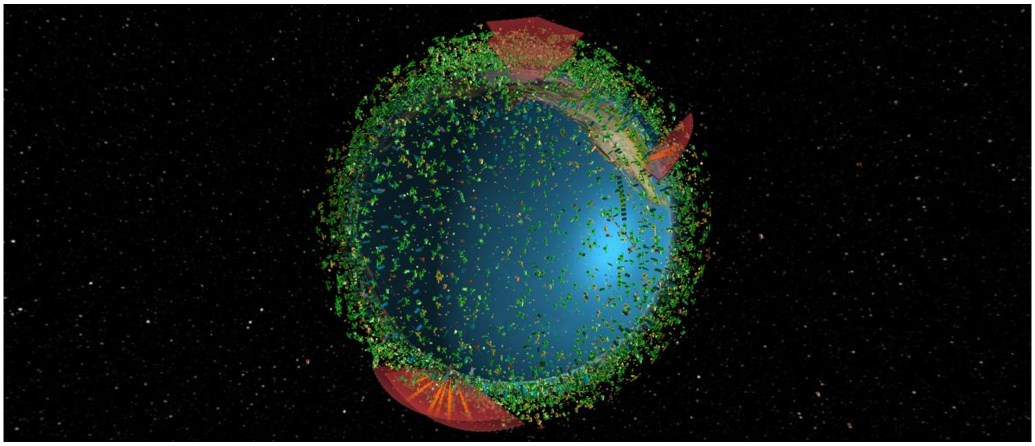

Figure 7. LeoLab's Interactive Visualization of LEO Objects[150]

LeoLab's services for regulators are of particular interest. LeoLabs promotes itself as a regulatory and sustainability platform that allows regulators to assess actionable information when needed.[151] LeoLabs offers regulators real-time compliance dashboards so they can knowledgeably communicate with stakeholders.[152] For example, the New Zealand Space Agency (NZSA) is the first regulatory body to use LeoLab's services for compliance purposes.[153] Since June 25, 2019, the NZSA relies on LeoLab's information "to ensure satellites launched from New Zealand are complying with licensing rules."[154] This may prove as a model for space regulators and commercial SSA in the future.

3. NorthStar Earth and Space

NorthStar Earth and Space is an emerging Canadian company that plans to build the first commercial space-based SSA system and offer SSA data services. In October 2020, the company announced it had ordered three satellites with optical payloads devoted

[150] Source: "Low Earth Orbit Visualization," accessed March 10, 2021, https://platform.leolabs.space/visualization.

[151] "Regulators," LeoLabs, 2021, https://www.leolabs.space/regulators/.

[152] LeoLabs.

[153] Debra Werner, "Leolabs and New Zealand Announce Tool to Monitor Low Earth Orbit Activity," SpaceNews, June 25, 2019, https://spacenews.com/leolabs-and-new-zealand-announce-tool-to-monitor-low-earth-orbit-activity/.

[154] Werner.

to SSA.[155] The three satellites are scheduled to launch in 2022 and will operate in LEO. These three satellites are the first of twelve planned satellites. As for data services, NorthStar plans to offer space conjunction warnings, a space object catalog, and a variety of other customer services to space operators as a subscription service, similar to LeoLabs and ExoAnalytics.[156] NorthStar markets its services toward private and government clients, regulators, and insurance companies. Although technical details are not available for the emerging company's systems, NorthStar could fill the commercial space-based SSA gap.

4. Space Data Association (SDA)

Unlike previous SSA systems discussed so far, the Space Data Association (SDA) does not collect its own data. However, the SDA still plays an important role in SSA. The SDA contributes significantly toward a cooperative approach for SSA data sharing, safety of flight, and space sustainability.

The SDA was created in response to gaps in SSA services during the 2000s. Existing SSA products and services failed to meet commercial satellite operator needs.[157] Commercial satellite operators were also frustrated over the lack of customer service from the U.S. military.[158] Officially formed in 2009, the SDA was incorporated in the Isle of Man, Great Britain, and its founding members were Intelsat, SES, Inmarsat, and Eutelsat, which are private space operators.[159] The SDA "is a formal, nonprofit 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."[160]

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[155] Jeff Foust, "Northstar Orders Three Satellites to Collect Space Situational Awareness Data," SpaceNews, October 27, 2020, https://spacenews.com/northstar-orders-three-satellites-to-collect-space-situational-awareness-data/.

[156] "NORTHSTAR," NorthStar Earth & Space, accessed March 15, 2021, https://northstar-data.com/.

[157] Pascal Wauthier, "Space Traffic Coordination and Management Why Data Sharing Is Crucial" (Presentation, AIAA ASCEND Conference, October 21, 2020).

[158] Brian Weeden, "Trends in Commercial Space Situational Awareness" (Presentation, Space Situational Awareness: Strategic Challenges for India, Bengaluru, India, June 14, 2018), 2.

[159] Weeden, 2.

[160] Pascal Wauthier, "The Space Data Association: Ten Years of Flight Safety Services" (Presentation, Secure World Foundation Webinar, Webinar, July 29, 2020), 9, https://swfound.org/media/207036/safety-of-spaceflight-webinar_july-2020_swf.pdf.

The SDA also promotes responsible behaviors and best practices from space operators across all orbital domains to ensure safety, protecting key assets, and space sustainability.[161] For a fee, membership is open to all satellite operators and stakeholders. Over 30 satellite operators and over 600 satellites participate in the SDA.[162] American government agencies, such as NASA and NOAA, are included as participants.

The SDA offers its members a variety of SSA services and benefits. Its members have access to conjunction assessments and radio frequency interference geolocation.[163] The SDA ensures its data and collision warnings are transparent, timely, and actionable.[164] The SDA has the legal and organizational structure to "provide protections and enforcement mechanisms to ensure data is only used for intended purposes."[165] Members will be given "authoritative contact information for a given space object" to deconflict events, as necessary.[166]

The Space Data Center (SDC) is the operational arm of the SDA. Analytical Graphics, Inc.'s (AGI)[167] Commercial Space Operations Center (ComSpOC) powers the SDC.[168] The SDC uses a machine-to-machine interface that is effective and secure for sharing operational data.[169] The SDC fuses member-provided ephemerides, TLEs, special perturbation data, and other available sources to ensure accurate data and warnings are

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[161] Wauthier, 2.

[162] Daniel L. Oltrogge, "The Commercial Space Operations Center (ComSpOC)" (Presentation, Bariloche, Argentina, May 29, 2017), 21.

[163] Weeden, "Trends in Commercial Space Situational Awareness," 2.

[164] Oltrogge, "The Commercial Space Operations Center (ComSpOC)," 23.

[165] Wauthier, "The Space Data Association: Ten Years of Flight Safety Services," 9.

[166] "Space Data Association," Space Data Association, accessed March 13, 2021, https://www.space-data.org/sda/.

[167] AGI is a commercial company that provides multi-domain mission-level software for the aerospace, defense, and telecommunications industries.

[168] Oltrogge, "The Commercial Space Operations Center (ComSpOC)," 23.

[169] "Space Data Association."

tailored to SDA members.[170] This SDC system benefits from AGI experts who closely monitor data from various sources for quality.[171]

SDA announced a transition to SDC 2.0 in 2017. Prior to SDC 2.0, the SDA pointed to at least three limitations:

- "Inter-system biases in operator systems"[172]
- "Availability and accuracy limitations of debris data, particularly for objects" smaller than 1 m[173]
- "Lack of transparency and consistent availability of government-provided data"[174]

SDC 2.0 aims towards complete independence from the U.S. military's data and services by "using commercial SSA data to feed their own catalog."[175] The catalog will evolve to include all objects greater than 20 cm and to be more extensive than existing public space catalogs.[176] The SDA believes commercial service agreements will also lead to increased transparency, reliability, and timeliness.[177] Regulators could either take note of the SDA's accomplishments in SSA if creating government SSA systems or even participate in the SDA as a member.

5. Space Safety Coalition (SSC)

The Space Safety Coalition (SSC) is a commercial approach to influence policy and promote long-term space sustainability. Formed in 2019, the SSC is "an ad hoc coalition of companies, organizations, and other government and industry stakeholders that

[170] Space Data Association.

[171] Wauthier, "Space Traffic Coordination and Management Why Data Sharing Is Crucial," 2.

[172] Oltrogge, "The Commercial Space Operations Center (ComSpOC)," 25.

[173] Oltrogge, 25.

[174] Oltrogge, 25.

[175] Weeden, "Trends in Commercial Space Situational Awareness," 2.

[176] Oltrogge, "The Commercial Space Operations Center (ComSpOC)," 25.

[177] Oltrogge, 25.

actively promotes responsible space safety through the adoption of relevant international standards, guidelines and practices, and the development of more effective space safety guidelines and best practices."[178] The SSC released its "Best Practices for the Sustainability of Space Operations" in 2019 to address space governance gaps and promote better "spacecraft design, operations, and disposal practices."[179] With 48 endorsees, the SSC aims to make a difference in advance of space treaties, guidelines, and regulations.[180]

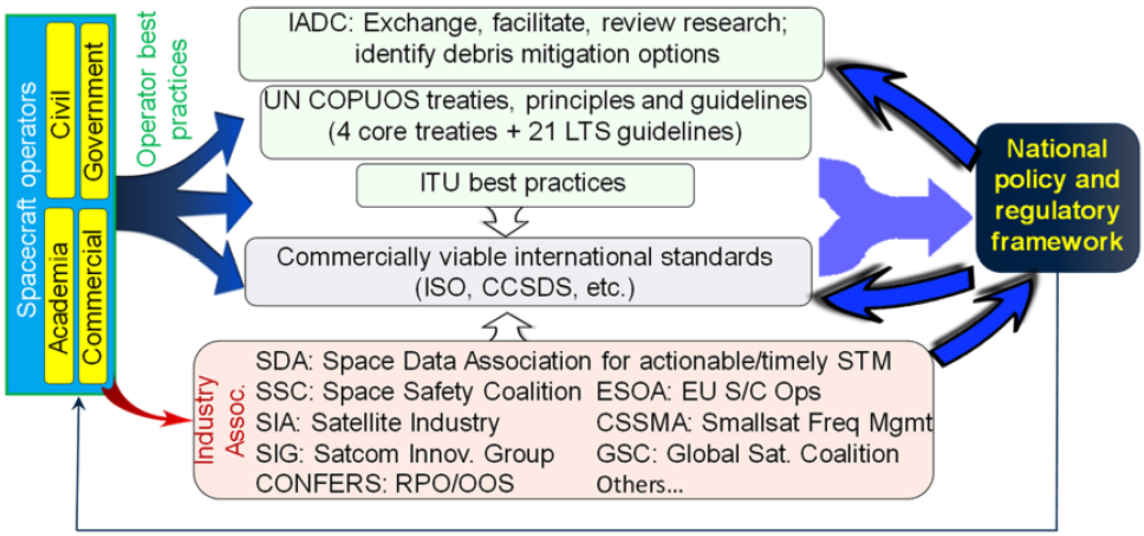

Figure 8. "Virtuous Cycle Interaction of Global Space Debris Mitigation Activities."[181]

The SSC plays "a key role in codifying and promoting established commercial best practices for all phases of the spacecraft life cycle" and can advocate for a holistic approach

[178] "Space Safety Coalition," Space Safety Coalition, accessed March 15, 2021, https://spacesafety.org/.

[179] Space Safety Coalition.

[180] Daniel L. Oltrogge, "The Space Safety Coalition in the Context of International Cooperation" (Presentation, United Nations Office for Outer Space Affairs Scientific and Technical Subcommittee Fifty-Seventh Session, February 5, 2020).

[181] Source: Daniel L Oltrogge, *The Contributions of Commercial Best Practices to the Global Space Governance Continuum*, 2020, 1.

toward space debris mitigation.[182] Figure 8 shows the interaction between various space and regulatory organizations that influence global space debris mitigation activities. The SSC already made an impact by making several appearances in the 2020 report "Space Traffic Management" by the National Academy of Public Administration (NAPA). Although not a technical SSA system, the SSC could very well influence national and international regulators on the best way forward for establishing a verification mechanism for orbital debris mitigation.

C. LIMITATIONS

No single commercial entity provides comprehensive end-to-end SSA services for all orbital regimes. In essence, each company contributes toward a complete catalog for all orbital regimes in order to be fully independent of the U.S. government. ExoAnalytics excels at ground-based optical sensors for MEO, GEO, and HEO. LeoLabs focuses on LEO via its ground-based phased array radars. The SDA relies on SSA data from outside sources. A regulator would have to maintain multiple contracts and ensure data from numerous sources are properly fused.

Long term, there could be challenges with the private industry in general as commercial SSA matures. The commercial SSA companies discussed all advocate transparency, but will profits or bottom lines conflict with doing the right thing? The private industry may not be held to the same accountability as democratic governments without the right regulations. Conversely, regulations could negatively impact the free market.

D. CONCLUSION

Commercial SSA systems may serve as an alternative to individual-government SSA systems. The functional modularization of commercial SSA allows regulators to contract companies based on the needs of the regulator. One step further, commercial companies can tailor their products and services to meet each customer's needs. Commercial SSA is significantly less costly than every spacefaring nation and international

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[182] Oltrogge, "Contributions of Commercial Best Practices," 8.

organization building, maintaining, and operating a complete SSA system. Innovation and the free-market drive companies to offer better quality SSA products and services. Commercial SSA offers regulators transparency, which is something government and scientific community SSA systems lack.

V. FUTURE OPTIONS FOR A SPACE DEBRIS VERIFICATION MECHANISM USING COMMERCIAL SSA SYSTEMS

A. INTRODUCTION

Recent advances in the private sector support that commercial SSA systems can either augment or serve as an alternative to government and scientific community SSA systems. The previous chapters examined existing SSA technical infrastructures around the world. With the capability of commercial SSA systems to detect and track 2 cm objects in LEO and 10 cm objects in GEO, regulators could use commercial SSA data to hold space operators accountable to space debris mitigation and other compliance measures. This chapter will focus on exploring the advantages and disadvantages of four possible future options for how commercial SSA systems could be applied as a verification mechanism for space debris mitigation while taking into account applicable policy. To narrow the scope of the global space debris issue, this chapter will consider the international framework and the United States for the domestic level. The four options are (1) continuation of the status quo, (2) international enforcement, (3) domestic enforcement, and (4) commercial best practices.

B. THE STATUS QUO AND EXISTING SPACE DEBRIS MITIGATION POLICIES

The status quo represents a situation in which government systems dominate, and commercial SSA plays a secondary role as a space debris verification mechanism, although it allows incremental policy changes over long periods of time. Current space debris mitigation policies include international treaties and non-binding guidelines and domestic laws and guidelines. The use of commercial SSA as a regulatory mechanism by governments is not widespread, except for the partnership between New Zealand and LeoLabs. The U.S. military remains the primary source for most SSA data and services to space operators around the world. Since commercial SSA is not primarily used as a verification mechanism for space debris mitigation, this section will provide a background of existing international policy and U.S. domestic policy to provide context on where commercial SSA could effectively be applied. To stay on the path of the status quo, commercial SSA would continue to supplement existing SSA data sources, such as the DOD's SSN.

1. International Space Debris Mitigation Policy

Four key international space organizations significantly influence current international space traffic management and space debris mitigation policies. However, none operate their own SSA infrastructures. The 2020 National Academy of Public Administration (NAPA) space traffic management report succinctly describes each organization:

- International Telecommunication Union (ITU). The ITU is a U.N. agency that governs the use of the radio frequency spectrum. ITU assigns physical satellite orbital slots in geostationary orbit.
- United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). COPUOS was established in 1959 as a forum for discussing international governance of outer space. In recent years, COPUOS members have discussed issues like space debris management, creating guidelines for the long-term sustainability of space, and determining if more concrete solutions are necessary or possible.
- Inter-Agency Space Debris Coordination Committee (IADC). Composed of national space agencies, IADC's facilitates research on space debris and fosters international cooperation on responses and mitigation techniques.
- The United Nations Office for Outer Space Affairs (UNOOSA). UNOOSA assists U.N. Member States to establish legal and regulatory frameworks to govern space activities. It also works to strengthen the capacity of developing countries to use space science technology and applications for development.[183]

The current legal framework for space debris mitigation policy can be traced back to the 1967 Outer Space Treaty and the 1972 Space Liability Convention. The Outer Space Treaty has been ratified by 111 countries, and the Space Liability Convention has been ratified by 98 countries.[184] The Outer Space Treaty generally calls for the peaceful use of

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[183] Michael Dominguez et al., *Space Traffic Management: Assessment of the Feasibility, Expected Effectiveness, and Funding Implications of a Transfer of Space Traffic Management Functions*, Academy Project Number: 102252 (Washington, D.C.: National Academy of Public Administration, 2020), 30.

[184] "Status of Treaties," United Nations Office for Outer Space Affairs, accessed April 18, 2021, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/status/index.html.

space and declares that all nations should have access to and benefit from space. Although space debris mitigation is not explicitly mentioned in the Outer Space Treaty, Article VII broadly states each nation is internationally liable for damages to another nation in outer space.[185] The Space Liability Convention goes on to further define liability for damages in space. However, neither the Outer Space Treaty nor the Space Liability Convention could predict the growth of commercial space activities. Also, neither specifically address liability for damages caused by non-trackable space debris nor discuss space debris mitigation when debris cannot be associated to a launching state.

The first set of international policies to specifically address space debris was the 2007 United Nations Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. The U.N. guidelines can be divided into two broad categories: those that limit creating debris in the near term, such as avoidance of break-ups, and those that limit creating debris in the long term, such as end-of-life procedures. However, there are no quantitative restrictions or specific timelines. These U.N. guidelines are voluntary and not legally binding under international law.

Most recently, UN COPUOS ratified the Guidelines for the Long-term Sustainability of Outer Space Activities (LTS) in June 2019. While this was an international space cooperation achievement, the LTS guidelines did not advance existing space debris mitigation guidelines. Instead, the LTS guidelines state, “Although the international guidelines and standards on space debris mitigation were not legally binding, they could nevertheless facilitate the practical application of the fault-based liability regime set out in the five United Nations treaties on outer space.”[186] The LTS also points to the IADC’s existing 25-year post-mission disposal guidelines as a reference for U.N. members

[185] United Nations Office for Outer Space Affairs, *United Nations Treaties and Principles on Outer Space: Text of Treaties and Principles Governing the Activities of States in the Exploration and Use of Outer Space, Adopted by the United Nations General Assembly.*, ST/SPACE/11 (New York: United Nations, 2002), 5.

[186] Committee on the Peaceful Uses of Outer Space, *COPUOS Long-Term Sustainability Guidelines*, 27.

to adhere to. There are still many gaps concerning international space debris mitigation policy, and COPUOS members agree this issue is far from over.[187]

2. United States Domestic Space Debris Mitigation Policy

Regulatory bodies are spread across several federal government agencies in the United States. They play important roles from pre-flight to space sustainability. From the 2020 NAPA Report, the leading civil agencies are:

- The Department of Commerce: The Department of Commerce (DOC) is a government department concerned with promoting job creation and economic growth through providing data and research necessary to support commerce, and by setting standards that foster innovation.24 Commerce is organized across 13 Bureaus and 15 Offices, including the National Oceanic and Atmospheric Administration (NOAA). The Office of Space Commerce currently sits within NOAA. The mission of this office is to foster an economic and policy environment that ensures the growth and international competitiveness of the U.S. commercial space industry.
- The Department of Transportation: The Federal Aviation Administration (FAA) at the Department of Transportation (DOT) regulates all aspects of civil aviation and the movement of space vehicles through the atmosphere. Established under the Commercial Space Launch Act of 1984, the Office of Commercial Space Transportation (known by the initials AST) was tasked to regulate the U.S. commercial space transportation industry, to ensure compliance with international obligations of the United States. Currently, AST conducts launch and re-entry permitting and licensing for commercial space flights.
- The Federal Communications Commission: The FCC is an independent government agency that regulates interstate and international radio, television, wire, satellite, and cable communication. Considering orbital debris mitigation plans to be within its responsibilities and obligations, FCC has issued regulations that state that unless the FCC has already authorized a satellite system, the satellite system must submit a description of the design and operational strategies it will use to mitigate orbital debris.
- The National Aeronautics and Space Administration: Along with its broad responsibilities for civilian space travel and aeronautics and space research, NASA tracks space debris associated with the protection of

[187] Peter Martinez, "The UN COPUOS Guidelines for the Long-Term Sustainability of Outer Space Activites Fact Sheet" (Secure World Foundation, 2019), 4, https://swfound.org/media/206891/swf_un_copuos_lts_guidelines_fact_sheet_november-2019-1.pdf.

NASA assets in space and conducts a broad portfolio of basic research about the use of space for research and commercial purposes.

- Department of State: The State Department is the external facing federal entity that discusses and mediates international space policy. Its Office of Space and Advanced Technology handles international space issues and represents the United States in the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the United Nations and the United Nations Office for Outer Space Affairs. This office also maintains the official United States registry of objects launched into outer space and supports U.S. civil space entities in upholding international agreements.[188]

In addition to the mentioned regulatory bodies, "the Department of Defense (DOD) is the government authority tasked with coordinating and supervising all agencies and functions of the government directly related to national security and the U.S. Armed Forces."[189] The National Space Council (NSC) and the United States Congress generate domestic space policy. Reestablished in 2017, the NSC is chaired by the vice president. However, it must be noted the NSC exists at the discretion of the president. In March 2021, the Biden administration announced it will continue the NSC.[190] The NSC operates as an office of policy development and handles a portfolio of civil, commercial, national security, and international space policy matters.[191] As for Congress, there are various Senate and House subcommittees that deal with space-related activities. Congress provides oversight, policy framework, and funding for all government space activities and policy implementation.

U.S. domestic policy on space debris mitigation is more progressive than its international counterparts. NASA was the first organization in the world to develop orbital debris mitigation policy and guidelines with its "NASA Management Instruction (NMI)1700.8 Policy for Limiting Orbital Debris Generation" in 1993.[192] Along with the

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[188] Dominguez et al., *NAPA Report*, 24–25.

[189] Dominguez et al., 23.

[190] Sandra Erwin, "Biden Administration to Continue the National Space Council," SpaceNews, March 29, 2021, https://spacenews.com/biden-administration-to-continue-the-national-space-council/.

[191] Dominguez et al., *NAPA Report*, 26.

[192] Liou, "Orbital Debris Briefing," 5.

Department of Defense, NASA then led the effort to establish the 2001 U.S. Government Orbital Debris Mitigation Standard Practices (USG ODMSP). The USG ODMSP applies only to U.S. government space activities, not commercial space activities.[193] Civil space activities follow the regulations set forth by DOC, DOT, and FCC. The USG ODMSP adopted the rule for disposing space objects no longer than 25 years after mission completion.[194] The IADC later adopted the 25-year rule into its guidelines in 2002.

The most recent domestic space debris policy updates include President Trump's "Space Policy Directive-3" (SPD-3) in 2018 and the update to ODMSP in 2019. SPD-3 calls on the Department of Commerce to become the civil space traffic management agency for the U.S. government. Furthermore, it calls on OSC to create an Open Architecture Space Situational Awareness Data Repository (OADR) and "to ensure [the] safe coordination of space traffic in this future operating environment…in recognition of the need for DOD to focus on maintaining access to and freedom of action in space."[195] SPD-3 lists the following essential features of the OADR:

- Data integrity measures to ensure data accuracy and availability;
- Data standards to ensure sufficient quality from diverse sources;
- Measures to safeguard proprietary or sensitive data, including national security information;
- The inclusion of satellite owner-operator ephemerides to inform orbital location and planned maneuvers; and
- Standardized formats to enable development of applications to leverage the data.[196]

This is a major shift of responsibility from the DOD to the DOC. What the OADR will look like, however, remains to be determined.

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[193] United States Government, *U.S. Government Orbital Debris Mitigation Standard Practices* (United States Government, 2001).

[194] United States Government.

[195] The White House, "Space Policy Directive-3, National Space Traffic Management Policy," The White House, June 18, 2018, https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/.

[196] The White House.

The National Academy of Public Administration (NAPA), an independent organization chartered by Congress, released a report in August 2020 to identify the best federal agency best suited to be the lead agency for civil space traffic management. NAPA evaluated the DOD, NASA, FAA AST, and DOC OSC on functional and technical competency, organizational leadership and capacity, partnerships, and stakeholders and customers. After careful consideration, the NAPA report concluded that DOC OSC is best suited to perform non-military SSA and STM tasks over the other federal agencies because of competencies and potential in each evaluated area.[197]

3. Advantages

The advantage of the status quo is that change would take place gradually. Gradual change often leads to relative predictability and reduces uncertainty, which is generally preferable for the private sector. Additionally, the status quo allows the United States to maintain its leadership in space policy since it historically set the trends for space debris mitigation. If the United States remains on the path directed by SPD-3, the outcome will be in line with the third future option of primarily domestic enforcement. If OSC does not get the required funding, the United States will remain with the status quo of incremental changes over time.

4. Disadvantages

Continuation of the status quo may be unsuitable to meet existing space debris mitigation guidelines. Space policy expert Brian Weeden criticizes the current system stating, “A study was done by the European Space Agency that found large constellations need better than 90% compliance with the 25-year rule to avoid a significant impact on the space environment. Current compliance for existing satellites is around 60% and shows only a slight upward trend.”[198] Stricter and more binding space governance will likely be required to meet the already lenient space debris mitigation guidelines.

[197] Dominguez et al., *NAPA Report*, 101.

[198] Brian Weeden, “The United States Is Losing Its Leadership Role in the Fight Against Orbital Debris,” The Space Review, February 24, 2020, https://www.thespacereview.com/article/3889/1.

There are several other disadvantages of the status quo. First, regulatory organizations will continue to rely on U.S. DOD-provided SSA data, which lacks transparency for the international space community. There is no formal SSA entity for international matters, and the United States is in the middle of transitioning civil SSA responsibilities from the military to a civil agency. Second, the existing space debris legal framework remains to be tested after a debris-creating event has occurred. For example, the 2009 collision between Cosmos 2251 and Iridium 33 was a seemingly clear case where the 1972 Space Liability Convention could have been applied. However, space law expert Frans von der Dunk summarized, "The absence of a clear, or at least workable definition, of 'fault'" led to the Space Liability Convention not being invoked.[199] To this day, the 1972 Space Liability Convention has not been invoked despite multiple debris-creating events since the convention was ratified.[200] Third, the original ratified space treaties were unable to predict the rise of the commercial sector. In summary, many of the disadvantages of the status quo are tied to weak international policies and enforcement mechanisms.

As for the United States, the 2019 USG ODMSP was, unfortunately, not as groundbreaking as it could have been. The latest ODMSP was more of an incremental update, albeit a welcomed one. The ODMSP still only applies to the U.S. government, still maintains the 25-year rule, and it still does not address the commercial sector. It does, at least, address small satellites (CubeSats), large constellations of 100 or more satellites, and active space debris removal. The United States missed an opportunity to expand the application of the guidelines for the commercial sector or at least tighten the 25-year rule for government space programs.

C. WORKING AT THE INTERNATIONAL LEVEL: INTERNATIONAL ENFORCEMENT

In this future option, a global governance regime could use commercial SSA systems as a space debris verification mechanism. A global governance body, such as the

[199] Frans von der Dunk, "Too-Close Encounters of the Third Party Kind: Will the Liability Convention Stand the Test of the Cosmos 2251-Iridium 33 Collision?," *Proceedings of the International Institute of Space Law,* 2009, 205.

[200] von der Dunk, 206.

United Nations, could either take a top-down or bottom-up approach. In a top-down approach, the United Nations would enforce international debris mitigation measures. In a bottom-up approach, the United Nations would set a framework for individual nations to enforce international standards. The United Nations could use commercial SSA data in both cases, either to use it as a verification mechanism to enforce the international standards itself or to hold nations accountable to enforce the international standards. Considering commercial SSA data is readily available, the U.N. would not need to create its own independent SSA system. Both approaches require restructuring the current international framework since the current space debris mitigation guidelines are voluntary and non-binding. Whether a top-down or bottom-up approach, a global solution may be ideal for addressing the space debris problem, which is non-discriminatory toward national borders on Earth.

To achieve a top-down governance regime, restructuring the existing national framework requires an international governing body with authority to enforce and updated space debris mitigation policies that are legally binding. The 2018 "Global Trends" report points to the International Civil Air Organization (ICAO) as a model for a top-down approach to harmonize and standardize regulations.[201] The ICAO is a United Nations agency responsible for air transportation standards. However, the ICAO is not a true top-down governing body because the ICAO is not a global regulator.[202] Furthermore, U.N. agencies "do not have any authority over national governments in the areas of international priorities they are established for."[203] Since there are no international top-down models to follow, space debris mitigation may be one of the first instances where one should be established.

A regulatory enforcement body could be added to COPUOS, IADC, or UNOOSA, if the U.N. were to undertake a top-down approach. Although this would require tremendous political will, establishing binding space treaties, such as the Outer Space

[201] Oltrogge, *Contributions of Commercial Best Practices*, 78.

[202] "About ICAO," International Civil Air Organization, accessed May 6, 2021, https://www.icao.int/about-icao/pages/default.aspx.

[203] International Civil Air Organization.

Treaties, is possible. Updating rules and processes would matter greatly. A centralized international regulatory body with enforcement authority could primarily use commercial SSA data instead of government-provided data to overcome any bias or transparency concerns of using a particular nation's government SSA system.

There are several bottom-up models for a space debris international governing body to follow. Two models are the ITU and international maritime navigation. The ITU is already involved with space traffic management in that it assigns physical satellite orbital slots in geostationary orbit.[204] More relevant to a bottom-up approach, however, the ITU does not enforce its policies itself. Enforcement occurs at the national level. For example, the United States FCC applies ITU rules to all U.S. spacecraft and satellites that use radio spectrum.[205]

Similarly, international maritime navigation rules are enforced by individual nations through navies conducting freedom of navigation operations and local coast guards. The U.N. Convention on the International Regulations for Preventing Collisions at Sea established the international maritime rules of the road in 1972 and became effective in 1977.[206] All vessels flying the flags of nations that ratified the treaty are bound to the rules.[207] For the United States, whoever violates the international rules is liable to a civil monetary penalty.[208] Since the 1972 Space Liability Convention generally follows this model, a future updated version could specifically address orbital debris mitigation enforcement.

1. Advantages

Restructuring the current international framework to form legally binding policies to achieve results in space debris mitigation may be the ideal future option. All spacefaring

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[204] Dominguez et al., *NAPA Report*, 30.

[205] Dominguez et al., 30.

[206] United States and Coast Guard, *Navigation Rules: International-Inland* (Washington, D.C.: The Guard : [For sale by the Supt. of Docs., U.S. G.P.O., distributor, 1999), iv.

[207] United States and Coast Guard, iv.

[208] United States and Coast Guard, 199.

actors would be held to the same standard, whether the enforcement itself occurs at the international level or the domestic level. Additionally, the process to reach international agreements could foster cooperation along the way. Using commercial SSA systems as a verification mechanism to enforce legally binding measures could be a transparent solution as opposed to using individual government SSA systems or even the scientific community's SSA system that are often tied to governments.

2. Disadvantages

One of the major disadvantages of an international solution is how the political and space communities will get there. The 2018 "Global Trends" report finds, "It does not appear from current trends that there will likely be agreement on a binding global STM framework in the next decade."[209] The global community generally lacks the political will to establish further legally binding treaties on space debris mitigation, as recently demonstrated by the 2019 Long Term Sustainability guidelines.

Two possible disadvantages for commercial SSA systems could be the perception of international governments relying on a commercial means as a verification mechanism and the notion of international organizations using a for-profit company in general. Commercial companies are ultimately tied to their country of origin, and currently, the major commercial SSA companies are based in the United States. The international community could perceive the United States as having too much of a hand in space debris mitigation and space traffic management. International commercial consortiums like the SDA may be better suited for this role over individual commercial SSA systems.

D. WORKING WITH INDIVIDUAL GOVERNMENTS: DOMESTIC ENFORCEMENT

In contrast to international enforcement, individual nations could take it upon themselves to create and enforce both international and domestic space debris mitigation measures. Although the lines between domestic enforcement and bottom-up international enforcement are blurred, this domestic enforcement option assumes no new international

[209] Lal et al., *Global Trends*, 77.

policies have been created. Both the skepticism toward military SSA systems and the lack of comprehensive standalone civil SSA systems are opportunities for commercial SSA systems to be a solution for regulators. Commercial SSA can be a transparent solution for individual nations seeking to have a verification mechanism for orbital debris without acquiring, operating, and maintaining a comprehensive SSA system. Furthermore, regulators can tailor commercial SSA services to meet their individual needs to enforce domestic space debris mitigation policies as they see fit. Canada, New Zealand, and the United States provide insight on how regulators and the commercial SSA could work together at the domestic level.

First, Canada's privatized air traffic control experience can provide a model for using commercial SSA as a space debris mitigation verification mechanism. "On November 1, 1996, the Canadian federal government transferred responsibility for its air traffic control system to a private nonprofit corporation," NAV Canada, to respond to budget strains and inflated acquisition costs.[210] Commercial aviation management, airline pilots, and air traffic controllers formed a coalition to search for a solution to meet the needs at the time.[211] The answer was privatization. NAV Canada formed as a nonshared capital corporate structure where a private-sector corporation was independent of the government. Still, they maintained a business-style board of directors and management structure.[212] The nonshared capital structure model allowed the airline industry to accept NAV Canada's monopoly status.[213] Through the ANS Act and the International Civil Aviation Organization's Policies on Charges for Airports and Air Navigation Services, customers funded NAV Canada directly in place of taxes.[214] "Ever since NAV Canada assumed responsibility for ANS operations from the [Canadian] government, it has increased the pace of technological modernization, dramatically improved the system's

[210] Patrick Floyd, Tae Mee Park, and Prithviraj Sharma, "Canada's Experience with ATC Privatization," *The Air & Space Lawyer* 30, no. 2 (November 2017): 1, https://www.cba.org/Sections/Air-and-Space-Law/Articles/ATC-privatization.

[211] Floyd, Park, and Sharma, 1.

[212] Floyd, Park, and Sharma, 1.

[213] Floyd, Park, and Sharma, 2.

[214] Floyd, Park, and Sharma, 2.

efficiency and productivity, and achieved a one-third reduction in user fees."[215] Canada's transition to a privatized air traffic control experience shows how the commercial sector could meet public safety needs.

Similarly, commercial SSA companies could partner with national governments as NAV Canada partnered with its government to act as a verification mechanism for orbital debris mitigation and space traffic management. Key stakeholders such as the Space Data Association, Space Safety Coalition, and space operators could advocate for commercial SSA companies to follow such a model of how the commercial aviation industry and other stakeholders supported a privatized solution in Canada. In the example of the United States, following this model would allow the DOD to focus on national security and civil agencies to focus on orbital debris mitigation and space traffic management without acquiring, operating, and maintaining its SSA system, leveraging existing commercial SSA companies.

Second, New Zealand's partnership with LeoLabs, which was introduced in Chapter 4, is an example of the commercial sector working hand-in-hand with regulators. Following this example, SSA companies would not have to give up their for-profit status in the NAV Canada model. The New Zealand Space Agency (NZSA) is New Zealand's lead government agency for the commercial use of space. New Zealand took a proactive approach to minimize space debris by partnering with a commercial SSA company.[216] In September 2018, LeoLabs and New Zealand's Ministry of Business, Innovation, and Employment announced a memorandum of understanding that implemented the use of LeoLab's regulatory platform.[217] Through LeoLab's Space Regulatory and Sustainability Platform, the software analyzes SSA data from LeoLab's global radar system to ensure satellites launched from New Zealand are complying with licensing rules.[218] Peter

[215] Floyd, Park, and Sharma, 2.

[216] "LeoLabs and New Zealand Space Agency Unveil Regulatory Platform for Low Earth Orbit," LeoLabs, June 25, 2019, https://www.prnewswire.com/news-releases/leolabs-and-new-zealand-space-agency-unveil-regulatory-platform-for-low-earth-orbit-300874417.html.

[217] LeoLabs.

[218] Werner, "Leolabs and New Zealand Announce Tool to Monitor Low Earth Orbit Activity."

Crabtree, head of the NZSA, commented, "As a new era of transparency in LEO emerges, LeoLabs and our space agency will continue to prove state-of-the-art regulatory practices to keep pace with the changing requirements of space commercialization."[219]

Lastly, the United States' proposed OADR presents an opportunity for commercial SSA companies to be the primary contributors of SSA data. The NAPA report discusses a future where the United States separates its military and civil SSA data. In this future, the DOD's SSA data will be part of the Unified Data Library (UDL), and civil SSA data will be part of the OADR.[220] This division of data repositories is part of the effort to transition civil SSA responsibilities from the DOD to OSC as directed by SPD-3. While the OADR can still use data from the UDL, the NAPA report recognized the limitations of the DOD's inefficient closed, internal system being incompatible with non-DOD entities.[221] By primarily using commercial SSA data, the OSC's OADR can overcome the DOD's limitations. The OSC could then transparently exchange data with the international community and space operators, especially those that do not have sharing agreements with the DOD or pay fees to be part of SDA.

1. Advantages

There are several advantages for national governments to use commercial SSA systems as a space debris verification mechanism. For one, it is a practical solution since there are already models to follow. Governments concerned about data sharing would not need to create an additional SSA system for those that already have military SSA systems. Likewise, scientific community SSA systems can focus on science rather than civil regulatory matters. For governments that do not have a comprehensive SSA system, commercial SSA services could offer a more affordable alternative to acquiring, operating, and maintaining their own SSA system. By using commercial SSA systems to achieve situational awareness, regulators could build confidence to establish better domestic space debris mitigation policies. For example, once the framework matures in the United States,

[219] "LeoLabs and New Zealand Space Agency Unveil Regulatory Platform for Low Earth Orbit."

[220] Dominguez et al., *NAPA Report*, 70–71.

[221] Dominguez et al., 70.

the OSC could pursue an updated 5-year or even 1-year deorbiting rule, as proposed by space debris expert Darren McKnight.[222] Maturing domestic space debris policies could lead to building norms to influence international binding policies.

2. Disadvantages

The major disadvantage of domestic enforcement has to do with policy, not commercial SSA systems. Unless all major spacefaring nations buy-in, domestic enforcement does not address the space debris problem because it is a global issue. Also, domestic policies will likely not be standardized, and commercial companies would have to provide services to meet the demands of each country. A holistic international approach may be required to achieve long-term space sustainability.

E. COMMERCIAL LED: COMMERCIAL BEST PRACTICES

In response to slow incremental policy changes at both the international and domestic levels, the commercial space industry has often taken upon itself to set best practices to adhere to. Organizations like the Space Data Association (SDA) and the Space Safety Coalition (SSC) have led the effort in the debris area. Overviews of these organizations were covered in Chapter 4. Instead of waiting on policy to catch up with the space community's consensus on the orbital debris problem, the commercial community could simply continue to regulate itself through best practices of space sustainability.

The SDA and SSC already provide a model on how commercial best practices can move forward. The SDA offers the technical means of SSA data exchange and a network for space operators to communicate. The SDA already leverages commercial SSA, so it can continue to expand the use of commercial SSA as it matures over time while still using the government SSA if it so chose. The SSC maintains its "Best Practices for the Sustainability of Space Operations" to address policy gaps. To advance commercial best practices, the SDA, SSC, and similar organizations should continue to grow their partnerships with each other while expanding their network of space operators, commercial and government alike.

[222] Darren McKnight, "STM – Do Not Build on a Weak Foundation," 8.

The next step in commercial best practices would be to enforce agreed-upon space debris mitigation measures amongst each other, preferably before collisions occur or when regulatory regimes must intervene. A future where the commercial industry can effectively police itself, while idealistic, could be done through the SDA and SSC model using communication and accurate and timely SSA. Commercial SSA companies like LeoLabs and ExoAnalytics could tailor their services toward such an endeavor more quickly than the U.S. government's SSN. A future such as this could ease the burden of governments on creating their own SSA and STM infrastructures, especially for governments that cannot afford to develop and maintain their own systems.

1. Advantages

Although the commercial space sector regulating itself is idealistic, commercial best practices add value for the greater space community and are applied simultaneously at the national and international levels. Daniel Oltrogge, the founder of the Space Safety Coalition, remarks, "It's not just about treaties, guidelines, and standards. It is all of those, plus commercial best practices with aspirational goals of not only meeting but exceeding minimum consensus requirements."[223] Groups like the SSC could mature into policy think tanks that can continue to advocate for better space sustainability policies at the domestic and international levels. Organizations like the SDA offer the rest of the space community an avenue to communicate and prevent debris-creating events. International space operators and policy groups can foster cooperation via the commercial industry while aspiring to achieve long-term sustainability in space. In essence, commercial best practices could be a bottom-up approach to influence future international and domestic policymaking.

2. Disadvantages

Commercial best practices are not a long-term solution. First, joining a commercial consortium, such as SDA or SSC, is voluntary. Notable space operators like SpaceX and Blue Origin currently do not formally participate. Second, commercial best practices

[223] Oltrogge, *Contributions of Commercial Best Practices*, 8.

organizations are not as accountable to the public as a democratic government would likely be. Finally, commercial organizations lack enforcement mechanisms to ensure space debris mitigation measures are met. If enforcement mechanisms are too strict, participants could simply opt out.

F. CONCLUSION

Commercial SSA systems have strong potential to be applied in all four future policy options. At present, they have the capability to act as a verification mechanism for objects as small as 2 cm in LEO and 10 cm in GEO. Smaller, non-trackable debris will continue to be a problem until technology improves. Their capabilities and services will only get better over time as companies innovate, technology progresses, and services mature. However, the issue is with policy. There is a need for firmer and clearer space debris mitigation measures that are legally binding. There is also a need to formalize civil SSA at both the international and domestic levels. The verification mechanism to conduct enforcement exists technologically. While this chapter presented four options, the solution may not be only one or the other. For instance, commercial best practices in the United States could influence regulators to establish better domestic policies. The United States could then use its leadership to set international norms, which then could influence the international space community to establish legally binding space debris mitigation measures.

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VI. CONCLUSION

A. KEY POINTS

This thesis explored two research questions. First, could commercial SSA systems be used as a verification mechanism for space debris mitigation accountability? Second, how could such a verification regime lead to future enforceable space debris mitigation policy? To answer the first question, this thesis surveyed the capabilities and limitations of the significant SSA technical infrastructures around the world. For the second research question, this thesis explored how commercial SSA systems could be used as a space debris verification mechanism in four possible future options. The four options were the status quo, international enforcement, domestic enforcement, and commercial best practices.

The SSA technical infrastructures were divided into three categories. The categories were individual government SSA systems, multinational and scientific community SSA systems, and commercial SSA systems. Individual government SSA systems generally are unable to meet the space community's needs for transparent data sharing because many of these systems are tied to military use. While the United States Space Surveillance System (SSN) and Russia's Space Surveillance System (SSS) are the most capable in the world, they may not be the best solution for civil regulatory uses as a verification mechanism for orbital debris where transparency and trust are required.

The next category of international and scientific community SSA systems do not entirely overcome the limitations of individual government SSA systems. While bilateral and multilateral agreements foster cooperation and trust through burden-sharing, many of these SSA systems are still tied to military uses, as seen in the European Space Agency SSA Program (ESA SSA). However, the European Union Space Surveillance and Tracking (EU SST) may serve as a model for an international SSA framework as a verification mechanism for orbital debris mitigation because the technical infrastructure is tied to a regulatory body. As for the scientific community SSA systems, the two most significant SSA systems are the International Scientific Optical Network (ISON) and the Asia-Pacific Ground-Based Optical Space Object Observation System (APOSOS). With ISON directly tied to Russia and APOSOS directly tied to China, there are transparency and trust concerns from the international community. Additionally, both ISON and APOSOS rely on optical sensors, which do not have comprehensive coverage of LEO. Unless future international SSA systems resemble the framework of EU SST, the existing international and scientific community may not be the best solution for a space debris verification mechanism.

The third and final category, commercial SSA systems, presents promising alternatives to the first two categories. Today's commercial SSA systems have the technical capability to detect and track space objects as small as 2 cm in LEO and 10 cm in GEO, which is comparable or possibly better than non-commercial SSA systems based on public data on military SSA systems. International commercial consortiums like the Space Data Association (SDA) fuse data from multiple sources and provide participating space operators a network to communicate. While no single commercial company offers comprehensive SSA capabilities like the United States' SSN, regulators and space operators could use SSA data from multiple commercial companies as needed or participate in the Space Data Association's data exchange services, which fuse data from various sources. Commercial SSA companies also offer their customers transparency and the ability to tailor their services to meet the needs of their customers, some benefits the SSN does not provide to the global space community.

Once it was determined that commercial SSA systems had the most potential of the three categories to serve as a space debris mitigation verification mechanism, this thesis then examined how four possible future policy options could apply commercial SSA systems. The four policy options were: (1) continuation of the status quo; (2) international enforcement; (3) domestic enforcement; and (4) commercial best practices. While commercial SSA systems have a place in all four options, each option has its advantages and disadvantages.

The status quo represents a weak regulatory regime at both the international and domestic levels, where the United States military provides the bulk of SSA data to space operators. The status quo lacks an enforcement mechanism and is constrained by non-legally-binding policies, such as the United Nation's Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space and the United States' Orbital

Debris Mitigation Standard Practices. Although commercial companies could continue to augment the United States SSN's SSA data, restructuring the current regulatory framework to establish legally binding policies will be required to achieve better results in space debris mitigation.

The second future option was international enforcement through either a top-down or bottom-up approach. In the top-down scenario, the United Nations would both establish and enforce space debris mitigation standards. There are no actual examples of an international top-down approach analogous to space debris mitigation, so space debris mitigation could be the first consideration to establish such a framework. In the bottom-up scenario, the United Nations would establish space debris mitigation standards, but enforcement would be left to each spacefaring nation. The International Telecommunications Union (ITU) and international maritime laws are both models international regulators could look to. Since commercial SSA data and services overcome the transparency issues of the other categories of SSA systems, international regulators could primarily use commercial SSA systems as a space debris verification mechanism. Although an international regulatory framework with legally binding space debris mitigation measures may be an ideal solution to a global issue, the international community currently lacks the political will to get there.

As for the third option, individual nations could establish and enforce stricter debris mitigation measures and use commercial SSA as a space debris verification mechanism. The sooner countries that are more active in space establish enforceable space debris mitigating policies, the sooner international norms could be set. However, domestic enforcement does not entirely address the space debris issue since it is a global issue that requires buy-in from all stakeholders. Nonetheless, it is generally a quicker process for countries to change their domestic laws rather than wait on the international community to agree upon a holistic approach.

Using commercial SSA systems may be a practical solution for domestic enforcement. Governments looking to separate military and civil SSA systems could look to commercial SSA to manage civil matters. Additionally, governments that do not have a comprehensive SSA system could use commercial SSA systems as a cheaper alternative to the acquisition, operation, and maintenance of a homegrown SSA system. Canada's use of privatized air traffic control is a model for a successful public-private partnership. New Zealand's partnership with LeoLabs is an example of regulators working directly with a commercial SSA company. Once countries have an SSA infrastructure in place, regulators could then turn their attention to updating domestic space debris mitigation policies and establishing international norms that work toward space sustainability.

The fourth option discussed commercial best practices, whereby the commercial sector establishes and advocates better space sustainability policies. The Space Data Association (SDA) and the Space Safety Coalition (SSC) are examples of the commercial sector being proactive in addressing space sustainability issues. The SDA focuses on SSA data exchange and communication, while the SSC concentrates on policy matters. The membership of both organizations includes various commercial and government space operators that participate voluntarily. Through commercial best practices, the commercial sector could influence policymakers for the better.

Although four policy options were presented, the solution may require pursuing more than one. Commercial best practices in the United States could influence regulators to establish better domestic policies. The United States could then use its leadership to set international norms, which then could influence the international space community to establish legally binding space debris mitigation measures.

B. RECOMMENDATIONS

International and national regulators should consider commercial SSA systems as the primary source of SSA data for a space debris mitigation verification mechanism. SSA systems that are tied to military systems are generally constrained by transparency and data-sharing challenges. This is not to suggest that regulators ignore non-commercial SSA systems, but rather utilize commercial SSA data and services to promote transparency and data exchange. By using commercial SSA data and services as a primary mechanism, regulators would not be burdened by acquiring, maintaining, and operating expensive SSA systems. Canada's privatized air traffic control and New Zealand's partnership with LeoLabs may be viable models for such a public-private approach.

International and national regulators should formalize SSA requirements and data sharing. Furthermore, SSA systems should be separated by military, scientific, and civil taskings. For instance, the United States SSN should not be the SSA system for everyone. The United States military should focus on national defense and should not provide civil space services. It may be the right move to create a separate Unified Data Library (UDL) for DOD and the Open Architecture Data Repository (OADR) for OSC. By separating SSA this way, the military could focus on defense, the scientific community could focus on research, and regulatory regimes could focus on civil space matters. Although separating SSA systems by function could lead to stove-piping information, data sharing should still be highly encouraged.

However, SSA systems are the technical answer to the orbital debris verification problem. Policy and organizational changes will also be needed to attain a verification regime that could enforce future legally-binding space debris mitigation policies. In September 2020, the authors of a white paper published by the Aerospace Corporation suggested two key action-items to enhance orbital debris mitigation. First, they argued that regulators should "establish definitions of nationally 'acceptable' thresholds for orbital debris and space safety consequences."[224] Second, they urged regulators to "organize and streamline the U.S. regulatory structure for debris mitigation."[225] Although the white paper was tailored for the United States, the concepts could be applied to other spacefaring countries and international regulators too. By adhering to these key actions, regulators could set the foundation needed to establish a space debris verification regime and more specific space debris mitigation rules.

Once space situational awareness and space debris verification regimes are established, policymakers should develop legally binding space debris mitigation measures that result in improved compliance and, ultimately, long-term space sustainability. Both pre-launch and post-launch policies should be considered. In a 2020 journal article titled

[224] Marlon E Sorge, William H Ailor, and Ted J Muelhaupt, *Space Traffic Management: The Challenge of Large Constellations, Orbital Debris, and the Rapid Changes in Space Operations* (The Aerospace Corporation, 2020), 7.

[225] Sorge, Ailor, and Muelhaupt, 7.

"Space Governance in the New Space Era," the authors propose "initiating efforts to reform and streamline existing licensing process for space launches" and "a 'mission authorization process'...for commercial space applications and services not covered under existing licensing frameworks."[226] Regulators could also adopt commercial best practices, such as those presented by the Space Safety Coalition's (SSC) "Best Practices for the Sustainability of Space Operations." The SSC addresses information exchange, spacecraft design, and space operations concepts to attain space sustainability.[227] For example, the SSC recommends that "spacecraft with limited observability should include features that enhance visibility (e.g., laser retro-reflectors and/or radar-cross-section enhancements)."[228]

As for post-launch rules, space debris expert Darren McKnight proposed several policy recommendations during a presentation to the Department of Commerce's Office of Space Commerce in August 2020. One example of a measure that should be considered would require that "satellites above 400 km have propulsive collision avoidance capability."[229] Another recommendation by McKnight advocates for a "5-year or 1-year standard for post-mission disposal" instead of the current 25-year guideline.[230] If the United States were the first to establish such space debris mitigation measures, the United States could use its leadership in the space community to help set new norms for the international community.

C. OPEN THE DOOR FOR SPACE TRAFFIC MANAGEMENT REFORM

Space traffic management (STM) was not explicitly addressed because it is a separate problem set that warrants its own diligent research. The U.S. government defines STM as "the planning, coordination, and on-orbit synchronization of activities to enhance

[226] Daniel L. Oltrogge and Ian A. Christensen, "Space Governance in the New Space Era," *Journal of Space Safety Engineering* 7, no. 3 (September 2020): 6–7, https://doi.org/10.1016/j.jsse.2020.06.003.

[227] "Best Practices for the Sustainability of Space Operations," Space Safety Coalition, September 16, 2019, https://spacesafety.org/best-practices/.

[228] Space Safety Coalition, 11.

[229] McKnight, "Do Not Build on a Weak Foundation," 8.

[230] McKnight, 8.

the safety, stability, and sustainability of operations in the space environment" in SPD-3.[231] Of note, the definition of STM varies from institution to institution, and STM is not yet defined in other pertinent policy documents, such as the U.N.'s LTS guidelines nor the USG ODMSP. Be that as it may, space debris mitigation is part of the safety aspect of STM. Space debris mitigation and space traffic management also share similar political framework obstacles. The 2020 NAPA report determined that SSA is the precursor to performing STM.[232] As such, this thesis lays the foundation of existing SSA technical infrastructures that could also support STM.

In the journal article "A Practical Perspective on Space Traffic Management," Darren McKnight, quoted earlier, outlines how space environment management (SEM), space situational awareness (SSA), and space traffic management (STM) interact with each other to achieve space operations assurance (SOA). SOA, a term proposed by McKnight, is the overarching domain that encompasses SEM, SSA, and STM, as shown in Figure 9.[233] SEM includes natural space hazards and debris mitigation efforts.[234] SEM activities drive SSA requirements. Next, SSA focuses on both long-term (weeks to decades) issues, such as space debris remediation options and statistical collision risk, and mid-term (minutes to months) issues, such as space catalog maintenance and the discovery of newly created space objects.[235] SSA is the primary source of information to STM. The third component, STM, has immediate and real-time needs (seconds to days), such as collision avoidance.[236] With this relationship between SSA and STM, the commercial SSA systems explored in this thesis could also support STM.

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[231] The White House, "Space Policy Directive-3, National Space Traffic Management Policy."

[232] Dominguez et al., *NAPA Report*, 10.

[233] Darren McKnight, "A Practical Perspective on Space Traffic Management," *Journal of Space Safety Engineering* 6, no. 2 (June 2019): 101, https://doi.org/10.1016/j.jsse.2019.03.001.

[234] McKnight, 102.

[235] McKnight, 102.

[236] McKnight, 101.

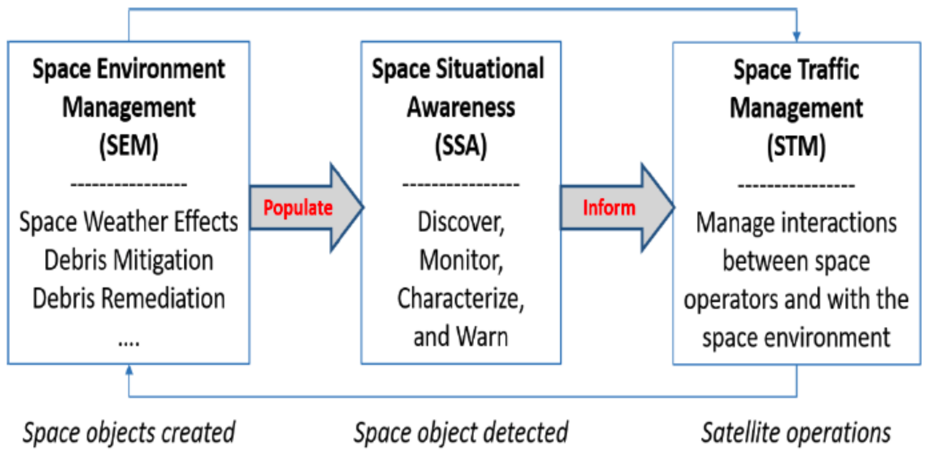

Figure 9. The interaction between SEM, SSA, and STM to achieve SOA[237]

D. AREAS TO CONDUCT FURTHER RESEARCH

There are several areas of future study that may be worth exploring. For example, a study on the successes, failures, and lessons learned from the New Zealand and LeoLabs partnership would be a relevant follow-up to this thesis. Another set of studies could look into commercial SSA services as a solution for other countries since this thesis only considered the United States in detail. This could help other spacefaring nations find an SSA solution that is more specific to their domestic regulations until policymakers come to a consensus on further international guidance. If the OADR comes into fruition, a case study should compare the OSC's OADR and the DOD's UDL. Additionally, such a study could also look into improving OSC's civil STM framework.

Another area of future work includes topics that will benefit the space community and regulators more directly. This thesis only covered major SSA systems, not all SSA systems that exist. Research that leads to a public database of SSA systems and data fusers could aid regulators and space operators in finding an SSA system that meets their needs more efficiently. Such a list should include basic sensor capabilities for each orbital regime, available services, and contact information. As for regulators, future work should define the consequences of violating legally binding space debris policies. More specifically, the

[237] Source: McKnight, 102.

study could determine the monetary costs of debris-creating events then tie those costs to licensing, insurance, and penalties.

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