A Study of Emerging Space Nation and Commercial Satellite Operator Stakeholder Preferences for Space Traffic Management

by

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Submitted to the Department of Aeronautics and Astronautics and the Institute for Data, Systems, and Society
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Abstract

The near-Earth space environment is a finite, shared resource. Trends including reduced launch costs, electronics miniaturization, and preference for resilient, disaggregated architectures are driving significant growth in the orbital population. Existing systems to coordinate and manage space traffic do not scale to this higher level of utilization or promote the efficient and equitable use of space. There is growing need for both new technical space traffic management (STM) systems and policy regimes to coordinate activities going to, in, and returning from space. This thesis describes several contributions to developing this integrated corpus. A literature review of proposed STM architectures highlights gaps in understandings of emerging space nation STM perspectives and commercial operator attitudes on data sharing. Based on United Nations documents and interviews with emerging space nation representatives, a set of four recommendations is developed for future international STM development efforts. These recommendations stress affordability, achievable technical requirements for participation, inclusive system design, and careful consideration of satellite control allocation. Through a review of operator U.S. regulatory filings and new interviews with operators and experts, operator attitudes are traced successively through 1) potential STM domains and functions; 2) per function data requirements; 3) concerns about data sharing; 4) attitudes towards data protection mechanisms; and 5) influence on potential STM system design. Key insights include the importance of operator perceived self-benefit from data sharing, and significant heterogeneity in operator data sharing attitudes.

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Professor Richard Linares, thank you for letting me share in your work exploring future technical systems for space traffic management. Much of the work in this thesis predates my joining your team, but it informs the work I do every day. I am excited for what we will build together.

Thank you to Sreeja Nag for offering me a summer researcher position at the NASA Ames Research Center and exposing me to the fascinating challenge that is space traffic management, as well as your feedback and insights on the work in this thesis.

Thank you to Thomas Roberts for being the first person to read this thesis cover to cover. Your countless suggestions and insightful questions were immeasurably helpful.

Chapter 2 includes a description of work I contributed to during the summer of 2018 and 2019 as a contractor to the NASA Ames Research Center. During that time, I supported efforts to adapt work on Unmanned Aircraft System Traffic Management to architect and develop a concept for operational space traffic management autonomy. I gratefully acknowledge my co-authors on several publications relating to that work, Sreeja Nag, David Murakami, Parimal Kopardekar, and Nimesh A. Marker, as well as research collaborators Jannuel Cabrera and Nolan Johnson.

More than 35 individuals at commercial satellite operators, think tanks, non-governmental organizations, international inter-governmental organizations, embassies, and various national governments graciously shared their thoughts with me in support of the work described in Chapters 2, 3, and 4. Their patience, insights, and generosity with their time are acknowledged with the utmost gratitude. With this thesis, I seek to distill and organize the collective wisdom and experience they kindly shared with me. I hope I have succeeded. Any errors are my own.

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Chapter 1

Introduction

Now is an exciting time for the space sector. Numerous megaconstellations have been proposed and some have begun launching. Launch costs continue to decrease, due to a combination of increased cadence and re-usability. Technical capabilities in both satellite technology and general electronics have advanced and been miniaturized, rendering many missions achievable using low-cost, rapidly iterable small satellites. The reduction in cost, size, and complexity has in turn expanded access to space to more actors. Among commercial actors, lower cost has enabled new (and old) business cases that previously would not close. Start-up capital is flooding into the space sector to fund these efforts [33].[1] Estimates from investment banks have projected sustained industry growth in the coming years [142, 67]. Governments are likewise increasingly looking to and using space-dependent data and services to support their activities, including efforts towards the United Nations (UN) Sustainable Development Goals. These factors all point towards a proliferation of space activities and increases in missions and satellites over the coming years. While this trend is tremendously exciting, it also portends increasingly intense utilization of the finite near-Earth space environment, and especially low-altitude orbits.

Facilitating this future will require measures to ensure that operators are able to access this environment and operate safely within it, both immediately and in the long term. Among the most significant threats to this future is the potential for on-orbit physical collisions. Because of the high velocities involved, such collisions can fragment colliding objects (whether they are active satellites or debris) and produce long-lived orbiting fragments that then imperil other objects. Managing this threat will require:

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[1] It remains to be seen, as in every other investment market, what impact the COVID-19 pandemic will have on space sector investment, and how long-lived the effect will be.

1. Efforts to prevent the generation of future debris (debris mitigation);
2. Mechanisms to remove existing high-threat debris objects already in orbit (debris remediation); and
3. Systems to coordinate space traffic to avoid collisions (collision avoidance), both between satellites and debris as well as between active satellites. Coordination to avoid physical collisions between operational satellites is major component of the broader concept of space traffic management (STM).

Each of these tasks rests upon a strong and actionable understanding of space situational awareness (SSA), the current and near-future state of the space environment. None of these tasks are adequate to enable sustainable access and use of space on their own, and all four concepts (debris mitigation, debris remediation, STM, and SSA) are connected by various feedback mechanisms. The Space Operational Assurance model proposed by McKnight and Maclay provides a useful way to categorize and conceptualize the interrelationship of these elements [104, 100].

This thesis seeks to make a contribution towards efforts to build future STM systems to meet rapidly emerging demands, specifically through characterizing a subset of stakeholder needs for these systems. Nevertheless, it does so with full recognition that STM alone is inadequate to achieve the long-term sustainability (LTS) of outer space, defined by the 2019 Guidelines for the Long-term Sustainability of Outer Space Activities (discussed further in Subsection 1.1.7) as:

> [T]he 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 order to meet the needs of the present generations while preserving the outer space environment for future generations. [40, 50]

1.1 Introduction and Background

This section seeks to provide a very brief and high level introduction to some of the relevant concepts necessary to understand the work carried out in this thesis project. This content should be familiar to anyone who has taken a course in satellite engineering or worked in the satellite industry, but is included to assist readers coming from other backgrounds. It is not intended to be comprehensive, and the interested reader is encouraged to consult dedicated texts including [155, 161, 64, 15, 48, 102] as needed for a deeper or more technical treatment of these issues.

1.1.1 Orbits

The Earth is surrounded by a vast, but finite volume of near-Earth space. Satellites and other spacecraft can be placed into orbits that move through this space. The orbital volume is generally divided into three regimes: low Earth orbit (LEO), with orbital altitudes as low as 80 or 100 km[2] up to approximately 1500 or 2000 km, geosynchronous orbit (GEO) with circular orbits at an altitude of approximately 35,768 km, and medium Earth orbit (MEO), comprised of orbits from the edge of LEO up to GEO. Geostationary orbits are geosynchronous orbits with an inclination of 0 degrees (meaning their orbital planes are perpendicular to the axis of rotation of the Earth), and appear essentially fixed in the sky to an observer on the Earth's surface. MEO is less utilized than LEO or GEO. Some satellites use highly elliptical orbits (HEO) with peak altitudes, or apogees, that extend past GEO to increase dwell time at high latitudes. HEO orbits are sometimes considered a fourth regime. While the orbital volume in LEO, MEO, and GEO is extremely large, certain orbits with convenient properties are much more limited. Two particularly congested orbit types are geostationary orbits, especially above particular land masses, and sun-synchronous orbits (SSO), a subset of LEO orbits which take advantage of the non-spherical nature of the Earth to preserve a particular orientation of the spacecraft with respect to the Sun when overflying a particular location of the Earth's surface. GEO orbits are implicitly allocated through management of satellite receive and transmit frequencies by the International Telecommunications Union (ITU). Other orbits are not allocated, and subject simply to approval by a launching state.

One common legacy data format for sharing information about satellite orbits is the two-line element set (TLE). The TLE format is a fixed width format, originally developed for use on punch cards. TLEs are generally propagated using the Simplified General Perturbations 4 algorithm, but suffer from limited accuracy that inhibits their usefulness for collision avoidance purposes.

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[2] This lower bound, and whether one exists, is not agreed internationally and is an ongoing and fraught topic of discussion in space law. See [103], for instance, for further discussion.

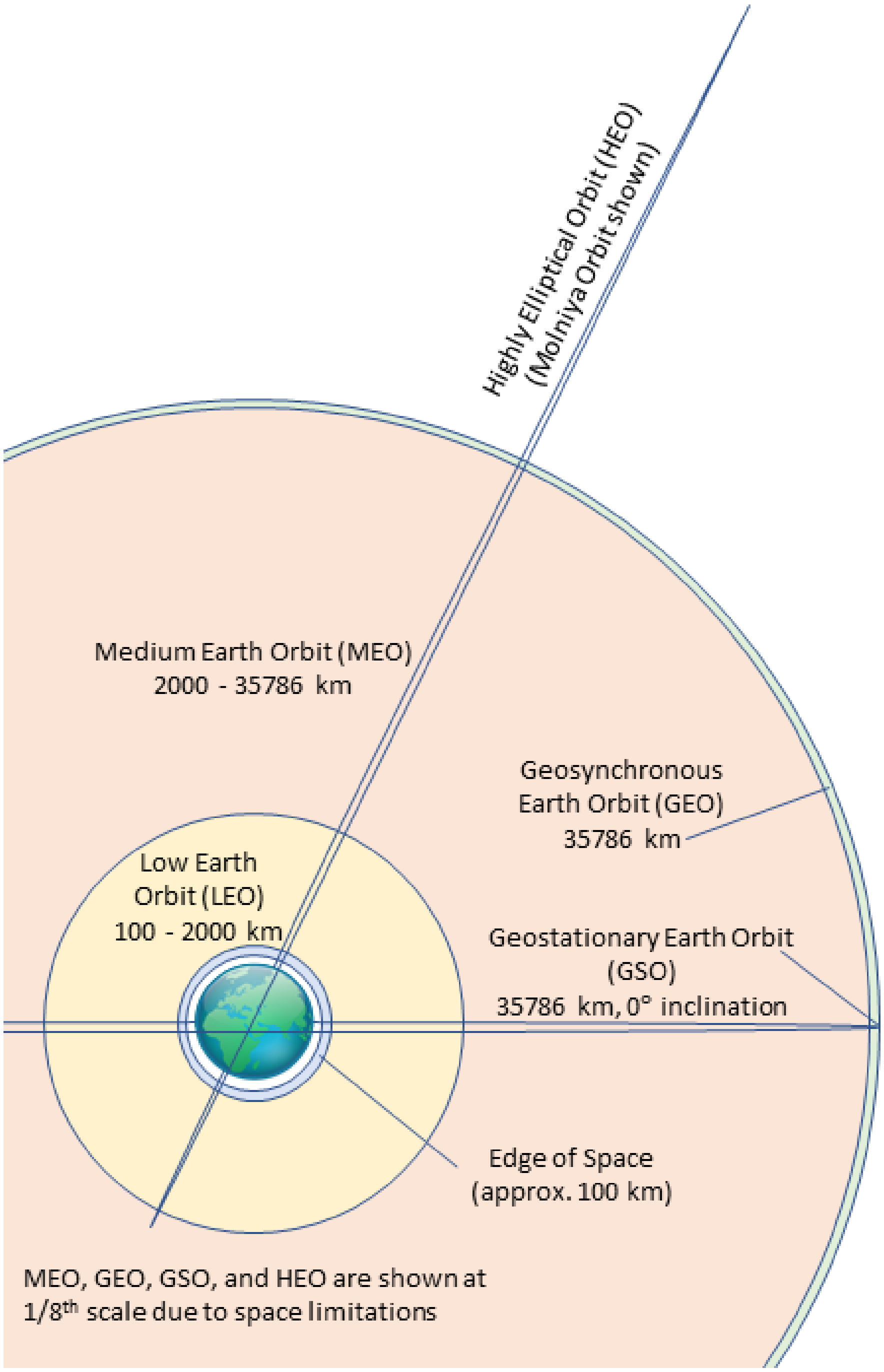

Figure 1-1: Near-Earth Orbital Regimes

1.1.2 Orbital Debris

Significant numbers of anthropogenic resident space objects (RSOs) are already orbiting the Earth.[3] These objects include active satellites, as well as non-functional debris objects like dead satellites, rocket upper stages, and fragments generated from prior collisions and on-orbit explosions.

The energy of orbiting objects scales with their mass and is proportional to the square of their velocity. Because objects in Earth orbit move very quickly (approximately 7.7 km/s in low LEO decreasing to 3.1 km/s at GEO), orbiting objects are highly energetic and orbital collisions can involve significant energy even for very small objects. Murakami et al. note that the energy of a 2 mm diameter 0.1 g aluminum sphere during a 10 km/s impact event is equivalent to a handgun bullet, while a 2.4 cm, 140 g object is equivalent to a hand grenade, and a 10 cm, 16 kg object is like an anti-aircraft missile warhead [107].

The acknowledged capabilities of the U.S. Space Surveillance Network (SSN) include tracking objects larger than 10 cm in LEO [145]. The next-generation Space Fence System recently reached initial operational capacity [49] and will enable the tracking of high-interest objects as small as 1 cm if radar resources are specifically tasked for this precision tracking [72, 53, 96].

As a rough classification, RSOs can be broken down into three size classes [107]. Objects smaller than 1 cm cannot be reliably tracked and pose threats to spacecraft subsystems, but can be protected against using adequate shielding and probabilistic models such as the National Aeronautics and Space Administration (NASA)'s Orbital Debris Engineering Model (ORDEM) [111] or the European Space Agency (ESA)'s Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) [50] to estimate collision risk. Objects larger than 1 cm and smaller than 10 cm in LEO, the so-called "Lethal Non-Trackable" (LNT) objects, are large enough to cause mission-ending risk, but are not generally tracked with sufficient fidelity to support collision avoidance maneuvers [107]. Objects larger than 10cm can be tracked and collision avoidance maneuvers can be used to help mitigate risk of collision with these objects. Maclay and McKnight observe that improved satellite shielding designs, as well as better SSA and collision avoidance, can shrink the LNT size range and provide marginal benefit to reduce, but not eliminate, the risk posed by LNT objects [100, 2].

As seen in Figure 1-2, the number of debris objects and the cumulative mass varies

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[3] There are natural micrometeoroids and other objects in the near-Earth space environment that do influence shielding considerations for spacecraft, but they are fairly small in size (and not necessarily Earth-orbiting) and are ignored for the purpose of this work.

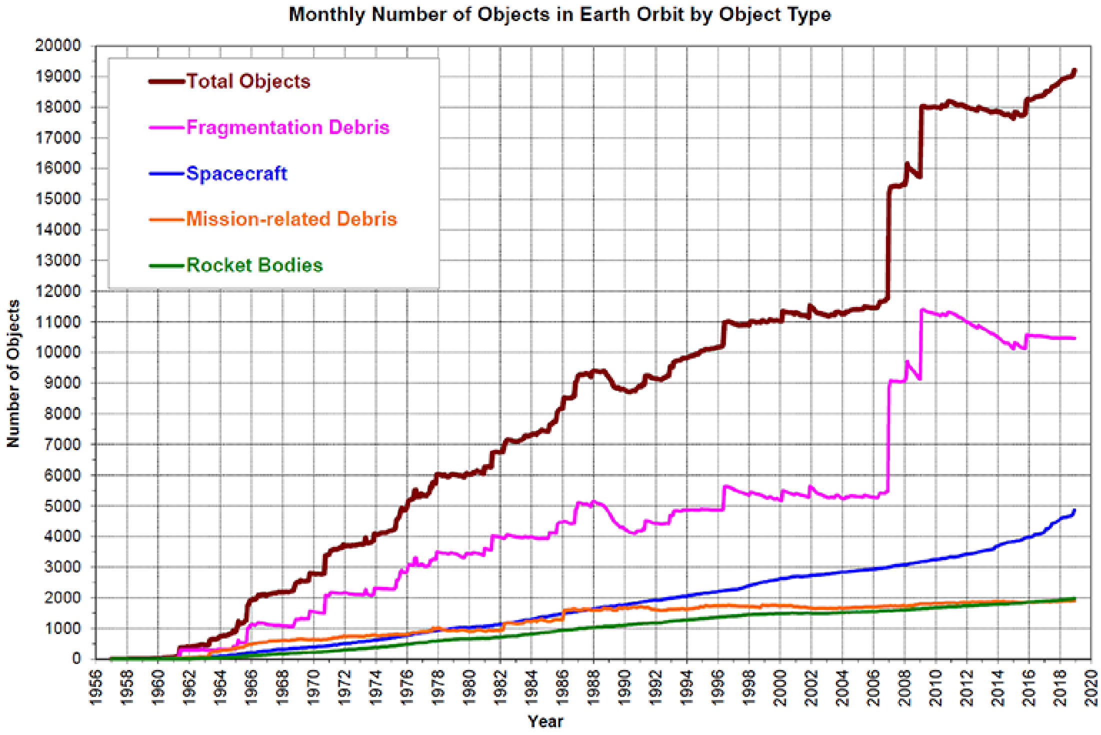

Figure 1-2: RSOs by Altitude. Chart by NASA Orbital Debris Program Office [95]

significantly by altitude, and has grown significantly over time. The sharp double spike visible from 2007-2009 corresponds to a Chinese anti-satellite missile test and a collision between an American communications satellite and a defunct Russian military satellite.

LEO orbital mass clusters in several altitude bands, as seen in Figure 1-3. The bars highlighted in yellow below are speculative satellites included as part of a NASA Orbital Debris Program Office study on large constellations and are not actual on-orbit satellites.

As atmospheric drag-induced re-entry is the only significant self-cleaning mechanism for the LEO regime, debris lifetime depends strongly on altitude and solar activity as both these factors significantly influence atmospheric density. A chart illustrating this dependency is available at [113, 29].

Kessler and Cour-Palais published a paper in 1978 identifying a potential cascading effect whereby collisions between orbiting debris objects would produce an intensifying feedback reaction such that the fragments from these collisions would increase collision risk and lead to a further increase in collisions and fragments [71]. This phenomenon is referred

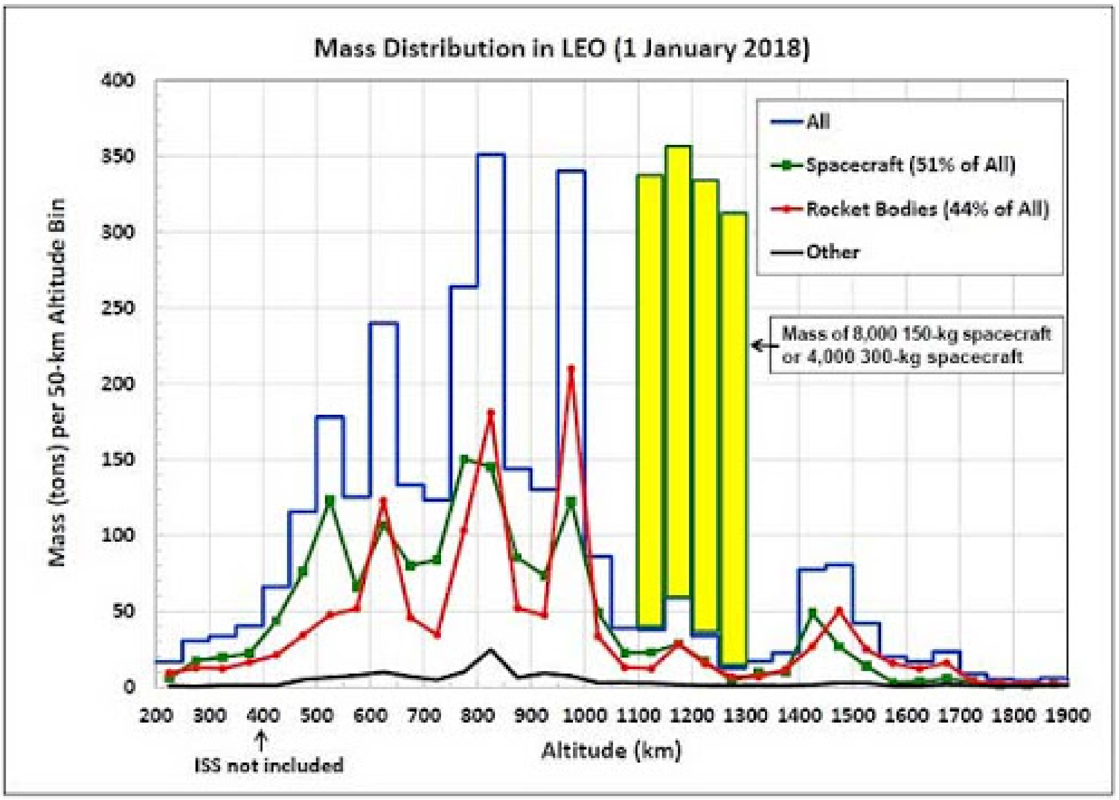

Figure 1-3: Orbital Mass by Altitude. Chart by NASA Orbital Debris Program Office [112]

to as the Kessler Syndrome. It was further clarified and developed by Kessler et al. in [70].

Modeling tools are used to help understand the way the debris environment will develop over time, critical inflection points for debris density at different altitudes, and the risk of future debris-on-debris conjunctions. NASA's Space Debris Office maintains the LEO-to-GEO Environment Debris Model (LEGEND), an evolutionary space debris model to study the long-term debris environment [112], and has conducted studies examining the debris environment under different assumptions for post-mission disposal and active debris removal (ADR) [93, 94, 92].

1.1.3 Conceptualizing Earth Orbit as a Common Pool Resource Problem

The economics community has long recognized a special category of common pool resources (CPRs), goods which possess both subtractibility of use, i.e. use by one entity degrades use for another, and high difficulty of exclusion, meaning that it is hard to control the use of the resource (or the extent to which a given actor derives benefit from the resource). A sandwich possesses subtractibility of use because when consumed by one person, it is no longer available to be eaten by another. Digital music files generally do not possess subtractibility of use. One user listening to a file does not prevent another from doing the same. A gym might have low difficulty of exclusion; one simply needs to add a door with a code to the front of the building. On the other hand, it might be challenging to exclude users from a large wilderness area. Fencing would be inordinately expensive as would paying people to patrol the borders of the area. Examples of CPRs, goods that possess both these properties, include fisheries, forests, and public roads.

The conventional wisdom, laid out in Hardin's classic 1968 paper [59], argues that CPRs create misaligned incentives for individual users to rapidly over-consume the resource to the detriment of all. In the fisheries example, users will fish as much as they can, as quickly as they can, to maximize their own short-term benefit even at the cost of depleting the fishery in the long term. To prevent this outcome, either the CPR must be privatized or some kind of governmental framework must be put in place to save users from themselves. Nobel Laureate Elanor Ostrom has studied CPRs in great depth, and challenged this notion, demonstrating (among other things) that not all scenarios with CPR goods produce suboptimal outcomes, that coordination in CPR management can arise through multiple mechanisms, and that different CPR goods in different scenarios actually produce distinct types of problems with different solutions [55, 120].

Weeden and Chow apply lessons from Ostrom's work to treating near-Earth orbit as a CPR, and argue for a system of adaptive governance whereby "rules, norms and enforcement mechanisms adapt and evolve over time as information about or characteristics of the commons environment expand or change" [159].

Work by ESA's Space Debris Office has described methods to derive quantitative environmental limits for the near-Earth space environment which could facilitate management [76] and developed and applied a debris index to evaluate debris mitigation techniques [85] and help guide mission design [86].

The ESA methodology is being used as part of an effort by the World Economic Forum (WEF) to develop a Space Sustainability Rating (SSR) for satellite operators analogous to ENERGY STAR for energy efficiency or the Leadership in Energy and Environmental Design system for green buildings [124]. The SSR is intended to incentivize and recognize responsible behavior that promotes space sustainability. The SSR is being designed for WEF by a consortium including ESA, the Massachusetts Institute of Technology (MIT), the University of Texas at Austin, and Bryce Space and Technology.[4] Maclay and McKnight note that the SSR system provides a mechanism to recognize and reward companies that pursue aspirational practices that go beyond industry-defined best practices, norms, and standards or the less-strenuous requirements set as a mandatory floor by government regulators [100].

1.1.4 Defining SSA and STM

Broadly speaking, SSA is concerned with understanding where objects are, what they are doing, and where they will be in the future. STM is concerned with coordinating (and potentially controlling) objects in the space environment. High quality, timely SSA is necessary to achieve effective STM. If one begins to investigate either of these concepts in further detail, both become quite amorphous. The two phrases are used differently by different people, mean different things in different contexts, and multiple partially-overlapping definitions have been proposed (both by regulators and in the literature, and are cited as authorities). Work has been done comparing and characterizing some of these differences, see for instance [77, 3] or [117].[5]

In the case of STM, one can easily see this challenge when considering the two most prominent definitions. Space Policy Directive 3, signed by U.S. President Donald Trump on

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[4] I have been a volunteer contributor to the MIT team working on the SSR.

[5] Oltrogge has recently begun using the term space traffic coordination and management (STCM) instead of STM. There is disagreement between different actors internationally about the potential scope for activities to be carried out as part of a space traffic system, and especially whether there is a need for coordination or true aircraft-style control. The STCM term is intended to include both of these concepts without implying preference.

June 18, 2018, states that STM is "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment" [114]. The definition used by the 2006 International Academy of Astronautics (IAA) Cosmic Study and re-endorsed by the IAA 2018 STM report reads "Space Traffic Management (STM) means the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference" [62, 15]. Both are similar, but differ in various aspects. For instance, the first definition includes sustainability as part of the defined purpose for STM while the second does not. The second definition limits consideration to two specific domains: physical and radio-frequency interference (RFI). The first does not.

This thesis is intimately concerned with both SSA and STM, but does not propose or use a particular set of definitions (although a particular definition of both is used in Chapter 3 for clarity during interviews). The reason this thesis does not adopt a specific definition is because adopting a specific definition influences architecture, and the bulk of this thesis is concerned with exploring stakeholder preferences. While this thesis does not use a specific definition, there are two "flavors" to the use of SSA and STM that are worth highlighting. First, this thesis is overwhelmingly focused on civil considerations rather than those more closely related to military or national security missions. It considers SSA is in terms of data needed to support civilian purposes and excludes things like adversary intent or capability estimation that were previously considered part of the term SSA in a U.S. national security context and are certainly part of the newer term Space Domain Awareness.[6] Secondly, within STM the set of domains considered is deliberately allowed to be a broad super-set of potential responses to avoid limiting consideration of potentially relevant system objectives and functions.

1.1.5 SSA

Understanding what objects are in space and how they are moving is critical for collision avoidance and space safety. Gathering this information with sufficient accuracy and precision can be quite challenging, especially for small objects, distant objects, and those whose operators decline to share their own information about object states. Measurements made by those other than the operator without coordination with the spacecraft are known as non-cooperative measurements and are typically made with telescopes and radars, but

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[6] Space Domain Awareness unfortunately shares an acronym with the Space Data Association (SDA), which will be referenced repeatedly in this thesis, as well as the Space Development Agency, which will not.

other sensor phenomenologies also exist. Most of these sensors are on the ground, but the United States operates multiple satellites to collect space-based SSA information [21, 22]. Canada operates Sapphire, a dedicated LEO SSA mission [139]. Multiple private companies also offer SSA-related data and services on a commercial basis. Owner/operators often have much better state knowledge for their own satellites than can be achieved by non-cooperative observations. Pooling data from various sensors and parties can yield a better overall picture of the space environment.

The U.S. Department of Defense (DoD) has provided SSA and related services to users globally without direct user fees for many years with increasing levels of openness and formalization over time, in particular since the 2009 collision between an active Iridium Communications Inc. (Iridium) satellite and an inactive Russian Cosmos satellite. The DoD has sought to transition provision of SSA services to a civilian agency to focus its own resources on its core defense mission. Some users have been interested in a transition to a civil agency because of transparency limitations associated with DoD methodologies and sensor capabilities, as well as a need to implement more modernized systems and a perception that users might have greater ability to shape the offerings of a civil agency. The Department of Commerce (DoC) was tasked with the civil SSA mission in Space Policy Directive 3, although it has not been given such authority by Congress. It is currently conducting work towards development of an Open Architecture Data Repository (OADR) to support civil provision of SSA services.

1.1.6 Collision Avoidance

Understanding where objects are and projecting where they will be allows operators or other analysts to screen orbits for upcoming close approaches between RSOs, conjunctions, which pose a risk of collision. There are a variety of methodologies and assumptions that can be used to support collision avoidance screening and analysis [64]. For well-characterized objects, it may be sufficient to calculate the miss distance between objects at closest approach as a simple metric or compared against a certain keepout geometry. Other analysis will estimate and propagate covariance for objects based on limitations in state knowledge derived from the sensors and measurements available. In this case, a probability of collision can be estimated. This is often done for small objects, where objects are tracked with less fidelity and the larger quantity of objects may require an operator to accept some presence in a zone around the spacecraft smaller than the operator would consider acceptable for large objects. In probabilistic conjunction analysis, it is critical that covariances are estimated realistically and that values are low enough to provide support for actual decision making.

Large covariance values can artificially reduce probability of collision metric values and lead to a misleading sense of safety [23]. Maximum probability of collision can be used as a highly conservative metric. Maneuvers can significantly change the projected path of a satellite, so maintaining knowledge of maneuvers and accurately propagating satellite future states is both incredibly important and generally done with greatest fidelity by the operator. This is especially true for low-thrust maneuvers which take place over an extended period of time and may be harder to detect/characterize from the ground, especially in close to real time.

If analysis indicates an unacceptable risk of collision between a maneuverable satellite and another satellite or debris object, the operator will generally develop a collision avoidance maneuver to mitigate the risk of collision while avoiding other potential high risk conjunctions and minimizing impact to mission operations and resource consumption. When two maneuverable satellites experience a conjunction, coordination is especially important to avoid uncoordinated maneuvers which could potentially increase rather than mitigate risk.

1.1.7 Existing International Law

International law relating to space draws primarily from five treaties[7]: The Outer Space Treaty (1967), Rescue Agreement (1968), Liability Convention (1972), Registration Convention (1976), and Moon Treaty (1984, although it has been ratified by many fewer nations and no major space powers).[8]

The Outer Space Treaty declares that outer space "shall be free for exploration and use by all States," forbids "national appropriation" of outer space, affirms that states bear international responsibility their own space activities (including authorizing and providing continuing supervision for any national non-governmental space activities), and stipulates that states retain jurisdiction and control over their launched objects [151]. The Registration Convention obligates states to furnish information concerning launched objects and their orbits to the UN. [152].

The Inter-Agency Space Debris Coordination Committee (IADC), an inter-governmental organization comprised of national space agencies, developed a set of space debris mitigation guidelines reflecting current best practices by member space agencies. In 2007, the U.N. General Assembly endorsed these voluntary guidelines [154].

In 2019, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) adopted a set of 21 voluntary "Guidelines for the Long-term Sustainability of Outer Space Activities

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[7] Dates are dates of entry into force.

[8] France and India have signed, but not ratified the Moon Agreement.

of the Committee on the Peaceful Uses of Outer Space" [153], and established a working group to further consider topics relating to space sustainability. The guidelines are broad in scope, addressing aspects relating to policy and regulatory frameworks for space activities; safety of space operations; international cooperation, capacity-building and awareness; and scientific and technical research and development. Nations are encouraged to implement the guidelines through domestic laws and regulatory regimes.

1.2 Research Questions, Methods, and Organization

This thesis is concerned with facilitating future work towards the development of more effective SSA and STM systems, with an emphasis on the coordination component of STM. In support of this work, it provides a discussion of STM at an architectural level, addressing three main topics (each in its own chapter): existing architecture concepts for STM, emerging space nation perspectives on STM, and attitudes of commercial satellite operators regarding data sharing for SSA and STM or related purposes.

More specifically, this thesis is organized into five chapters. This chapter has provided a brief introduction to SSA and STM and will now summarize the thesis' research questions, methods, contributions, and organization.

Chapter 2 introduces the system architecture analysis framework and surveys existing STM architectures to identify key points of distinction and gaps in the literature. It seeks to answer:

1. What architectures have been proposed for STM systems?
2. What are key architectural trade-offs in the potential design of STM systems?
3. What gaps exist in the definition or study of STM systems to date as documented in the relevant literature?

These questions are addressed through a literature survey and subsequent analysis, compiled through the lens of the system architecture analysis framework. Two keys gaps in the literature are identified, relating to emerging space nation perspectives on STM and commercial satellite operator data sharing sensitivities.

Chapter 3 discusses the views of emerging space nation representatives on STM. It addresses:

1. What are the perspectives of representatives of emerging space nations on the design of a potential internationalized STM system, and what shapes these opinions? More specifically:

    (a) What are preferred forms of engagement to determine the design of future international STM systems?
    (b) What forms of STM/SSA capability-building are most needed?[9]
    (c) What capabilities should be provided by an international STM system?
    (d) What kinds of STM requirements would constitute ‘undue’ cost?

2. How do these opinions differ across interviewees and countries, and what shapes them?

3. What are the implications of these preferences for the design of a potential STM system?

These questions are explored using a combination of a literature review and a set of semi-structured interviews with representatives from emerging space nations. The chapter surveys existing literature and primary sources, chiefly relating to discussions at the COPUOS, regarding emerging space nation views on SSA, STM, and space sustainability; describes the motivation for and development, refinement, and administration of an interview protocol to representatives of emerging space nations; summarizes results of these interviews; develops a set of recommendations to guide future efforts to create internationalized STM systems; and validates those findings with a subset of interviewees. The findings form a potential set of process constraints to increase emerging space nation support for and participation in future STM systems.

Chapter 4 considers questions relating to commercial satellite operator sensitivities around data-sharing. It investigates:

1. What STM-related or adjacent domains exist where there could be significant benefit to operators or other STM stakeholders from information sharing?

2. What functions need to occur to deliver those benefits and what information do they require?

3. Are commercial satellite operators willing to share this data and what sharing-related concerns do they have?

4. What are different potential architectural forms for data sharing; what kinds of trust models do they support; and how well can those structures mitigate operator concerns about data sharing?

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[9] The word capability is used here deliberately, rather than capacity, to refer to measurable demonstrated behaviors.

These questions are answered using a combination of a review of commercial satellite operator filings before U.S. regulatory bodies—chiefly the Federal Communications Commission (FCC)—and interviews with representatives of commercial satellite operator as well as relevant non-governmental organizations (NGOs), governments, academics, and other SSA/STM experts. Operator attitudes and data sharing practices are strongly driven by their own perceived self-interest from such data sharing, with various architectural forms being available to mitigate potential data sensitivity when self-interest motivates sharing. Anomaly and threat information sharing is more contentious than coordination to prevent or mitigate physical or RF interference.

Chapter 5 summarizes the findings of the thesis, their implications for STM system design, and areas for future work.

1.3 Contributions

The primary contributions of this thesis are:

1. A review of architectures for STM proposed in the literature, identifying points of differentiation between architectures. Two gaps are identified that provide motivation for the work in the subsequent chapters: a need to characterize emerging space nation perspectives on STM and a lack of specificity regarding commercial satellite operator views on SSA and related data-sharing practices.

2. A primary-source data collection exploring emerging space nation stakeholder views on STM, to my knowledge the only academic effort to specifically do so. This is accompanied by derivation and validation of a set of high level recommendations to guide STM system design and development to increase acceptance by emerging space nations.

3. An assessment and summary of commercial satellite operator sensitivities relating to the sharing of data in support of SSA/STM and related functions. While data-sharing concerns are repeatedly mentioned in the literature in general forms, this chapter explores the topic in considerably more depth than any other treatment of which I am aware.[10]

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[10] A non-public ESA study addressing this question is cited in the literature, but I was unable to obtain access to it.

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Chapter 2

Review of Proposed Systems Architectures for STM

2.1 Introduction

In 2017, Brian Weeden wrote an op-ed for *SpaceNews* that called STM a "super wicked" problem that "involves balancing an indefinable set of technical, legal, and economic variables; conflicting interests and worldviews of many stakeholders; and a complex political environment with diffuse responsibilities and authorities" [157]. So called "wicked" policy problems are tremendously challenging because according to Rittel and Webber's formulation, they possess ten characteristics [129]. They:

1. Lack a definitive problem formulation;
2. Have no stopping rule to identify if the problem is solved;
3. Possess solutions defined in subjective rather than empirical terms;
4. Lack clear mechanisms to assess proposed solutions in either the short or long term;
5. Offer only a limited number of attempts to try solutions and cannot be solved by trial and error;
6. Possess a non-enumerable set of possible solutions or actions that could be incorporated into potential solutions;
7. Are unique in key characteristics;

8. Can be seen as consequences of another problem;
9. Can be attributed to multiple possible causes with different causes recommending different solutions; and
10. Oblige the problem solver to get the solution right on the first attempt.

A successful solution or solutions for STM will necessitate the engineering of complex socio-technical systems. The word "complex" is used to mean "interrelated, interconnected, or interwoven elements and interfaces" as described by Crawley et al. in [41, 35-36, 286-310], and that these elements can interact in ways that produce properties and/or functionality (which may be desirable or undesirable) beyond the individual constituent components, a phenomenon known as emergence [41, 10-13][42]. The term "socio-technical system" means a system that involves both social and technical components and for which successful analysis must involve consideration of both elements and their interactions, a concept introduced by Trist and Bamforth in [147] and developed in subsequent scholarship [122].

This chapter reviews the literature describing various concepts and architectures for potential STM systems and key architectural trade-offs. It will focus on architectures for the physical collision avoidance problem rather than radio-frequency (RF), laser deconfliction, or other possible elements and does not treat in detail the specialized issues related to crewed space operations. It further focuses more, but not entirely, on on-orbit operations rather than launch and re-entry. The topic of RF coordination is already much more developed (for instance, see the description of ITU activities at [63]), and the physical coordination problem is a complex topic on its own. Laser deconfliction is a fairly minor problem in actual operations.[1] Chapter 4 explores a broader set of domains due to their inclusion in interviews with stakeholders including commercial entities, but does so in the more constrained context of identifying data-sharing concerns rather than full architectural specification. Architectures are considered chronologically in order of publication, to allow the reader to see how ideas have evolved over time.

This chapter seeks to answer the following three research questions:

1. What architectures have been proposed for STM systems?

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[1] Civilian lasers of concern are primarily limited to astronomical observatory laser guide star adaptive optics. The American Physical Society published an article complaining about limitations on guide star-equipped telescope observing time caused by overflight of satellites more than a decade ago, but the limited coverage since then implies that the issue has largely been resolved [99]. The DoD operates a laser clearinghouse service that is mandatory for DoD laser programs and available for other operators on a voluntary basis [78].

2. What are key architectural trade-offs in the potential design of STM systems?
3. What gaps exist in the definition or study of STM systems to date as documented in the relevant literature?

2.2 Overview of the Systems Architecture Analysis Framework

The systems architecture analysis framework is used here to summarize, analyze, and compare the various concepts and architectures present in the literature. The framework provides a useful tool to design, understand, and manage complex systems [42]. System architecture and system engineering are connected, but different disciplines. The system architect operates at a higher, more qualitative level and is concerned with identifying key decisions and trade-offs, while the systems engineer might be more concerned with developing a specific optimal solution in exhaustive, implementation-level detail or mathematically studying a particular engineering trade-off. Maier's work is the classic text on systems architecture analysis [101]. Reymondet offers a good review of many of the concepts in systems architecture for a reader seeking a deeper treatment [128].

This paper adopts and adapts the generic systems architecture analysis framework described by Wood et al. [165], which is summarized in Figure 2-1 and draws upon the thinking by Crawley et al. in [41]. Wood and colleagues have applied the method to a variety of complex socio-technical systems involving both social and technical considerations including complex international science, technology, and innovation partnerships, developing country small satellite programs, and malaria early warning systems [165, 123, 168, 69]. Joseph adapted and applied this framework to analyzing options for the micro-gravity research ecosystem following the de-orbiting of the International Space Station [68, 71-73]. Ovienmhada considered methods to design a decision support system for environmental governance, determined the systems architecture framework is the strongest methodology for complex systems, and applied it to a case study of Lake Nokoué in Benin [121]. Work by Reid et al. to integrate environmental, human vulnerability and social impact, human decision making, and technology design models is informed by the systems architecture analysis framework [126].

Under this framework, a system is composed of stakeholders, forms, and functions that are combined to fulfill one or more system objectives. The system exists in a particular context, which might include economic, political, technical, and other factors. Inputs enter the system from the context, and outputs of the system go to entities existing outside the boundaries of the system. While no prior author has used the systems architecture analysis approach described here, it is presented in detail below and then used to summarize, analyze, and compare aspects of the relevant system architectures described in this section.

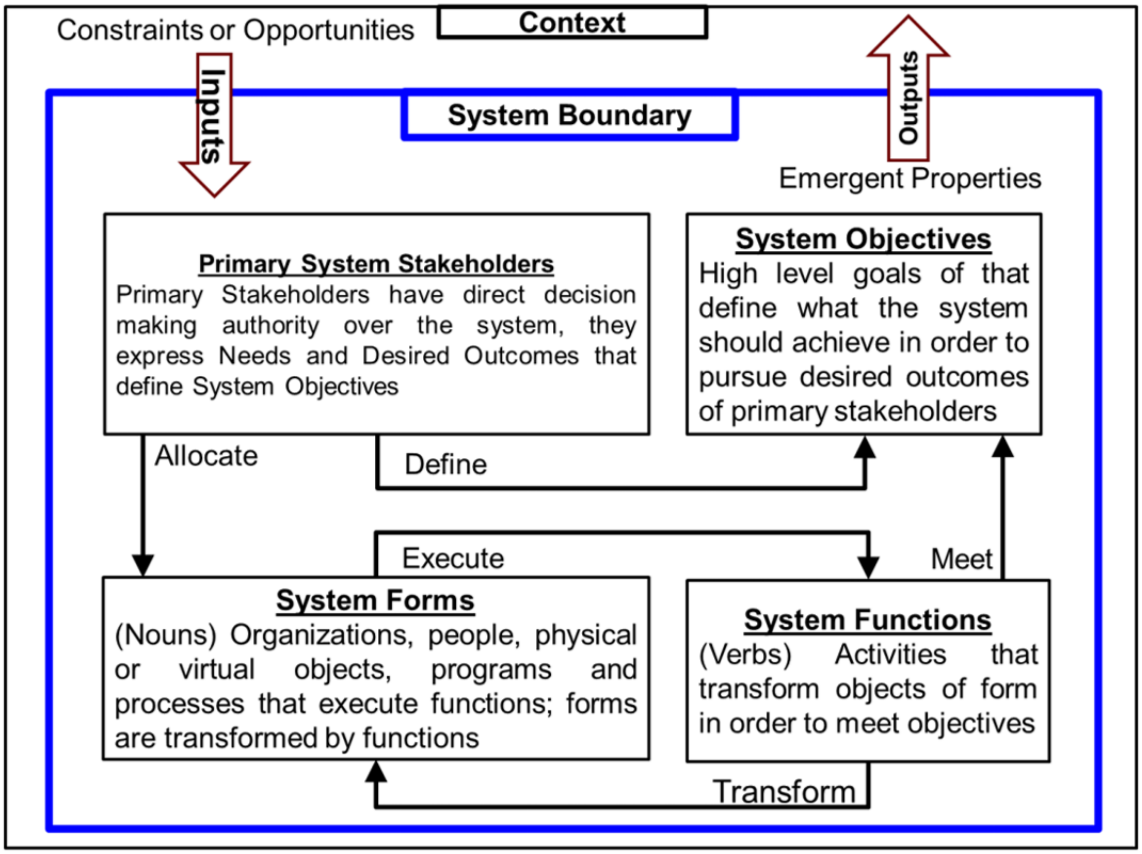

Figure 2-1: Generic Systems Architecture Analysis Framework (reproduced with permission from [165])

The systems architecture analysis framework, as adapted to STM in this work, can be broken into the following steps:

1. Understand the relevant STM system design context.

   This step involves two components. First, the architect must identify what is part of the system of interest and what is external to it in order to delineate the boundaries of the system under analysis. Next, the architect must describe the relevant context, generally by decomposing it into specific, relevant context factors.

For the first task, boundaries should generally be set such that all elements reasonably necessary to achieve STM stakeholder objectives included in each domain of functionality are included in the system. Which domains of STM objectives (and which mission phases) should be included is left as a free parameter for study, with options including RF, safety of flight/on-orbit collision avoidance, launch and reentry (including initial deployment information), space weather, near-Earth objects (NEOs), laser emissions, anomaly sharing, and cyber-threat and other threat information sharing. Similarly, a system may cover pre-launch design and development, best practice/guideline/standards development, launch and deployment, orbital operations, and/or decommissioning and re-entry or disposal. Among the chosen examples, analysis is heavily informed by the specific American context, while seeking to also have some generality to other national contexts. This boundary setting is appropriate because it recognizes the more advanced state of such discussions within the U.S. context while simultaneously acknowledging STM as a global problem and the need for coupled solutions that fulfill system objectives for multiple countries to achieve overall system success.

For the second task, a notional set of specific relevant contextual factors are defined as technology, the legal/regulatory/political environment, economics, and legacy forms and functions. As compared to Wood et al.'s approach in [165], this definition deemphasizes cultural and social factors, and combines consideration of political, regulatory, and legal factors into a single category. The diminution of cultural and social factors is acceptable, given the aggregated cross-national context of much of this analysis and the greater exploration of cultural and social factors as part of the work to characterize stakeholder views in the subsequent chapters, in particular the exploration with governments of emerging space nations in Chapter 3 and commercial satellite operators in Chapter 4. Not all authors address all of these facets, and context mentioned in the surveyed reports is generally only included in this chapter's review when specifically identified as system-driving context rather than a more general description of current or historical detail.

2. Identify primary, secondary, and tertiary stakeholders and their needs and desired outcomes.

   The approach here again follows the distinction made by Wood et al. in [165]. Stakeholders have needs and desired outcomes for the system that influence system objectives. Needs are internally facing, while desired outcomes represent the idealized (unconstrained) future state desired by the stakeholder. A need for a satellite operator might be to achieve the mission objective of its satellite. A desired outcome might be safety of the orbital environment. Primary stakeholders make direct decisions about the design of the system. In the STM context, one examples might include governments, or more specifically, the U.S. DoC's Office of Space Commerce, if given the authorities envisioned in Space Policy Directive 3. Secondary stakeholders influence primary stakeholders through relationships such as authority, funding, or other mechanisms. In the STM context, an example might be the U.S. Congress, which provides funding and oversight but would generally not dictate the specific details of a proposed STM architecture. Tertiary stakeholders are those who derive benefits from the system. An example might include commercial satellite operators, who gain access to a more efficiently coordinated, sustainable, and safer space environment. These categorizations are somewhat subjective and context-dependent. If commercial satellite operators were to be able to exert significant authority and funding over the STM system-defining organization, for instance if it were to evolve as a private consortium, then commercial satellite operator members would be secondary rather than tertiary stakeholders.

3. Define system objectives.

   System objectives arise out of stakeholder needs and are the actions the system will perform to help produce the outcomes desired by stakeholders, informed by the context. They are (or at least should be) defined from the perspective of the system and the system architect, rather than from the perspective of an individual stakeholder. In the STM context, a system objective might be the coordination of planned satellite maneuvers to identify potential conjunctions. Conflicts between stakeholder objectives can complicate the definition of system objectives, for instance if the system architect or primary stakeholders have different attitudes on the proper safety/cost trade-offs than secondary or tertiary stakeholders. In the case of STM, system objectives are largely decomposable to a domain-by-domain basis, even if the architectures to achieve them are more interconnected.

4. Select STM system functions that the system needs to execute to fulfill the identified objective(s).

   According to the old adage, there are multiple ways to skin a cat (although I remain happily unaware of the particulars of any of them). In the systems architecture context, specific functions are necessary to achieve the system objective(s). These functions are often interconnected and there may be multiple ways a system objective could be achieved. For instance, the coordination of planned satellite maneuvers could be achieved by having a party screen maneuvers before execution to identify issues, or through banning the use of maneuverable spacecraft at that altitude. One of these solutions is much more practical than the other, but both could potentially achieve the system objective.

5. Allocate functions to STM system forms to achieve system objectives.

   For each set of functions necessary to achieve one or more system objectives, it is necessary to allocate those functions to forms. To continue the example from the prior step, a screening mandate could be given to a centralized government system or to a private organization funded by satellite operators. In some architectures, forms and functions are defined without an allocation of functions to forms. In others, specific allocations are identified or only one allocation is possible given the nature of the function.

   Form and function are often interconnected. If the maneuver-screening function is changed to operate on a decentralized peer-to-peer basis between satellite owners, the form that conducts the screening must become an algorithmic consensus through the network rather than a particular entity within the network.

6. Explore consequences of various allocations of functions to forms for completion of system objectives, as well as emergent properties.

   For most potential objectives considered within the STM system framework, there are multiple ways to allocate form and functions, and multiple sets of functions that could achieve system objectives with varying levels of efficacy and other trade-offs. Rather than enumerate all possible options, or describe any of them in particular detail, the goal of the framework is to identify key trade-offs in system design and their impacts.

Because the studies surveyed do not use this particular formulation, they do not engage in all of the steps of this framework. For instance, none of the surveyed architectures conduct a formal stakeholder mapping and delineate stakeholders into primary, secondary, and tertiary. Across these studies, the objective is to take the content provided by the original authors and allocate it into this common framework to facilitate comparative analysis. In some cases, it is useful to provide additional commentary or analysis in addition to relaying what is contained in the cited work. Such additions are either self-evident or labeled as such.

2.3 Review of Relevant Literature

Many studies have proposed different architectures for STM. This section will survey a subset of these architectures, with a focus on examples that are high profile, recent, novel, or particularly synthetic. It is not and does not seek to be exhaustive. Rather, the objective of this summary is to survey a sufficient portion of the literature to identify common trends, ensure that major considerations within the literature are considered, and identify gaps in the literature that might motivate future work.

2.3.1 International Space University 2007 Space Traffic Management Final Report (ISU 2007)

In 2007, one of the International Space University (ISU) Summer Session team projects addressed STM and proposed a set of traffic and environmental rules [29]. This report followed the original IAA 2006 Cosmic Study [62], and is one of the earlier articulations of the idea of an international STM system.[2]

Context Relevant context explored in the report includes current international space law, current debris mitigation practices, the growing debris population and number of conjunction warnings, and certain technical assumptions regarding feasibility of ADR, launch rates, launch costs, and object tracking accuracy. The system boundaries include the development of traffic rules, international negotiations on the development of an STM system, implementation of that system, and arbitration procedures.

Stakeholders Stakeholders include states, operators (LEO non-SSO, SSO, GEO, human spaceflight), various international organizations including the ITU, IADC, COPUOS, International Civil Aviation Organization (ICAO), and a potential new international STM organization. Depending on the phase, states are either primary or secondary stakeholders, and operators are generally tertiary. Stakeholders are discussed repeatedly, but a formal stakeholder needs analysis is not conducted. Operator needs, both state and non-state, implicitly include freedom from physical collision into the future (space sustainability) and

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[2] The IAA 2006 Cosmic Study is not described in detail in this chapter. It was updated by a more recent 2018 report, which is described in Subsection 2.3.10.

ability to operate in space in ways that allow them to accomplish their missions at minimal additional cost.

System Objectives The system adopts the six strategic objectives from ICAO. They are safety, security, environmental protection, efficiency, continuity, and rule of law [29, 45].

Forms and Functions The operational forms considered in the system include SSO operators, other LEO operators, GEO operators, the STM system (the service provider), and human-rated spacecraft.

The proposed traffic rules imply various functions, some allocated to particular forms and some left free. These include:

- Screening for all potential conjunctions and calculating the probability of collision, impact velocity, and probability of breakup; and
- Designing a collision avoidance maneuver and transmitting that to the owner/operators involved if the probability of collision is greater than 1/10,000 and the conjunction involves one or more maneuverable spacecraft.

Functions that are fixed to certain operators include:

- GEO operators would be mandated to provide position information for collision avoidance to the STM system, and would be required to provide notification of "station acquisition, station-keeping and relocation maneuvers."
- GEO operators would be encouraged to provide consent for distribution of their spacecraft position information to adjacent operators, implying a need to detect which spacecraft are "neighboring," a consent method for operators, and means for ephemeris sharing by the system.
- The system would mandatorily provide position information for spacecraft performing relocation maneuvers to other operators impacted by the maneuver, requiring an ability to identify and notify these operators.
- Human-rated spacecraft would be required to submit flight plans in advance for coordination.

A dispute resolution function is proposed with a Space Traffic Arbitration Commission as the form to perform this function.

Other rules do not directly impact the system architecture, but impose regulatory practices around slotting of SSO, probability of collision thresholds where maneuvers are mandatory, minimum requirements for low-altitude flight overlapping human spaceflight[3], and compliance with debris mitigation guidelines.

Consequences for System Design The authors break establishment of the STM system into a four-stage process of 1) rule development, 2) consensus building, 3) implementation, and 4) arbitration that could occur in different organizational contexts based on the respective strengths of those organizations. The report assumes a centralized STM service provided by an international organization. The authors do so because they claim international organizations are "the most effective means for coordinating and regulating the actions of several nations in both physical and electromagnetic space that are not the clear or obvious purview of any single nation" [29, 42] and that development must occur at an international intergovernmental level because of "the international nature of space activities" and legal principles rooted in international space law [29, 43].

Summary The ISU report is an early study that explores potential traffic rules to prevent collisions on-orbit, coordinate traffic in the densely populated SSO and GEO regions, assure safety for human space operators, and preserve the usability of the space environment. It focuses on a top-down international approach and the development of an international organization to implement the rules.

2.3.2 The Need for an Integrated Regulatory Regime for Aviation and Space: ICAO for Space? (Jakhu et al. 2011)

This report proposes that ICAO take responsibility for near-space safety, including STM and discusses some of the necessary legal components, but does not define a full architecture to do so. The treatment is primarily from a legal rather than technical perspective.

Context Key trends identified include the growing number of nations and commercial actors operating in space in increasing volumes [66, 4-5], the rise of commercial space transportation [66, 8-10], the promise of commercial human spaceflight [66, 10-12], the increasing reliance on satellite navigation systems by a diverse set of users [66, 12], and

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[3] This topic is considered in a more modern context by U.S. regulators in one of the rulemaking processes described in Subsection 4.4.5 [18, 14]. Such rules are complicated by the strong adoption of such altitudes for small satellites in the time since the ISU report was released.

the growing orbital debris hazard. The system boundaries are limited to a scope similar to ICAO's oversight of air traffic operations, including no direct enforcement mandate and a focus on standard setting and harmonization.

Stakeholders Under the ICAO system, member states are the primary stakeholders, bearing responsibility for ensuring conformity in national law and interacting with operators (as secondary or tertiary stakeholders depending on their levels of influence). A formal stakeholder needs assessment and desired outcomes analysis was not conducted.

System Objectives The identified objectives are broadly similar to the safety and economic vitality objectives of the SAIC study discussed later in Subsection 2.3.4. The regulatory regime should focus on "enhancing the safe and efficient use of space by all actors and the long-term sustainability of Earth orbit without imposing undue restrictions that stifle innovation and commercial development" while avoiding being "so onerous that it undoes benefits for Earth by limiting potential for use" [66, xii] . The study adopts the IAA definition of STM.

At a more detailed level, safety issues are identified as including:

1. Ground processing safety including ground support equipment and flight hardware (and interfaces between the two);
2. Launch safety (to protect supporting personnel, as well as the general public on the ground, at sea, and in the air, and to avoid collisions between launch vehicles and other space objects);
3. Suborbital safety (involving similar considerations but more complex integration with air traffic);
4. Orbital safety (concerned with minimizing collision risk and debris generation or risk to human life aboard crewed vehicles);
5. Orbital debris ground risk from re-entering objects; and
6. Risks to people on the ground or in aircraft from returning vehicles, and rescue of personnel during aborted launches or on-orbit.

Overall, this list both considers human spaceflight in more detail than other concepts reviewed in this section and de-emphasizes connections to other domains such as RF, space weather (although this is briefly mentioned in the operational proposal), and anomaly reporting.

Forms and Functions The significance of the ICAO for Space proposal is that it assigns to ICAO responsibility for achieving the system objectives and assumes the adoption of ICAO processes and ICAO's structure of reaching agreements on technical standards for implementation by states.

In particular, it emphasizes the use of international standards and recommended practices (SARPs). ICAO adopts SARPs in order to "secure the highest possible degree of international uniformity in regulations and standards, procedures, and organization regarding civil aviation matters" [66, 4]. The study describes the process by which SARPs are introduced and approved [66, 40-43]: SARPs are compiled by individual experts nominated by member states for a limited term and and who act in their role as individuals rather than representatives of their nominating state. SARPs are adopted by a two-thirds vote of the committee, and can be blocked if a majority of states register disapproval. Individual countries can file differences from SARPs if they consider them "impracticable." However, states that do not do so are responsible for implementing them and ICAO maintains audit processes for safety and security.

Consequences for System Design The ICAO model requires a top-down approach to STM, and sharply defines the role of the body in STM. Reception for this model will depend significantly on how stakeholders view both the ICAO model and their expectations for the existence and development of relevant technical experience within ICAO, the importance of air-space system integration, as well as the ability of STM to achieve sufficient organizational importance and standing to avoid being side-lined by the organization's air traffic mandate.

Summary The ICAO for Space model sees ICAO's role expanded to include the space traffic mission, but the concept is addressed at a high level from a largely legal rather than technical/operational perspective. At the time of the study's publication in 2011, it was a thought-provoking proposal that elicited strong reactions in the community. Since then, the operational details of a potential international STM approach have been further developed in a more organizationally agnostic way e.g. by Oltrogge [118] (as a private-public partnership potentially evolving to an international organization) and by the IAA (as the top-down approach in [15]). While Russia has advocated for a UN-hosted information platform for STM at COPUOS, such a choice has been a non-starter for the United States and various other nations (e.g. see annex of [131]).

2.3.3 Evaluating Options for Civil Space Situational Awareness (SSA) (STPI 2016)

This report primarily discusses options for transitioning provision of SSA from the U.S. military to a civil, commercial, or international organization [116]. It also briefly proposes several potential mechanism for achieving STM in the U.S. context [116, xii, 81-94]. These include:

- Granting the Federal Aviation Administration (FAA), already tasked to license launch and re-entry, authority to regulate on-orbit activities;
- Letting commercial space actors and other participants from relevant industries define best practices and standards;
- Having the U.S. government set rules for collision avoidance with punishments for non-compliance; and
- Developing a potential "active space traffic control regime" with an entity that can direct satellite operators to maneuver their spacecraft in particular ways at particular times to avoid collisions analogous to how air traffic control is performed.

These approaches differ on who bears responsibility for creating regulations, rules, or frameworks; authorities for issuing, revising, and administering rules; compliance/enforcement mechanisms; flexibility to change; and transparency of rule development and compliance.

The report also describes analogous systems that present potential models that could be adopted for STM:

The first is the ICAO as an intergovernmental organization with an advisory (but no enforcement) mandate setting standards for safety and technical considerations. Countries then implement these standards and policies in national law, with the ICAO forum providing value as a venue for regulatory harmonization and dispute resolution between states. The authors note that only a limited number of states currently oversee private space activities, limiting the need and benefit of harmonization, but that early action by states overseeing private space activities could prevent a period of disharmonization down the line by providing best practices before that happens. The ICAO model is a top-down process, beginning with action at the state level through a treaty.

The second is through a model similar to privatized air traffic control as it exists in some countries. Government retains oversight of safety considerations and regulatory duties, but air traffic control is performed on a commercial basis, using commercial software implemented incrementally and funded through user fees. One challenge the Science and Technology Policy Institute (STPI) authors flag is how to accommodate satellites owned/operated by international entities.

A third example described is the evolution of national practices into internationally agreed-upon, endorsed, but non-binding guidelines similar to the IADC debris mitigation rules. The key distinction here is that the goal is distillation of best practices as currently implemented by various states without an explicit intention of directing state implementation of the guidelines, a so-called bottom-up approach.

As a fourth example, the authors discuss maritime domain awareness, where long tradition has led to a very decentralized and ad hoc process for coordination. Responsibility is split across multiple agencies and nations bear responsibility for nationally-flagged crafts and their activities in international waters.

Summary and Consequences for System Design The study contains lots of very useful analysis regarding potential options for transition of SSA to a civil entity in the U.S. government (not summarized here). The analysis is nominally specific to the FAA's Office of Commercial Space Transportation (FAA/AST), which was expected at the time to receive the mission, but is highly relevant to the DoC as well, should Congress give it the mission as described in Space Policy Directive 3. STPI's thoughts on STM system design are more speculative, but present a useful set of possibilities and analogous organizations that could be looked to as potential models (and generally have been in subsequent work).

2.3.4 Report on Space Traffic Management Assessments, Frameworks and Recommendations (SAIC 2016)

In 2016, the Science Applications International Corporation (SAIC) produced a report for NASA headquarters on potential STM assessments, frameworks, and recommendations. The report identifies a set of five potential "Space Traffic Safety Governance Frameworks," each composed of actions in the policy, technology, and operations domains relating to space traffic safety [32, 13-22]. The five frameworks are arranged based on the intensity of U.S. governmental involvement. Ranging from least to most government intervention, they are:

1. Private space traffic safety monitoring and coordination;
2. DoD-based space traffic monitoring and data sharing;

3. Civil-based space traffic safety monitoring and facilitation;
4. Civil-based space traffic safety monitoring and coordination; and
5. Civil-based STM.

These frameworks are then evaluated against a set of objectives. The report uses a specific lexicon, including space traffic safety, to avoid the assumption of centralized command and control analogous to air traffic management that some feel is implied by the term STM [32, 1-3].

Context The SAIC report considered launch, on-orbit operations (including end-of-life operations), re-entry (if into U.S. air space), orbital debris mitigation, SSA activities necessary for space traffic safety, and space weather activities necessary for space traffic safety as being in scope for space traffic safety and the different frameworks. The authors specifically exclude consideration of spectrum management and RFI [32, 10-11].

Stakeholders Stakeholders considered include U.S. government entities with relevant interests (NASA, FCC, Department of Transportation (DoT), DoC, Department of State (DoS), and the DoD), academia, FFRDCs, university-affiliated research centers, NGOs, and industry (including operators, SSA providers, insurers, launch providers, and satellite manufacturers). Overall the stakeholder consideration is fairly extensive, particularly within the U.S. government ecosystem, and is based on interviews with many relevant stakeholders. The status of stakeholders as primary or secondary shifts within different areas of their space traffic safety governance framework conceptual model. Stakeholder need and desired outcome analysis is conducted, but is largely implicit in the report. Three objectives are identified and discussed in the next paragraph. Presumably the first and third objectives (space safety and space commercialization) are most relevant to commercial operators and civil space operators and regulators, with the second objective (national security space objectives) more relevant to the national security space community.

System Objectives The report identified a set of three objectives, with several considerations for each [32, 12-13]. The first is to "Ensure and Enhance Safety of the Space Domain" with considerations related to limiting space traffic safety incidents (collisions and breakups) to protect workforce health, public health, orbital assets, space sustainability, and provision of space-based services for the public. The second is to "Protect and Enhance National Security Space (NSS) Interests" by "enabling and enhancing" relevant policies, strategies, and plans as well as developing transparency and confidence-building measures to incentivize responsible behaviors relating to the peaceful use of space. The third and final objective is to "Ensure Economic Vitality of the Space Domain and Space Industrial Base" by minimizing costs on space systems and operators and restraints on established and emerging space actors, while maximizing opportunities to put systems into orbit and return them.

Forms and Functions Some key differences in the allocation of form and functions across the five frameworks include:

1. Responsibility for development of best practices, guidelines, and standards, the scope of such products, and how they are allocated between the U.S. government (especially a civil-based space traffic safety agency) and private/non-government parties;
2. Allocation of the generation of space traffic safety products and services, forms from which data is ingested to generate that data, and whether information sharing by operators and subscription to STM-produced data and analysis products is voluntary or mandatory; and
3. The extent to which a coordination and/or traffic management function exists.

This description unavoidably oversimplifies the rich, precise details contained in the original report. Interested parties should refer directly to the report itself for greater nuance and detail.

Consequences for System Design The report notes that the middle of the road structure for civil-based space traffic safety monitoring and facilitation (framework 3, representing a moderate level of U.S. government involvement) best meets the set of objectives identified, outperforming civil-based space traffic safety monitoring and coordination in the third objective (focusing on commercial/economic impact) due to a fear that that structure might make it harder for start-ups and drive companies to other countries due to real or imagined compliance burdens. The other three options (private-, DoD-, and civil-based STM) all perform worse across all three objectives [32, 22-28].

Summary The report structures a set of five possible frameworks with varying levels of government intervention, including possible actions relating to standardization, SSA data provision and related services, space traffic coordination, and space traffic control.

The report considers both regulatory and operational components, but operates in a U.S.-specific context. Overall, it is a very useful report and provides a nice outline of several instructive reference models for STM system design.

2.3.5 On the Implementation of a European Space Traffic Management System (Tüllmann et al. 2017)

A set of ESA-sponsored authors conducted a three-part study in 2017 laying out a roadmap towards a European STM system over the next two decades [149, 150, 148].

Context The papers focus primarily on crewed commercial space travel as the considered use case, and therefore include more emphasis on the connection to aviation systems.

Stakeholders A variety of stakeholders are described, particularly in the first paper of the series. They include the air and space traffic control operators, European and American level organizational and technical institutions (ESA, European Union Aviation Safety Agency (EASA), EuroControl (European Organisation for the Safety of Air Navigation), FAA, NASA, etc.), and spaceports. Formal stakeholder needs and desired outcome analysis is not conducted.

System Objectives STM is defined as the "[e]xecution of all necessary Managing and M&C operations to ensure safe ballistic travel of manned and unmanned space-planes through suborbital space and airspace under consideration of the existing European Air Traffic Management System and Infrastructure" [149, 29]. The objective of the system is defined by the steps necessary to achieve this this management of operations, integration with existing air infrastructure, and system safety.

Forms and Functions Aspects necessary for the system are first divided into pre-flight, in-flight, and post-flight operations. The list of identified aspects is non-exhaustive, but includes:

1. Pre-Flight Operations Phase:
    (a) Flight and flight corridor planning, adjustments, and emergency contingencies;
    (b) Sharing of space weather information;
    (c) Conducting risk analysis and disseminating risk information;

    (d) Information sharing for passengers, crews, and terminals;
    (e) Providing information about local weather;
    (f) Maintenance and infrastructure;
    (g) Safety and security;
    (h) Sharing of flight plans, traffic management operations and communications, and system status monitoring; and
    (i) Management of risks, logistics, and negative externalities.

2. In-Flight Operations Phase:
    (a) Regular operations and communication; and
    (b) Contingency operations and communications.
3. Post-Flight Operations Phase:
    (a) Maintenance and infrastructure;
    (b) Safety and security;
    (c) Coordination with traffic controllers, ground operations, and vehicles;
    (d) Information sharing for passengers, crews, and terminals; and
    (e) Information sharing for investigations and other special requests.

As can be seen, this list includes a significant number of items considered outside the system boundaries in other STM architecture formulations, or not considered in significant depth in other concepts such as local weather information and maintenance infrastructure.

Separate from this list, the authors identify key functional and performance requirements for space weather monitoring, space surveillance and tracking, STM system certification, regulations and standards, and other STM system aspects. These are defined in significant detail in an appendix. Certification, regulations, and standards are proposed to be generated through an ESA-led process. Interfaces between STM and air traffic management systems are also defined, along with numerous safety and reliability requirements. Additional STM-imposed requirements are further identified for air traffic management systems.

Consequences for System Design The need for tight integration with air traffic leads to an architecture closely mirroring European air traffic management infrastructure, and premised on tight coordination with American systems for air and space traffic. Collision avoidance processes include more consideration of air-space transitions, but appear similar for the on-orbit phase to other architectures considered. The proposed architecture is specific to the European context and is not directly intended for generalization to other regions/contexts.

Summary Most of the other sources described in this chapter deliberately focus on orbital, uncrewed missions. The suborbital focus of this paper provides a useful contrast, but also demonstrates that much of the on-orbit safety construct remains similar. The report assumes a control-oriented model with forms mirroring air traffic control. At least among orbital operators seeking deconfliction, this level of intervention is not popular and widely seen as overbearing.

2.3.6 Space Traffic Management (STM): Balancing Safety, Innovation, and Growth (AIAA 2017)

In 2017, the American Institute of Aeronautics and Astronautics (AIAA) released a position paper on STM. The document addresses many topics at a high level, but does not propose a specific architecture. Rather it seeks to serve "as a framework, for deliberation and action by a broad community...to initiate a structured dialog, preserve continuity of thought, and provide a catalyst for change with the best interests of a multi-faceted space community in mind." [20, 4]. The report assumes the FAA will fulfill the STM role, as this was the stated policy at the time of the report.

Context The AIAA report identifies the increasingly crowded space environment, with more spacecraft and debris, as a major motivation for STM. This increase is largely driven by the growing commercialization of space and a need to evolve current SSA systems to accommodate that growth [20, 4]. It identifies legacy NASA, DoD, and intelligence community systems as currently adequate, but unlikely to be so in the future. System boundaries are defined implicitly (and necessarily somewhat amorphously) by the purpose of the report.

Stakeholders Stakeholders mentioned include government, commercial operators, classified operators, NASA, the DoD, the intelligence community, the FAA, and operators offering satellite servicing and proximity operations. The report does not engage in a stakeholder need or desired outcome analysis.

System Objectives The system objective identified is safer space operations for the present and future, achieved through means including debris mitigation and better tracking and cataloging of debris to feed better conjunction screening. Collision avoidance, data sharing, debris mitigation, codes of behavior, communication strategies, and voluntary coordination are also proposed as methods to improve safety of space operations [20, 4].

Forms and Functions Functions for the system to perform include:

- Monitoring, oversight, coordination, and enforcement;
- Standardization and coordination of "assumptions, uncertainties in data, and confidence levels" for system algorithms [20, 8];
- Provision of continuously updated SSA by a non-DoD source;
- Timely communications with operators;
- Pre-flight and on-orbit collision avoidance, with enough lead time and realistic uncertainty measures to support actionable maneuver decision-making; and
- Pooling and normalizing SSA data from many sources while preserving accuracy and traceability of collection.

One identified constraint is a need to accommodate classified objects. The authors argue the operating body should be granted authority by Congress, adequate funding, and immunity for liability of actions. It will also need, they note, to produce a plan for developing STM, for coordination with commercial entities and other countries, and to obtain SSA data, as well as demonstrate a commitment to engage in discussions with international partners and support an eventual transition to an international effort.

The paper also recommends various improvements relating to debris mitigation, and the adoption of a code of conduct for space operations.

Consequences for System Design The report implies, but does not fully describe building a U.S. system first, paired with a research and consensus-building agency as a means towards a subsequent international system. The focus is on collision avoidance, associated data sharing, debris mitigation, and norms. The FAA is assumed as the key implementing form and stakeholder.

Summary The report lays out a research and decision-making agenda rather than a specific architecture to accomplish the stated objectives. The framework/list presented helps identify some of the major fields and is fairly consistent with prior and subsequent work. The list includes work towards a set of behavior guidelines/code of conduct, emphasizing that STM is more than just an operational system. It also includes specific consideration of communications strategies, which is an important element, but not explicitly highlighted in many of the other documents.

2.3.7 The "We" Approach to Space Traffic Management (Oltrogge 2018)

Oltrogge's paper for the 2018 SpaceOps Conference argues that best-available, all-source data fusion is the necessary approach to yield actionable SSA of sufficient quality to support STM. He then defines various tenets for potential STM system design, derives system traits to achieve these objectives, and proposes an architecture for an International Space Safety Center (ISSC) that would meet his system requirements [118]. The paper describes an organization with a broad, but realistic scope and well-defined interfaces to support various functions across a set of multiple domains of space safety.

Context As context for the system, he identifies a number of factors including the large number of untracked objects and their consequences, upcoming megaconstellations, and the high number of false alarms produced by current conjunction screening methods. These factors are common to the context identified in many other sources. Educational work and ISSC participation in standards development is included within the system boundaries along with an operational system, operators, and model development/refinement to support SSA/STM.

Stakeholders In the international orbital debris mitigation context, he identifies commercial operators and government/civil operators as stakeholders. Commercial operators and their space industry associations help produce standards through space standards development organizations, while government operators participate in international intergovernmental organizations as well as the standards-setting process. Both help set and influence national regulatory entities. National regulators also influence international intergovernmental organizations and are influenced by space industry organizations. For most groups, he does not conduct explicit stakeholder needs analysis. As part of the architecture proposed, he notes a special category of "Willing Non-Contributor Operators" who are unwilling to share their SSA or other data due to classification or proprietary concerns, but would be interested in accessing higher quality shared SSA data for other objects to inform their physical collision and RFI avoidance. The needs and desired outcomes for these users are considered, chiefly that they want access to the best possible SSA data to support their own conjunction screening and RFI avoidance, but cannot or do not wish to share their own SSA data.

Space operators are defined to include those controlling satellites, launch boosters and upper stages, suborbital and exoatmospheric flight vehicles, and high altitude balloons and airships. These operators may include governmental, commercial, academic or amateur users/organizations. Oltrogge recognizes that operators have data-sharing concerns and will want their data protected against misuse.

Stakeholder needs are considered with respect to cost and system funding.

System Objectives Oltrogge identifies a set of key tenets for STM system design and key traits for derived STM architectures. These include pooling and fusing of data in ways that ensure quality, and cover on-orbit lifetime, suborbital flight, hypersonic flight, launch/ascent and end of life de-orbit/re-entry/descent, and provision of SSA data to classified operators.

He then identifies a set of 18 design requirements that help define the scope of the system and its domains of operations. These include sharing of standardized Earth orientation parameters, space weather information (including data necessary to support various atmospheric models), standardized open-source high-fidelity propagators and force model settings, ADR, education for operators, and compliance monitoring such as a space sustainability rating.

Forms and Functions Oltrogge describes several notable existing architectures. These include the conjunction assessment system operated by the U.S. Air Force's 18th Space Control Squadron (18SPCS), the SDA's Space Data Center (SDC), and Analytical Graphics Inc.'s Commercial Space Operations Center.

Important functions he identifies include acquisition of SSA (which necessitates its own whole architecture), methods for data pooling and fusion, orbit determination and propagation, RFI flyby and mitigation, and provision of SSA analytics.

He then enumerates a non-exhaustive set of more than fifty "links" necessary to enable the SSA analysis chain to support STM. He divides this chain into a set of categories including the SSA system, sensors, data pooling and fusion, SSA analytics, space object metadata, orbit determination and propagation, and RFI flyby and mitigation.

He describes a potential architecture for the ISSC, established as a public-private partnership, either an international organization or through an evolution of the SDA.

In his proposed architecture for the ISSC, forms include contributing operators, the operational ISSC entity, willing non-contributor organizations, space object tracking organizations, the International Earth Reference Service, governmental agencies providing space weather and related alerts, an integration cell to interface with willing non-contributor operators, and various existing and conceptual standards for message formats.

Functions for the ISSC include data normalization, data fusion, provision of an aggregated list of operator contact information, provision of derived SSA products including conjunction assessment, re-entry assessments, quality assurance, and RFI analysis. Operators would share data on in-situ debris strikes, as well as spacecraft charging and single event upsets, with space weather and space debris model generators. Operators would also provide the ISSC with tracking data messages with observations, satellite models, authoritative contact information, attitude information, orbit data messages, anomaly messages, spacecraft RF characteristic messages, and RFI messages.

The educational, ADR, and compliance monitoring functions are not explicitly described in the graphic of the suggested framework he proposes, but would presumably also exist as functions to be oversee by the ISSC in some form.

Consequences for System Design Oltrogge [118] argues that the use of a single high-accuracy catalog of SSA information is unrealistic and is dependent on a set of requirements that are unlikely to be achievable including:

- Ingestion and fusion of all-source data;
- Universal sharing;
- Support for diverse sensor phenomenologies and networks; and
- A need to stay up to data with the best SSA algorithms, procedures, and standards.

Even if an entity would be willing to meet these standards, he observes that various entities will chose to not provide their own data and will have better SSA for their own objects, undermining the whole point of a single-catalog approach. He notes that currently mainstream operator practices already rely on combining analysis of aggregated owner/operator ephemerides and 18SPCS-provided, non-cooperatively tracked special perturbation and/or TLE catalogs.

He proposes various methods to evolve to the future end state, organizational structures, and trade-offs associated with various funding models including government funding, operator funding, or a hybrid.

Summary Oltrogge's paper does an excellent job laying out technical requirements for the STM system, informed by his own work with the Space SDC.[4] The set of domains is broad and inclusive, but includes specific and compelling architectural reasons for inclusion. He identifies relevant messaging standards, both existing and that would be required to be developed. His treatment of non-contributing operators addresses the needs of such operators while still achieving overall system objectives.

2.3.8 Conceptual Development of a Civil Space Traffic Management System Capability (Skinner 2018)

In a paper for the 2018 Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), Skinner describes a potential architecture to provide civil spaceflight safety services designed to be responsive to a set of priority principles enumerated by the FAA [143]. These principles include meeting user needs, protecting sensitive data, working with existing SSA architectures, being transparent about data sharing and security and associated plans, using an open-architecture format, maximizing use of commercial and NGO-provided data, encouraging innovation and development/integration of new capabilities from academic and commercial sources, and providing service free of direct user fees. The architecture largely focuses on civil provision of SSA information and data products, but does not feature any coordination or control mission.

Context Sources of observations are considered exogenous to the system, as are users who receive the catalog and/or data products, and other STM centers with which the catalog is coordinated.

Context factors include the U.S. National Space Policy [12], existing international treaties and data-sharing agreements, and DoD SSA systems.

Stakeholders Commercial satellite operators are identified as users, as are foreign (non-U.S. flagged) satellite operators. The U.S. government is a stakeholder and is expected to have full access to data within the system. A formal stakeholder needs analysis is not conducted.

System Objectives The primary system objective is a space safety cycle with feedback, which the author breaks into fusing observations, sharing data, determining orbits, produc-

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[4] A second paper by him goes into even further detail, but hews extremely closely to the existent architecture of the SDC [119].

ing a catalog, warning for possible collisions, and tasking new observations. He notes other value-added objectives are also possible, including geolocation of terrestrial interference, archival data to support anomaly diagnosis, and other unspecified uses. In the conclusion, he describes how this architecture could serve as the provider of space safety information for a civil agency tasked with a broader Space Operations Assurance role.[5]

Forms and Functions Several functions are identified for the system. These include:

- Data quality assurance (at most steps in the process), based on objects with known truth-values and through comparisons between different data sources;
- Standardization of observation formats with quality and meta-data information;
- Orbit determination and correlation, as means towards producing and disseminating a catalog;
- Conjunction assessment, to create and disseminate conjunction data messages;
- Collision avoidance, producing and distributing quality (bias, uncertainties, etc.) and situational reports;
- Coordination with other STM centers through a common data format; and
- A resource tasker to prioritize requests for observations across sets of SSA sensors.

For coordination with other SSA/STM centers, Skinner envisions a "distributed, multilateral 'peer to peer' sharing architecture" similar to the NASA/National Science Foundation International Virtual Observatory rather than a hub-and-spoke model [143, 4].

Consequences for System Design The author traces the extent to which the architecture responds to the high-level principles. Several of his design choices are worth noting specifically, including a decision to avoid accepting or generating any classified information, compatibility with (but not dependence on) existing DoD SSA architectures, an open-architecture approach to maximize commercial and academic data ingestion, and a decision to be free of direct user fees.

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[5] The framework seeks to include space environmental and effects monitoring, as well as space debris mitigation and remediation, as part of a broader construct that better captures the elements necessary for safety of flight and long term sustainability [104, 100]. The concept is also mentioned in the introduction of the prior chapter of this thesis.

Summary Skinner defines STM as a civil function to be distinguished from military SSA. This definition of STM is somewhat different than that used by most other authors and the architecture he proposes is concerned with SSA and SSA-product dissemination, but without the coordination and/or control roles others attribute to STM. The architecture he proposes is relevant to the U.S. context, and a method for interaction with DoD and other STM providers.

2.3.9 Space Traffic Management with a NASA UAS Traffic Management (UTM) Inspired Architecture (NASA Ames Research Center 2018-2019)

A team at the NASA Ames Research Center has produced several publications related to an application programming interface (API)-connected ecosystem for STM that relies on machine-to-machine communications and increased autonomy to handle STM objectives for a denser future system.[6] The concept and initial architecture is described in [107]. The development of a software prototype and application to a representative use case is described in [110]. Consideration of autonomy within the system is treated in [109], with [34] describing work related to automated collision avoidance. The work adapted an architecture and principles developed for management of unmanned aircraft system (UAS) traffic management (UTM) [73].

Context The concept of operations paper [107] contains an extensive survey of relevant context factors. In the technical domain, these include:

- The current state of governmental and commercial SSA provision;
- Standardized communication formats from the Consultative Committee for Space Data Systems (CCSDS);
- Efforts by the FAA to better integrate rocket launches with air traffic and reduce the impact of launch and re-entry traffic restrictions on airspace users; and
- The FAA/NASA UTM system concept of operations and development work.

The team also identifies emerging trends. Some worth specific highlight include:

- A diversification of space-actors and space capabilities with a particular rise in small satellite operators;

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[6] I contributed to this work during the summers of 2018 and 2019.

- Numerous planned megaconstellations that will require greater collision avoidance autonomy and agreement on handling aggregate risk and impact;
- Financial projections of significant growth in the space sector over the coming decades; and
- The development of on-orbit servicing (OOS).

In a legal and regulatory context, the authors survey international space law, the way space regulatory authority is divided in the United States, work by the IADC, and Space Policy Directive 3's guidance on SSA and STM.

Drawing from this context, they derive several conclusions with implications for system design:

- Automation will be needed to ensure that future space systems can operate safely in future environments with higher traffic densities;
- Hierarchical system control akin to aircraft management is unlikely, especially in the short term;
- The system should be able to tolerate and function in the presence of non-participating entities and malicious actors;
- The system should rely upon standardized open interfaces;
- The system should begin on a voluntary basis;
- The system should have sufficient flexibility to meet various potential future regulatory mandates;
- The system should integrate SSA data from multiple sources, while addressing data sensitivity concerns; and
- The system should be open access.

The proposed STM system's scope begins with physical collision avoidance during on-orbit operations of voluntarily participating small satellites and is planned to evolve over a set of gradually increasing technical capability levels. The paper notes that the architecture is designed to accommodate different possible legal, regulatory, and policy structures.

System Objectives The primary objective of the system is deconflicting RSOs in the physical, RF, and directed energy (laser) domains across all phases of a mission (launch, on-orbit, and re-entry or graveyard) [107, 6].

Various constraints identified include:

- Compatibility with all operators, across operator type (civil, commercial, or military) and nationality;
- Rapidly conveying information;
- Inclusion of all necessary stakeholders and participants; and
- Integration with other external stakeholders, with air traffic management and national security being identified as examples [107, 6].

Stakeholders Stakeholders identified include suppliers of SSA information (SSAs)[7], conjunction assessment suppliers (CASs), supplemental data source providers (SDSs), government regulators, and spacecraft owner/operators. A new STM Service Supplier (S3) role is defined with responsibility for coordination between operators, providing functional services including an automated maneuver advisor, and interfacing between owner/operators and the broader system.

Forms and Functions Roles are well defined and include SSAs, a System Gateway, S3s, CASs, SDSs, the Spaceflight Information Management System (SIMS), Owner/Operators[8], and spacecraft.

SSAs provide tasking to sensors, gather sensor data, and feed catalog information to other users in the network, as well as potentially ingesting data from other SSAs and ephemerides from operators.

An STM Gateway supports system-wide discovery, registration, and authentication/authorization for the prototype architecture [110].

The S3 role is defined, with operators either needing to contract with an entity who performs that role, or agree to take on the role themselves. They provide a coordination function with other S3s, and feed ephemerides and maneuvers back into the system. The

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[7] This acronym is only used in this subsection to match the terminology of the original paper. Elsewhere in the paper, SSA refers to the concept of space situational awareness, not this architectural role.

[8] When capitalized, Owner/Operator refers to the formal role within this architecture, rather than the concept of an owner/operator stakeholder, which is referenced with lower case.

project includes considerations relating to coordinating maneuvers across multiple operators for aggregate system-level risk reduction [110].[9]

The CAS screens satellites and maneuvers and provides results to querying users.

The SDS role is defined in more generic form to support use and dissemination of other useful data sources like those necessary to support space weather and atmospheric models.

SIMS provides the connection between regulators and participants for regulator use, analysis, or public safety purposes. The SIMS could also distribute restrictions or emergency warnings to system participants.

Owner/Operators retain ultimate responsibility for decision-making and control over their spacecraft, as well as regulatory compliance.

The interface between the Owner/Operator and the spacecraft is not defined and largely left to the discretion of the Owner/Operator.

Consequences for System Design Analysis I conducted in [109] considers the number of catalogs included in the system. Options explored include a single catalog, a small enough set of catalogs for manual integration and reputational assessment, a large number of catalogs with standardized interfaces, and a large set of catalogs with consensus generated by a distributed algorithmic approach. The paper also flags a need to consider operator concerns about data sharing as an input into the design of sharing mechanisms, and right-of-way as a potential future topic where action will be required for denser spacecraft states.

The API-driven open-architecture approach described in these papers is designed to enable close coordination between commercial and government entities in system development, and to support the development of value-added SSA and STM-related service markets on top of a free basic government-provided service.

Summary The paper provides a clear vision for a flexible STM architecture that could perform a variety of roles ranging from SSA provision to coordination and even control, while facilitating strong commercial involvement along the value chain and the possibility of expansion to many different domains and phases of flight. The architecture emphasizes the importance of machine-to-machine interfaces for requisite future scalability and provides mechanisms to facilitate those interactions. In many ways, it provides an example of a national-level architecture developed for comparison against the regional or international structure envisioned in Oltrogge [118]. Another key difference is the decentralization

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[9] Work I contributed to included the development and implementation of an objective function and a greedy algorithm for maneuver selection based on system-level risk characteristics. This algorithm could serve as a baseline reference for comparison against future more sophisticated techniques.

of the S3 role in coordination. Further work will be necessary to continue to expand the operational prototype to add capabilities and interface with additional industry partners. However, this approach has been proven in the UTM context and demonstrated as a proof of concept for STM. The proposed architecture provides potential advantages over a centralized approach when it comes to tailoring services for different actors, different trust relationships, and adding additional commercial services into the system.

2.3.10 Space Traffic Management - Towards a Roadmap for Implementation (Eds. Kai-Uwe Schrogl et al. 2018)

The IAA's 2018 report updates the Academy's ground-breaking 2006 report on the same subject and describes a roadmap to implement STM. It does not describe the architecture of a particular STM system or concept. The report distinguishes between a technical STM system and a regulatory STM regime, noting both are necessary and providing suggestions for each. It introduces two possible archetypes for progress on STM: a gradual bottom-up approach where norms develop and emerge in industry and national contexts before gaining acceptance and a top-down approach starting with international discussions, agreements, and organizations.

STM would cover launch, operations, end of life, disposal, and re-entry, with the recognition that traffic management, safety, and end-of-life considerations all impact a spacecraft as it moves through the design and development process [15, 93].

Context The report describes relevant context extensively, identifying current status of various national and commercial space programs, contemporary international diplomatic proposals and instruments, current regulations, analogous legal regimes for traffic management, technical and academic progress in STM-related domains, global trends (climate change, population growth, the development of an "information society", an increase in armed conflict, and the rise of new powers), and trends in space activities (including proliferation of launch capabilities, lower launch costs, outlooks for key satellite service sectors, growth in human space exploration, and increasing space commercialization).

Stakeholders Stakeholders are not formally identified, and are considered in the context of making progress towards developing STM rather than users impacted by a system at an operational level. These include relevant professional organizations, industry, governmental personnel, international intergovernmental organizations, and the broader public, which is engaged through awareness-raising activities.

System Objectives and Forms and Functions System objectives, forms, and functions are all described in more general terms given the objectives of the report and often are implicit.

The bottom-up approach is described more loosely and less prescriptively than the top-down approach. Eight areas are identified for a bottom-up approach:

- SSA;
- Private human spaceflight;
- Space debris mitigation and remediation;
- Development of standards for space safety;
- Traffic rules;
- Practices for management of space resources;
- National space legislation; and
- Organizational aspects.

SSA information would be shared more extensively through bilateral agreements between countries and among operators, and commercial SSA service offerings would expand. In the context of private human spaceflight, there would be further work to develop regulatory frameworks, with the U.S. taking an early role, and ICAO interested in further development. The authors recognize the emergence of initial guidelines from the IADC, ISO, and COPUOS but describe the need to begin building towards regulation of ADR. Standards for space safety would develop through intergovernmental organizations as well as international NGOs. Development of traffic rules is viewed as important, but difficult under a bottom-up approach. On space resources, the report describes many open questions. The authors also note that national space law is expanding in many countries and that harmonization will be needed, but is difficult to achieve under a bottom-up approach. At the international level, there would be further coordination between the UN Office of Outer Space Affairs (OOSA) and the ITU as well as between OOSA and ICAO, but without any plans towards an institutional home for STM at the international level.

For the top-down approach, a new Outer Space Convention would be created through one or more UN treaties with high-level principles that are legally binding, complemented by binding, but revisable Outer Space Traffic Rules (OSTR) and Outer Space Traffic Technical Standards (OSTTS), which would not be legally binding. The convention would, among the various articles, provide authority for SSA and space weather services, space traffic coordination, an international space organization, and mechanisms for verification and enforcement. The OSTR would be legally binding, but technical in nature and cover areas such as registration, spaceflight, operations, STM, SSA, safety and liability, and the space environment. The OSTTS provide a vehicle to facilitate interoperability between operators and systems, commercialization of space technology, and space sustainability.

Consequences for System Design One of the most significant outcomes of this report, is the two notional roadmaps to STM and their influence on how related system elements might come to exist, what roles they will perform, and who will operate them. The concepts help provide a way to categorize some of the results provided earlier. They also emphasize that STM requires both technical systems and legal and policy discourse, with new development of norms, guidelines, best practices, and standards across both areas.

Summary The IAA report provides an excellent high-level summary of research since the previous IAA STM report in 2006, relevant trends globally, space activities and regulations, analogous domains, and the current and projected state of the space environment. It provides two possible paths towards future action on STM, a top-down and a bottom-up methodology, describing how each might proceed.

2.3.11 International Association for the Advancement of Space Safety STM Working Group Summary (IAASS 2019)

This International Association for the Advancement of Space Safety (IAASS) article features various contributions from experts from a variety of perspectives and disciplines. It highlights the differing understanding of SSA and STM that different experts bring based on their own backgrounds. Several of the concepts described are addressed above in greater depth. The article helps emphasize the multifaceted nature of SSA/STM and the multiple conceptual models that exist in the field.

- Skinner (referencing work previously described in Subsection 2.3.8) draws a distinction between the military concept of SSA as being concerned with intent and STM as a civil/commercial concept concerned with safety, with certain overlapping elements between the two. He describes a U.S. civil STM system, which:

    1. Ingests observations, position information, and maneuvers;
    2. Performs data quality assurance;

3. Compiles a database of observations with appropriate controls and metadata (which could be shared bidirectionally with other STM centers);
4. Performs orbit determination and object correlation to produce a catalog;
5. Does conjunction assessments to produce conjunction data messages as appropriate; and
6. Supports collision avoidance with quality (including bias and uncertainties) and situational reports

This architecture is consistent with the understanding of STM as a civil/commercial domain focused on safety but specifically excludes much of the coordination or active traffic management that some other definitions use to distinguish SSA from STM.

- McKnight presents his concept of Space Operations Assurance, composed of space environmental effects and modeling (including space weather effects, debris mitigation, and debris remediation, with the goal of understanding why objects behave in certain ways), SSA to characterize what they are, and STM to manage how space operators interact with each other and the environment. The paper proposes that a public-private partnership consortium could be created to assist with stakeholder interactions and build out the identified framework.

- The NASA Ames STM architecture, derived from prior work for UTM already described in Subsection 2.3.9, is presented as well. This concept ties STM to enabling information infrastructure that achieves system objectives using a set of APIs that support machine-to-machine interaction and significant automation.

- Moriba Jah describes a set of functions that will be developed in response to community demand. Specifically:

  > Protection against the loss, degradation, and/or interruption of space capabilities and services [including] Threat/Hazard Warning and Assessment; Long-term Preservation and Sustainability of Space Environment and Space Activities [including] Free and unhindered access to and use of space; Launch/Orbital Safety of Operations and Re-Entry Risk Assessments; Autonomous and Resilient Space Systems; [and] Monitoring and Assessment of Space Laws, Policies, Guidelines, Recommendations, etc. [bullets in the original are omitted]

- Others authors cite the IAA STM definition or describe STM as a process of phased knowledge transfer and education for decision makers and the public on a set of topics at "the intersection of the technical, and space law and policy; industry, government, and education" to achieve long-term goals through collaboration.

Summary These categories represent a broad set of perspectives held by experts in the field, but support the proposition that this literature review has captured the breadth of proposed concepts. These concepts also largely can be seen as mapping to the options presented in the SAIC study [32]. The first architecture largely corresponds to the middle-of-the-road framework from the SAIC study described in Subsection 2.3.4. The second proposal, a public-private consortium that works towards space operational assurance, is a bit like the first framework from the SAIC study with a more involved government role and a broader scope. The NASA architecture corresponds largely to SAIC's fourth framework, but is presented in greater operational detail and has been partially implemented in demonstration form. Jah's definition offers a good set of objectives that can be compared against those identified in other work such as Oltrogge [117] or the SAIC study [32, 1-3]. While the items do not map perfectly to either set of criteria, they are largely consistent (although the autonomy/resiliency element is more implicit).

2.3.12 CNES STM Considerations (Bonnal et al. 2020)

In February of 2020, the National Centre for Space Studies/Centre National d'Etudes Spatiales (CNES), the French national space agency, released a paper describing initial thinking on the design of a potential STM system for implementation in 2030 drawn from a bottom-up workshop to identify top system-wide objectives and services to be provided by an STM system [31].

Context The paper conceptualizes STM as a “middle-man layer over SSA” [31, 297]. SSA, which is defined in terms of the European concept of space surveillance and tracking (SS&T) plus space weather (but excludes near-Earth objects). Air and maritime traffic are seen as exogenous to the system.

Stakeholders A set of five stakeholders are identified:

1. Regulators (who are concerned with long-term non-real-time approvals to ensure safety and space sustainability);

2. Operational coordinators (who facilitate real-time coordination between spacecraft);
3. Space operators (who own and operate spacecraft);
4. Manufacturers (who build spacecraft); and
5. The state (in its role defining legal frameworks and policy).

System Objectives They list several objectives for an SSA system [31, 297]:

- "To coordinate and optimize the use of orbital space...";
- "To guarantee safety of people and assets on ground and in space...";
- "To provide conditions for a long-term sustainable space...";
- "To define common rules for a shared space, hopefully non-congested..."; and
- "To deal with physical interferences (coordinated actions with close range relative operations, collision avoidance in orbit and at launch) and radio-frequency interferences (jamming)."

This list largely corresponds implicitly or explicitly to the set of STM objectives identified by Oltrogge [117], with the exception of explicitly defining SSA as outside the system boundaries and not directly addressing cyber security (although data security concerns are addressed as an explicit component of the system elsewhere in the text).

Two constraints were identified:

1. "[T]hat the STM system should not interfere with the sovereignty of states to ensure their own security and strategic needs in space[;]" and
2. That the system "should be an enabler for space business" [31, 297].

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Forms and Functions The paper considers forms and functions together, allocating functions to forms and only minimally exploring alternatives.

The operational coordinator is responsible for coordination between operators, interference management (both physical and RF), provision of warnings and alerts, providing emergency assistance, as well as general supervision, maintenance of real time status, and storing traffic histories. Operators are responsible for sharing mission plans, health status, and ephemeris data with the operational coordinator, applying to the regulator for licenses and registration, and providing incident declarations to the regulator. Operators purchase spacecraft from manufacturers. Manufacturers are responsible for applying to the regulator for necessary certification. The regulator provides flight and frequency licenses as well as registration and license control. The regulator also develops rules, standards, best practices, and the application process.

Consequences for System Design The CNES plan makes several interesting architectural arguments. First, they rightly observe that "fulfilling these top level objectives does not imply any obvious governance. STM could be envisaged globally for certain parts and at national level for other parts" and that collaboration is inherently necessary for STM [31, 297].

They argue that the operational coordinator role needs to be a public entity, even if some services are delegated to private companies. They offer two reasons to support this assertion:

1. That STM requires sharing of potentially sensitive data and that public entities are neutral and better able to ensure data security than a private entity; and
2. That private entities might be less capable of acting in the long-term interest of space sustainability if it goes against the short-term interest of operators.

The first justification seems to largely be a consequence of culture. In the French case, it may be that private sector entities see the government as more neutral and better at providing data security than private entities. In another country's context, private sector entities could see the government as being explicitly biased and therefore be more reluctant to trust the government than a third party (for instance, if a state-flagged operator is a competitor or if there are weak rule of law protections). Governments might be seen as more or less likely to suffer cyber incursions than private entities based on the perceived cybersecurity competency of the government and private entities in question.

The second justification rests on two premises, first that a government actor is less subject to regulatory capture than a private NGO or other entity, and second that operators are likely to believe their short-term interests are misaligned from long-term public objectives for space safety and sustainability.

It is plausibly debatable whether either of these assertions is the case. Consideration of both of these overall justifications would be even more complicated in the context of an explicitly international rather than national operational coordinator role. The CNES paper also seems to assume the simpler, but by no means only option of a single centralized coordinator (at least on the national level) versus having the role disaggregated to multiple entities.

While SSA is defined as being outside the considered system, the authors do note a need for SSA data fusion, and suggest that bilateral or multilateral agreements for sharing between regional SSA databases or sharing of information with operators or collision avoidance providers may be the best way forward to approach that goal while protecting sensitives associated with the use of military systems to gather SSA data.

2.3.13 Summary of Frameworks

Across this set of work, it is evident that there have been many thoughtful papers that examine the topic of STM and propose various steps forward ranging from research agendas to architectures and policy frameworks, with various levels of development. These works are summarized in Table B.1. While this literature review is not exhaustive, the fact that many concepts are repeated across many sources in similar form and most permutations of the factors below have been considered support the notion that this review has covered the major STM concepts considered in the field with a focus on on-orbit avoidance of physical interference.

Some key findings of this review are:

- Potential architectures range in system objectives, chiefly which phases of flight and problem domains are considered and whether there is an explicit economic or national security objective.

- Some architectures are conceived at the national level, while others are discussed in an international context. Most of the authors recognize an international system as an end goal, but there is divergence on whether a bottom-up approach (working from best practices in industry and at a national level towards eventual internationalization) or a top-down approach (beginning from international discussions among states) is preferable. Some concepts presented effectively split the difference, proposing a middle-of-the-road approach.

- In both national and international systems, the role of private industry stakeholders varies, from total system definition and ownership, to a public-private partnership model, or as users of an entirely government-defined and government-operated voluntary or mandatory system.

- There is uneven treatment of whether systems consider technical/operational elements of an STM system, regulatory aspects, or both.
  - For systems with an operational component, it varies in scope from SSA sharing and dissemination, to coordination, or potentially system-wide control of operator spacecraft.
  - Systems diverge on whether best practice, guidelines, and standards development (either on a voluntary or mandatory basis) is considered within the boundaries of the proposed system, and whether there are mechanisms for their enforcement (and the extent of those mechanism).
- System objectives and architectures are frequently presented, and in some cases stakeholders are consulted to help guide these objectives, but the results of this stakeholder analysis are generally not presented explicitly. The considered stakeholder classes are similar at a top level, but differ in how top-level stakeholder groups (e.g. operators) are broken into subclasses. Divergences in views between multiple stakeholders within a single stakeholder category are likewise not addressed in any depth. Many analyses do not contain explicit stakeholder consultations and rely on tacit knowledge of stakeholder needs and desired outcomes or proceed from the author's or authors' opinions on the needs for SSA and/or STM systems rather than stakeholder consultation.
- Data sharing and information security concerns are present and deeply important. These concerns (and how authors and architects understand them) influence architectures, especially how functions are assigned to forms.

2.4 Gap Analysis and Motivation for Subsequent Chapters

Across these architectures, two key gaps are present:

First, this set of work is heavily dominated by American and European authors and perspectives, with the notable exceptions of the ISU and IAA documents. It is possible that American and European views on STM differ from other national stakeholders, particularly those with less-established space sectors. While the ISU and IAA documents do feature a broad set of authors, they are consensus products and do not identify which authors are responsible for which components. In the case of the ISU report, it was produced by early-career individuals, who may or may not have been representative of either governmental or nationally common views, and was written more than a decade ago. The IAA report is helpful, but describes multiple possible futures without expressing preferences.

Understanding how perspectives vary across nations would be particularly instructive, especially given the prevalence in the work of many of the American authors for preferences towards bottom-up architectures that are subsequently internationalized. Without work to understand the views of representatives of other nations early on, there is a risk that systems will be developed, particularly using a bottom-up approach, in ways that meet the needs of established space actors at the cost of emerging actors. Should such a trend occur, it risks stifling the development of programs by emerging actors and delaying/limiting the eventual internationalization identified as an end goal for bottom-up approaches. This delay in internationalization increases the likelihood of fragmentation into several separate systems and would delay the involvement of emerging actors, to the detriment of safety for established actors and nations as well.

Second, many documents make note of potential national security and commercial operator concerns about data sensitivity. Some documents, in particular Oltrogge [118], address non-contributing operators, but they do little to examine what information commercial operators are willing to share or not share with other users, why, and what kinds of protection methods could address these concerns. This is a concern highlighted in work by the NASA Ames team [109], but is not treated in significant detail in any of the architectures.[10] Nevertheless, it has significant implications for the design of architectures. For instance, it is one reason CNES [31] proposes that the STM coordination role needs to be carried out by a public body instead of a private entity as proposed in some of the architecture concepts. This second gap ties into the last trend identified in Subsection 2.3.13, a tendency to both engage in little explicit articulation of stakeholder needs and desired outcomes, and to deemphasize intergroup and intragroup cleavages in opinions among members of stakeholder groups.

These gaps motivate the work in the subsequent two chapters.

Chapter 3 seeks to characterize the views of emerging space nations on the future design of potential STM systems through a set of interviews with representatives from emerging space nation governments and through study of the record of relevant COPUOS discussions on STM.

Chapter 4 assesses commercial satellite operator views on data-sharing sensitivities for potential SSA/STM systems through interviews with operators and SSA/STM experts, as well as a review of operator U.S. regulatory submissions.

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[10] While Oltrogge [118] does describe the SDA-like model of legally and technically protected sharing as meeting stakeholder concerns, he does not discuss the nature of operator concerns at a granular level, or potential alternatives architectures to address them.

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Chapter 3

Emerging Space Nation Stakeholder Perspectives on STM[1]

3.1 Introduction

Interest in space sustainability is growing, and SSA capabilities are proliferating globally, both among nation-states and commercial actors. Within the SSA community, there is increasing interest in data validation and fusion techniques, and ongoing professional and diplomatic discourse about the development of shared SSA capabilities. More speculatively, several nations including the United States have begun work to develop national systems for STM, seeking to provide capabilities for maneuver coordination, and to better understand the implicit allocation of orbits inherent in the authorization of megaconstellations and growing numbers of missions. Academic work on STM continues to flesh out potential legal/regulatory and technical architectures, as described in Chapter 2.

This chapter makes three arguments:

1. Representatives of emerging space nations have opinions and preferences on STM system design, even if they do not yet face space traffic coordination/management issues and do not anticipate facing them in the near future;
2. Discussions on STM should substantively involve emerging space nations from the beginning; any eventual system will be more responsive to the needs of a broader set

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[1] This chapter adapts and expands content from [91], a paper originally presented at the 70th International Astronautical Congress, 21-25 October 2019, Washington, D.C., United States. www.iafastro.org.

of stakeholders if discussions include these stakeholders and their preferences from the inception of the process; and

3. Direct interviews with relevant emerging space nation stakeholders are a valuable tool for characterizing emerging space nation preferences on STM system design and associated reasoning.

These arguments are derived from a series of interviews conducted with individuals associated with national governmental space activities in countries with emerging space programs (a list of interviewees can be seen in Table C.1) as well as a review of discourse on STM at COPUOS.

The remainder of Section 3.1 describes the motivation and research questions tackled by this project and reviews the relevant literature. Section 3.2 describes the methods used by this project, the reasoning behind the research design, how the questions were developed and used, and some considerations that may impact the validity of the chosen method and associated caveats. Section 3.3 presents results from the series of interviews. Section 3.4 ties these results to the research questions identified and demonstrates how such findings might influence the design of an STM system. Section 3.5 offers concluding thoughts and argues for further work to characterize emerging space nation views on the design of an internationalized STM system.

3.1.1 Motivation and Research Questions

While an international agreement on STM is unlikely to coalesce in the near future, discussions over the coming years and national initiatives to build associated technical capabilities will define the scope of such discourse and the decision space from which international negotiators will be tasked with extracting a universally acceptable outcome.

Because of this fact, efforts to shape an internationalized STM system are shaped not only by international law, norms, and negotiation, but also by the technical assumptions and system architectures of associated national systems.

Understanding the perspectives of nations with emerging space programs can help inform initial work towards the design of national STM systems and nudge architectures in directions that offer minimal additional cost during system definition, but that will improve international acceptability of such systems down the road when attempts are made to integrate and internationalize them.

On the other hand, a failure to do so risks repeating the mistakes of established space nations in discussions on the allocation of geostationary orbits, and the associated disputes and complications that have arisen [74, 169-173] [58][84, pars. 99-111]. There, the ITU initially processed space spectrum allocation requests on a first come, first served basis. In the 1960s, developing nations increasingly began to object to this process as inherently inequitable and called for reservation of geostationary capacity for their future use [24, 14-15]. This led to decades of discussions on how to best fulfill the ITU's competing mandates to ensure rational, equitable, efficient, and economic spectrum use and accompanying changes to geostationary allocation processes. The current system is a hybrid formulation that contains elements of both first come, first served and planned reservations [24, 14-24,]. Discussions continue to this day [138, pars. 251-257], and while a general compromise has formed, it is easy to see how earlier inclusive dialogue involving established and emerging actors, prior to the start of system allocations, might have converged more quickly to a mutually acceptable system and better allocation practices.

As an initial contribution towards such work for STM, this chapter addresses three main research questions:

1. What are the perspectives of representatives of emerging space nations on the design of a potential internationalized STM system, and what shapes these opinions? More specifically:
    (a) What are preferred forms of engagement to determine the design of future international STM systems?
    (b) What forms of STM/SSA capability-building are most needed?
    (c) What capabilities should be provided by an international STM system?
    (d) What kinds of STM requirements would constitute 'undue' cost?
2. How do these opinions differ across interviewees and countries, and what shapes them?
3. What are the implications of these preferences for the design of a potential STM system?

The chapter addresses these research questions using a sample of interviews conducted with representatives of fifteen emerging space nations. Rather than fully answer them, it seeks to describe how the responses to these questions gleaned from the interviews led to the three arguments made in the introduction, and describes initial findings.

3.1.2 Literature Review

Potential architectures for delivery of STM services are discussed in depth in Chapter 2. This section briefly reviews relevant literature in two additional areas:

1. The definition of an "emerging space nation"; and
2. The viewpoints of nations with emerging space programs on space sustainability and STM.

Defining "Emerging Space Nation"

Defining what constitutes an "emerging space nation"[2] is a critical antecedent for work that seeks to specifically solicit and characterize the views of such nations. Wood and Weigel propose several relevant frameworks, including the mission, management, and space technology ladders (suitable for in-depth study of a particular country or region), and the space participation metric (which allows for categorization of large numbers of nations) [166, 167]. Wood identifies sixteen developing countries in Asia, Africa, and Latin America for study based on "a long term commitment to national-level space activity" [164, 50]. Dennerley takes a prescriptive approach and chooses to specifically list a set of "established space nations" and refers to "emerging space nations" as those that are not established space nations but have "have demonstrated an intention to develop their own space capabilities and industries" [45, 28].

Discussions of STM at COPUOS

Discussions before COPUOS, and its Legal Subcommittee (LSC) and Scientific and Technical Subcommittee (STSC), provide a potential source of information on emerging space nation views on STM.[3] Most of these discussions have occurred at the LSC.

In 2015, STM was added as an agenda item for the 55th LSC the following year and a "General exchange of views on the legal aspects of space traffic management" has taken place in 2016 and every year since [80, 81, 82, 83, 84]. A rich discussion has occurred under this agenda item and been summarized in the committee's report each year. STM topics addressed frequently include the importance of STM, preferences for multilateral

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[2] Both "emerging space nation" and "emerging spacefaring nation" appear in the literature. This chapter interchangeably uses the more common and shorter "emerging space nation" and "nation with an emerging space program".

[3] While a 2020 STSC meeting was held, the 2020 meeting of the LSC has been canceled and the COPUOS meeting postponed, both due to COVID-19 concerns.

approaches, relevant measures taken by nations, the challenge of defining STM, the scope of a potential legal and/or operational regime (including whether there should be a UN-based system for sharing space data), and necessary steps to enable an eventual internationalized system. There have been relatively few emerging space nations making comments on this agenda item. Examples of such comments include Morocco (2015, 2017), Mexico (2017, 2019), Poland (2017), Indonesia (2018), Pakistan (2018), Brazil (2019), and Egypt (2019) [9].[4]

There has been limited mention of STM within the STSC. In 2016, it simply acknowledged discussions by the LSC [135, 48]). In 2017, there was a comment about multilateralism and a working paper from the Russian Federation [136, pars. 34, 67(i)]. In 2019, the United States delivered a presentation on Space Policy Directive 3 and its efforts towards STM. Various others comments expressed concerns about unilateral national action on STM, the connection between STM and space debris, and calls for consideration of STM as part of future work on the LTS of outer space activities [137, pars. 31, 40(d), 136, 138, 254)]. In 2020, the body acknowledged a side-event on STM [138, par. 33(d)].

A handful of comments on STM are present in COPUOS's report each year from 2016 to 2019, generally in the context of comments on the report of the LSC [36, 37, 38, 39, 40].

In 2019, COPUOS adopted the LTS Guidelines, which do not directly address STM but provide many related guidelines and inform the context of work on STM [40, par. 163]. It also established a working group under the STSC to further consider the LTS of outer space activities [40, par. 165] and endorsed further consideration of STM by the LSC [40, par. 240].

There are a variety of views presented at the most recent LSC meeting that are relevant for this work, some of which are broader than STM specifically.[5] These include:

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[4] Committee and Subcommittee reports do not attribute most remarks to specific countries, but recordings of sessions are made available. Unfortunately, transcripts are not available for most meetings and the tagging of recordings is both limited and frequently inaccurate. Accordingly, this list is not intended to be comprehensive.

[5] While this list draws solely from the 2019 LSC meeting, similar concerns are present in prior years' discussions. For instance, in 2018, these included concerns from some participants that international legal frameworks should "refrain from further developing the international legal framework in a manner that set overly high standards or thresholds that could hinder the enhancement of capacity-building for developing countries" [83, par. 41] and that the cost of compliance with space debris mitigation guidelines is preventing access for emerging space nations [83, par. 177]. Likewise, there was a call for common but differentiated responsibility in debris mitigation and remediation [83, pars. 175, 176, 178] as well as "data-sharing, information-sharing, capacity-building and technical assistance" to help develop conjunction-assessment [83, par. 206] and debris mitigation [83, par. 176] capabilities in nations with lower levels of space development. There were also concerns raised about allocation of geostationary orbit slots in ways that exclude new entrants [83, pars. 102-110].

- A concern that space sustainability, backed by a legal framework, is necessary to ensure that the benefits of space are available for future generations [84, par. 31];
- Support for building national space capacity in developing nations through space technology transfer and other mechanisms in a manner "based on the principle of fair and mutual benefit as well as on full respect for territorial integrity and the sovereignty of States" [84, par. 33];
- A need for capacity building in space law and space policy [84, par. 34, 123-140];
- The importance of avoiding the development of "norms, guidelines, standards or other measures" that would restrict the ability of nations with emerging space capabilities to access space [84, par. 35];
- Concerns about the allocation of geostationary orbit [84, par. 99-111];
- "[C]ommon but differentiated responsibilities" for space debris remediation based on involvement in creating space debris [84, par. 176-178];
- Knowledge transfer on STM [84, par. 214];
- A need to encourage "the broad participation of developing countries and emerging spacefaring nations in substantive discussions on space traffic management" [84, 213]; and
- Concerns about first-come, first-serve extraction and utilization of space resources as being inconsistent with the "letter and spirit" of the Outer Space Treaty [84, 254].

Concepts including technology transfer and capacity-building, avoiding exclusionary legal and technical measures, fairness of allocation of finite space resources, and common but differentiated responsibilities all provide useful concepts to explore deeper in individual interviews with representatives of emerging space nations.

Emerging Space Nations and STM

Lopez conducted interviews with experts and a literature review to describe approaches to space sustainability in Brazil, Colombia, and Mexico [98]. While the work addressed space sustainability in terms broader than just SSA/STM, the conclusions Lopez reaches are relevant for STM: the three countries all view space sustainability as a priority and favor inclusive processes to develop binding measures to address space sustainability as opposed to soft law.

Dennerley identified the power disparity that exists in international standard-setting and described mechanisms by which that power disparity favors established space nations, potentially at the cost of emerging space nations [45]. However, the solutions he proposed are less persuasive and put a burden on emerging space nations to increase their engagement at the international level rather than asking how international systems could be designed to be more inclusive [45].

The 2018 STPI study included interviews with some interviewees from emerging space nations who indicated a perception of "STM as a mechanism for restricting access to space and space activities" [77, 62]. It also briefly described the state of regional space cooperation efforts in Europe, Asia, Africa, and Latin America [77, 72-74]. Nonetheless, it includes only a limited subset of emerging space nations and focuses on SSA rather than STM.

The global discussion regarding implementation of the LTS Guidelines, particularly in the context of emerging space nations, raises many points that are potentially generalizable to the topic of STM. The Secure World Foundation (SWF) recently held a webinar on Capacity-Building for Space Sustainability [141]. Panelists were asked to identify the three most pressing challenges to building capacity to implement the LTS Guidelines and propose three steps to address those challenges. One of the panelists during the government session offered particularly relevant remarks. That panelist identified three key gaps faced by emerging space nations: limited awareness of the LTS Guidelines, their purpose, and space sustainability (and transfer of awareness from COPUOS delegations to the rest of national governments); uncertain and potentially conflicting authorities within national governments for implementing the LTS Guidelines in domestic law; and lack of qualified personnel and capacity to actually implement the guidelines. The representative proposed a need for education and international cooperation to fill this need, including sharing of best practices and approaches for implementation that avoid assuming a specific level of national capability. That representative also called for establishment of a collaborative forum or creation of other resources to help introduce newcomers to the LTS Guidelines and ways to translate from the guidelines into domestic regulations.

Prior to conducting individual interviews with representatives of emerging space nations, I conducted an informal review of national laws and policies on space sustainability in advance of each interview, but found that these documents did not always exist, were not always available (especially in English), and were generally too high-level to directly inform answers to the previously described research questions. Further, laws and policies by their nature describe an outcome or objective, but do less to explain the motivation or reasoning behind that outcome. I did not attempt to reconstruct legislative history regarding national space sustainability language, as the exercise was judged to be very challenging and unlikely to yield significant insight.

Summary of the State of the Literature with Respect to the Research Questions

The literature provides a useful starting point for the objectives of this paper but indicates that new data gathering from primary sources is needed, both due to a limited amount of primary source material that is available, and to better permit comparisons across countries.

With respect to a working definition of "emerging space nations," the literature demonstrates two approaches: one heavily metrics-driven and one involving implicit classification. These approaches can be thought of as forming two ends of a spectrum, from which a prospective author can draw a definition based on his or her objectives. In this case, they inform a decision to adopt a pragmatic approach that is neither as metric-based as Wood and Weigel, or as prescriptive as Dennerley. Specifically, this approach seeks to identify a set of countries which possess some demonstrated level of national interest and involvement with space (evidenced by membership in COPUOS or a national space agency or program), but that are not so engaged in space as to be considered established space actors. To achieve this distinction and a sample appropriate to interrogate the questions described in the introduction, the sample for this work excludes the 13 countries with national space entities that are members of the IADC. These countries possess more advanced space operations capabilities, and can be seen as representing a self-selection by established space actors of which countries they consider established space actors.

Based on this review, there is limited existing work that describes the opinions of emerging space nations on potential STM system design, and virtually no publicly available information regarding emerging space nation views and reasoning on internationalized STM at sufficient depth and specificity to support the objectives of this study. This conclusion motivates and justifies the need for direct data collection, and a focus on analysing these data rather than existing literature.

3.2 Methods

To design an appropriate data-collection methodology, it is necessary to determine the purpose of data collection. A spectrum of research methods exist with one major trade being between breadth and depth of exploration. Determining the purpose of research, and thus the right point on this spectrum, informs the development of an appropriate research methodology. Runeson-Höst distinguishes between four kinds of interviews, based on earlier classification by Robson: exploratory, descriptive, explanatory, and improving [130, 135]. For this study, the goal is work at the border of exploration and description. More specifically, this work seeks to cover a broad set of emerging space nations to identify where suggestive trends and commonalities or differences exist.[6]

To achieve these objectives, a survey-based data collection methodology was chosen. Where possible, the survey was administered through a 30 to 60 minute semi-structured interview format. Remote interviews were conducted using a variety of platforms including WebEx, Skype, WhatsApp, Zoom, and telephone. Video was used when connection quality and the interviewee permitted. When the interviewee consented, interviews were recorded for subsequent data analysis and review. When the interviewee did not consent, I took notes to document the conversation and answers. When the interviewee was unable to participate in a spoken interview, or requested to provide written answers due to limited English fluency, survey answers were clarified in subsequent written correspondence as needed to improve validity.

According to Gillham [56, 62], interviews are appropriate for data collection when:

- The number of people to be interviewed is relatively small;
- Interviewees are available;
- The interviewees are crucial and you wish to avoid losing respondents;
- Your questions are open and require follow-ups and clarification to elicit answers; and
- The material involved is potentially sensitive.

Here these factors all apply and a moderately deep interview of a small set of individuals is indicated. National space experts are generally available either through a national embassy or space agency (for both emerging and established space nations). There are

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[6] This chapter will not seek (or claim) to fully characterize the views of representatives in a particular nation, or to include a sufficient number of representatives to allow the results gathered to achieve formal measures of statistical significance. A case study methodology would allow deeper study of a limited number of instances, while a written survey-based approach would be more appropriate for a study to establish trends with mathematical rigor. The former is too narrow given the early stage of STM discussions globally and limited consideration within most emerging space nations (and nations more generally). The later is premature, given the lack of exploratory work to date to understand what should be asked in such a survey. It also raises numerous validity concerns, discussed further in Subsection 3.2.4.

only one or a few key individuals per nation who are best equipped to answer these questions. The questions require repeated follow-ups and prompts to both ensure understanding across various individual professional, linguistic, and cultural contexts and to understand the reasoning behind preferences or views expressed. For some nations, these viewpoints are sensitive, as they represent predecisional perspectives of relevant stakeholders, but not a whole-of-government consensus view or require a frank discussion of potentially unflattering considerations (e.g. national ability or willingness to pay for a potential STM system).

3.2.1 Interview Protocol Development

Questions developed for these interviews are informed by various sources. These include consultation with space sustainability experts, the SSA scenarios developed for the 2017 AMOS Conference dialogue [140, 133][7], and initial pilot testing of the interview protocol with several young professionals from emerging space nations at events like the Space Foundation's annual Space Symposium and the SWF's Summit for Space Sustainability.

Questions were divided into three categories:

1. About the interviewee;
2. About the associated county; and
3. About the interviewee's thoughts on an international STM system.

The STPI report's case study protocol and list of interviewees (listed in Appendix C and Appendix E of their report) informed both protocol development and the shortlist of potential interviewees [77]. Recognizing that individual interviewees would significantly vary in their background, level of familiarity with SSA/STM, and understanding of the terms space sustainability, SSA, and STM, the interview protocol included several elements designed to improve validity. First, definitions were provided for space sustainability, SSA, and STM as used in the interviews. Second, a future scenario was identified to provide a standardized context in which to ask interviewees about their preferences for a potential STM system. The future draws on the trends identified in the IAA's report [15] including the presence of megaconstellations, increases in reusable and suborbital launch, private LEO space stations, and a drop in launch prices driven by higher launch cadence and reusability. Third, three scenarios were presented for potential future STM systems. These scenarios are described in Subsection 3.2.1. Fourth, an infographic (Figure D-1) was developed and

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[7] AMOS is a major conference for the SSA/STM community. The dialogue, an annual event co-hosted by SWF, is discussed further in the next heading.

provided to interviewees listing potential technical elements that could be performed by an international SSA/STM system, along with brief descriptions of potential advantages and disadvantages of including that element in the architecture. These elements focus on physical interference and collision avoidance for the reasons identified in the IAA report [15, 22], chiefly the maturity of existing RF traffic coordination and management through the ITU.

Prior to administration of the survey, several drafts of the questions were reviewed with space sustainability experts for feedback with an eye towards both gathering useful and novel information and asking questions in a clear and accurate manner. The protocol was then delivered to several young professionals from emerging space nations for practice and to solicit their feedback on the protocol.

Several questions asking about specific preferences and desired best practices for STM system design were added to the protocol for subsequent interviews part-way through the data collection based on results from the first set of interviews in a desire to enable more direct cross-comparison between answers to open-ended questions. These were tracked across three revisions. Revision 1 was administered to one individual. Revision 1.1 was administered eight times, and Revision 1.2 was administered six times.[8] The added questions are noted in Appendix D.

Developing Reference Concepts for an Internationalized STM System

The interest of this chapter is on internationalized STM systems, as countries with emerging space programs are much more likely to partner and participate in an internationalized STM system, or partner with a national STM system from another nation, than to create one themselves. To support the work identified in Section 3.2, it was necessary to generate a set of reference STM designs for which individuals could offer their opinions and feedback.

The reference concepts developed and used during interviews for this work are informed by the following three principles:

1. There should be a manageable number of reference concepts presented.

   This was important so that interviewees could keep track of and understand the distinctions between the presented options.

2. Concepts should be relatively simple.

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[8] Multiple interviewees from a single country interviewed together are counted only once for the purpose of these totals

This was intended to facilitate discussion. A focus on explaining a long list of concepts at the start of an interview risked decreasing interviewee engagement, would have changed the dynamic between the interviewer and interviewees, and spent scarce interview time (or asked busy interviewees to invest extensive time prior to the interview). This decision meant concepts were not provided in extensive detail and needed to be simplified relative to the literature.

3. Concepts should, subject to the above constraints, meaningfully cover the space of STM architecture options identified in Chapter 2.

   This stemmed from wanting to meaningfully explore preferences among interviewees.

The defined reference concepts draw heavily from the IAA's report [15]. Aspects of this report that inform the reference concepts include the trends identified, the conceptual distinction between bottom-up and top-down approaches, the descriptions of relevant legal regimes, and the dichotomy between a technical STM system and a regulatory STM regime.

In 2017, SWF hosted a not-for-attribution discussion about future potential SSA scenarios at AMOS. The discussion presented participants with four potential future SSA scenarios and asked two questions:

1. Which scenario was most likely?
2. What scenario would be most desirable?

Participants believed a continuation of the status quo of U.S. provision of global SSA was the most likely, but that a global SSA system overseen by an intergovernmental organization would be most desirable [133]. STPI collaborated with SWF for the AMOS dialogue and authored a more extensive report on SSA and STM that forecast no likely international STM agreement over the next decade, but increasing levels of SSA capacity in non-U.S. nations [77]. The reference concepts for this work also draw from this option-set, recognizing a need to adapt the scenarios to consider STM rather than just SSA.

Ultimately, three scenarios were selected for inclusion as a prompt to interviewees. This set seeks to capture consideration of a breadth of possible futures in a level of detail appropriate for the interview format. The language used verbatim can be seen along with the rest of the questions in Appendix D

The first scenario is the ICAO for Space proposal developed by Jakhu et al. in [66]. This corresponds to a top-down international-first approach to STM. The ICAO for Space model strikes a careful balance with respect to encouraging internationally harmonized standards while respecting national sovereignty. If asked by an applicant whether the organization had to be ICAO, or if it could be a new international organization, applicants were provided with both options and allowed to react accordingly.

The second scenario was an entirely private STM network operated by an international, NGO on a voluntary basis, of the sort that might exist if the SDA chose to take on an STM mission. This model was presented to offer another extreme, similar to the first scenario posed in the SAIC study [32]. This model is bottom-up, but led by industry and academia rather than by states.

The third model presented anticipated one or more national STM systems (American or otherwise) that were open to participation by others, and would potentially be connected and made interoperable/integrated over time. This is in effect a state-led, bottom-up model similar to the fourth option in the SAIC Study [32] or if Skinner's proposal [143] was expanded to include a coordination mission in addition to SSA. In some cases, the country which owned the system was material. If an interviewee asked about this factor, that person was asked to explain how the country owning the STM system would impact the interviewee's consideration.

Less focus was placed on the specific functions to be performed by the system or allocation of functions to forms, as this was explored in a scenario-agnostic form elsewhere in the questions.

3.2.2 Interview Administration

The protocol was administered in person where possible, but primarily via teleconference or video communication. In some cases, representatives provided written feedback, due to a need to clear responses within their organization, limited English proficiency, or scheduling limitations.

Individuals were allowed to specify whether their name, title, or affiliation would be included in the appendix of interviewed individuals (Table C.1) and whether quotes from their answers could be included in the body of this publication or attributed. Because many of these questions are speculative, respondents were encouraged to answer in a personal capacity when unable to answer a question in an official/professional capacity.

While the interviewer attempted to follow the protocol, in some interviews some questions listed in the protocol were omitted either due to limited time or because the interviewee's prior responses either answered or rendered a question irrelevant.

3.2.3 Countries and Interviewee Selection Methodology

A list of 66 countries was developed based on the definition of emerging space nation described in Subsection 3.1.2. This was narrowed to a shortlist of approximately 25 nations, with an eye towards diversity across region, level of space experience, and socioeconomic development as measured by human development index. Additional consideration was given to nations where I or my advisor was aware of a relevant representative with whom to request an interview.

When selecting potential interviewees, I targeted individuals with a broad awareness of their country's space activities, direct involvement with those activities (in either a technical, managerial, or policy role), involvement and subject-matter expertise related to the country's space sustainability, SSA, STM, and/or satellite operation activities (if the country had such activities). In many cases, I or my advisor were aware of relevant interviewees based on pre-existing connections or general awareness of a country's space activities. In some cases, interviewees were identified through networking at events like the Space Foundation's Space Symposium, Satellite 2019, the U.S. DoS and U.S. DoC's Space Enterprise Summit, and SWF's Summit for Space Sustainability. In many cases, I sent interview requests based on recommendations from D.C. or Vienna embassy staff, direct outreach to national space programs, or recommendations from SSA/STM space professionals.

3.2.4 Factors Potentially Affecting Validity

There are several considerations that could adversely affect the validity of the data collected during this study, and these considerations should be borne in mind in interpreting or generalizing these results.

First, the views presented should not be considered to represent the opinions of the nations with which interviewed representatives are affiliated. A limited number of individuals were interviewed per nation, generally one or two. Interviews with more than one representative from the same country were frequently administered simultaneously, allowing the views presented by one individual to shape those expressed by the other. Revisions to the protocol and interview time constraints mean that some questions were only answered by a portion of the interviewee pool. Individuals were asked to offer personal perceptions and predictions when a national consensus position did not exist. This chapter does not report per-country results both to allow the interviewed representatives to speak freely and honestly and because interviewee responses do not necessarily align with country-level views (which in many cases do not exist). For this same reason, anonymity has been granted to some interviewed individuals, and the name of some of the countries are suppressed. These trade-offs are acceptable given the practical constraints on interviewees, but it should be noted that these decisions significantly limit the ability to use triangulation across interviewees, as recommended in the literature [43, 126-127], to ensure per-country validity.

Second, this project faces significant threats to internal validity. In this case, a major concern is whether the terms and conceptual categories believed by the researcher and interviewee to be shared are actually shared. LeCompte and Goetz describe internal validity in the context of ethnographic research, but in a way that is highly applicable to this project [79]. Interviewed individuals are not necessarily experts in space sustainability, SSA, or STM, may have only limited English fluency, and the term "sustainability" is overloaded with several different meanings. During interviews, clarification questions and follow-up probes were used to help assess and maximize internal validity. Additionally, a set of definitions, scenario context, and infographic were provided, as described in Subsection 3.2.1.

As described at the start of Section 3.2, interviews were conducted through both interviews and written surveys. The threat to internal validity is higher in the written survey responses. These responses were generally shorter than an equivalent interview, and there was less of an ability to ensure shared understanding and probe reasoning, even with follow-up correspondence. While interviewees received the definitions and questions contained in Appendix D in advance, respondents did not necessarily review the provided definitions and context before answering questions.

I coded all interview responses for reporting and analysis. This approach minimizes access to the potentially sensitive raw interview data, but adds another source of potential error and subjectivity. Verification of my coding by another party was not feasible, given the data sensitivity issues and extensive time that such verification would have taken.

3.3 Results

This section describes the results of interviews on a per-question basis. Seventeen individuals participated in these interviews. Counts are provided for many answers as a rough indicator of level of frequency, but will often not total to seventeen due to the semi-structured nature of the interviews. For any given question, some respondents may have provided multiple answers to an item or ranked several answers and others may not have addressed the topic, addressed it in a manner different than other respondents, or may not have been asked a specific question (due to time limitations or format revisions described above). In interviews with multiple interviewees, sometimes one interviewee addressed a point and the view of the other interviewee was not clear. Accordingly, reporting percentages or fractions would be methodologically challenging and potentially misleading.

3.3.1 Per-Question Results

Please describe how you would like to engage in international discussions on STM. What capabilities and strengths does your country bring to global discussions on STM?

Every representative indicated an interest in engaging in international discussions on STM in some form. Two representatives discussed participation in regional organizations. The most common contribution mentioned by countries was involvement in SSA collection and sharing. Four representatives indicated interest in offering land in their country as a site for potential SSA sensors. Two indicated an interest in contributing SSA gathered by the country. One mentioned the nation's ability to act as an honest broker between various world powers. One indicated interest in contributing data processing and related services.

Would you like to see the development of a global SSA/STM system? Do you have preferences among the 3 scenarios (mentioned on the previous page) or others?

Interviewees indicated a strong preference (mentioned by ten interviewees) for an international system over a country-led or private system. Reasons included that such a system would be more open and collaborative. Some interviewees were more specific. Four preferred the role to be taken by an expanded OOSA, with one interviewee saying that expanding OOSA seemed easier than giving the mission to ICAO. ICAO was preferred by two interviewees, arguing it was already established and would better fuse air and space operations, and that OOSA was too scientific. One preferred an ICAO/OOSA merger for better air/space integration, and one proposed a new operational body. Two interviewees specifically mentioned that the body should not be the ITU, with one complaining about the ITU's allocation of geostationary orbits.

Four of the representatives, including several with more specific background in SSA/STM, indicated scepticism of an internationalized system in the near future. Three preferred a country-based approach, and one preferred a hybrid of country-based and NGO efforts. One of those who preferred a country-based approach indicated that a hybrid between country and private systems would be that representative's second choice, and that a UN system was ideal but unrealistic.

Would you want the system development process to use consensus, a voting-based decision-making processes, or a hybrid? Why?[9]

Three representatives expressed a preference for consensus processes. As one representative explained, while consensus processes are slow and take significant time and effort, they ensure that all parties have a stake in the success of the system and provide a means to ensure that a system with the potential for considerable harm will be beneficial rather than deleterious. One of the representatives who preferred a consensus system noted that eventually voting may be possible, but that trust would need time to develop. Four representatives preferred a hybrid approach. Two proposed that political-level dialogue should be on a consensus basis, but that detailed technical work may be better suited for voting. Another representative noted a preference for consensus when possible, but that voting might be needed for time-sensitive decisions which did not allow for consensus.

Would you prefer binding rules, non-binding rules, or a hybrid? Why?[10]

Hybrid approaches were preferred by five of six respondents, with different reasoning from each individual. One preferred differentiation based on topic. Another representative argued for a hybrid approach, fearing that higher technical standards would result in exclusion of emerging space programs. A third respondent thought that a hybrid is preferable because totally optional standards will simply not be implemented by a certain set of actors. Another expressed hope that voluntary standards could evolve over time to becoming bindings. The last noted that consensus-based norms-building can help move towards a world where binding standards are possible. The representative who preferred binding rules indicated concern about free riders prioritizing their own interests above others. Overall, the responses highlighted that an STM system involves significant scope, and that a layered approach is probably necessary depending on the topics, objectives, methods, and diplomatic feasibility.

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[9] This question was added in protocol version 1.2 and only asked during seven interviews and received responsive answers in five. It was addressed as part of other discussions in two more interviews.

[10] This question was added in protocol version 1.2 and only asked during seven interviews. One respondent declined to answer and one answered as part of other discussions.

Role of Industry Participants[11]

Interviewees generally supported a greater role for industry, noting that industry has significant investment, expertise, and can play a role in transitioning from norms/standards to law or operational practices. They acknowledged that the state-focused nature of the UN makes greater industry involvement potentially challenging. Specifics varied heavily. One representative proposed an expanded university role, noting that his or her country had minimal direct industry involvement in space. Another proposed direct industry involvement for only more technical/operational aspects. One opposed direct industry participation but supported the participation of industry trade organizations or similar conglomerative bodies. Yet another supported inclusion of satellite operators, but not industry generally.

Two representatives supported participation through states similar to the status quo. One representative identified a tendency in their culture for government to lead and industry to follow, which that representative contrasted with the United States.

What benefits would your nation seek to achieve from a global SSA/STM System?[12]

The two most commonly cited benefits related to access to space (either protecting/ensuring safe access, or expediting it) (six interviewees) and equity of access or better management of the space environment (four interviewees). One of the equity-based responses focused on coordinating which satellite should move during a satellite-on-satellite high-risk conjunction. Other purposes include preventing conflict in space (two interviewees, with one worried about legal claims as a form of conflict), promoting sustainability (two interviewees), promoting international collaboration (one interviewee), access to SSA information (two interviewees interviewees), economic development (one interviewee), and public outreach (one interviewee).

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[11] This question was added in protocol version 1.2 and was addressed by nine respondents (with one explicitly declining to comment, and one who provided an answer in absence of a specific prompt during earlier versions of the protocol).

[12] Several respondents provided responsive details earlier in the interview as part of their response to how their nations would like engage in international discussions on STM. These earlier responses have been included here.

What functions would you like that system to perform? Alternatively, what objectives should it fulfill?

Two representatives were uncertain and declined to answer this question and one provided a non-responsive answer. A plurality (five interviewees) indicated support for all of the functions listed in the infographic. These representatives tended to have less exposure to SSA/STM as part of their daily work. Two of these representatives also proposed inclusion of ADR within the scope of the body. One called for inclusion of space resource management.

One representative preferred only communication facilitation and conjunctions screening. One specifically excluded SSA collection and registration, but supported the inclusion of all other listed functions.

Three called for SSA sharing specifically, with one noting that a shared SSA catalog would be required for conjunction screening or conjunction assessment.

What capabilities do you believe are needed for SSA and STM at the national or regional vs. international level?

This question was only asked of representatives who had opinions about what capacities should be included in an SSA/STM system and respondents answered the question in very different ways.

Two indicated that licensing/registration should remain at the national level. One of these also thought policies on data sharing should be defined nationally. Another stressed a need for nations to retain control of assets including decisions regarding what to move, when, and how. Two indicated that conjunction screening, conjunction assessment, collision avoidance maneuver generation should be done at the national level, with other functions done regionally or internationally (although one of these respondents was skeptical that SSA data fusion could be done at the international level anytime soon). One indicated that national capabilities will depend on the resources, objectives, and needs of each country.

What venues and methods do you think representatives of your country would prefer to provide input into the potential design of a future international SSA/STM system?

Ten respondents considered COPUOS and OOSA to be the best place for these discussions to take place (without necessarily commenting on where an eventual operational STM system would be housed).[13] At a broader level, two representatives noted that there are significant limitations on their ability to provide input if the meetings take place in a venue where they are not already represented or have the capability and budget to send a representative.

Bilateral dialogues were mentioned positively by two representatives, particularly in the context of nation-to-nation SSA sharing or integration into a national STM system. However, another representative cautioned that bilateral dialogs require mature capabilities on behalf of both nations.

Two representatives noted that the idea of combined capacity-building and input solicitation workshops is appealing, but one expressed scepticism that there would be an actor with funding interested in organizing such workshops.

Several representatives offered significantly different perspectives. One preferred engagement through international intergovernmental organizations (not just COPUOS) and bilateral meetings, supported by technical and regulatory cooperation, that took account of the LTS Guidelines and other UN work. The other felt that the inclusion of countries without significant technical capability in SSA/STM was counterproductive given the early stages of STM work and preferred for further development through expert conferences like AMOS prior to work at COPUOS and other broad-based organizations.[14] Two emphasized the importance of regional technical and political organizations and consortia, and emphasized that actions by those organizations and consortia were a significant driver to motivate action domestically by their own country.

Do you have thoughts on whether STM should be organized from the top down (starting from international discussions among countries) or from the bottom up (with national frameworks and discussions among private actors)? [15]

The discussion mirrored the results of the SWF Space Sustainability Summit. Seven representatives preferred a mixed approach, recognizing a need for technical work to occur from the bottom up and political engagement to occur from the top down internationally. However, there was not agreement on the temporal relationship between these two elements. Three representatives proposed starting with a bottom-up approach then transitioning to a

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[13] All but one nation (Estonia) from which representatives were interviewed are COPUOS members.

[14] This preference for SSA/STM capability as a prerequisite to participation is implicit in most of the bottom-up approaches to architecture discussed in Chapter 2. The representative who expressed it came from a country with more developed SSA capabilities relative to many of those interviewed.

[15] This question was not included in the first interview, but was added in protocol version 1.1 in large part as a response to discourse at the SWF's 2019 Space Sustainability Summit. Two declined to answer it and it was not covered in one interview due to time.

top-down approach that leverages developed national capabilities. One proposed a need for a top-down approach to build consensus that would then allow bottom-up detailed technical work. Two proposed a simultaneous meet-in-the-middle approach. Two representatives from a region with a strong regional space organization preferred a bottom-up approach.

Four representatives preferred a top-down approach. Of these, one expressed concern that systems would not be inclusive and meet the needs of all actors unless everyone is invited to participate from the start and has the capability to participation. In the mind of that representative (and echoed in another separate interview), bottom-up approaches are inherently exclusionary of those without developed national or industry capabilities.

Do you think your country would likely participate in an international SSA/STM system? What factors would influence the decision?[16]

All but one representative indicated that, in principle, they believed their state would participate. That one exception felt it was too hard to extrapolate in the abstract. Reasons for participation varied. Two representatives mentioned that participating would help build capacity, two mentioned a desire to be a good actor internationally, and two mentioned the expectation that participation would help bring external investment to their space activities. Another representative felt that the system would help improve national mission assurance. Two were concerned about cost-benefit analysis. One of these mentioned a need to participate to understand the system and help determine if it would be in the national interest. The other of the two representatives citing cost-benefit analysis mentioned a need to persuade political actors of the benefits of participation. One of these noted that if industry from that representative's country was involved in helping to build the system in some form, the country would be significantly more likely to participate. Cautionary notes included wanting to participate only if a system had universal buy-in from major space powers, budget concerns, the system needing to treat all countries equally, preserving national control of space assets, and skepticism that current SSA is precise enough for an operationally viable STM system.

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[16] This question was not included in the first interview and was added in version 1.1. However, it was substantively addressed in all interviews.

Do you have any concerns about the potential consequences/impacts of an international space traffic management system? What do you believe would constitute an 'undue' cost (monetary, or otherwise) for such a system?[17]

The most common concern was the STM system increasing the technical sophistication required for operating a space mission, raised by seven representatives. Several representatives mentioned a need for knowledge transfer and capacity building as necessary to compensate if the system significantly raises technical requirements for space missions. Otherwise, these requirements risked being exclusionary.

Another common concern was that the system might restrict nations' ability to operate freely in space, raised by six interviewees. While this concern was presented separately from concern about ceding some level of control to a foreign entity (selected by four interviewees), interviews largely saw these concerns as related. Representatives stressed the need for a system that was fair with opportunity for all nations to pursue space missions on their own time table, to have ultimate control over their spacecraft to choose what maneuvers they perform and when, and to avoid a scenario similar to GEO where the system places significant restrictions on the ability of emerging space nations to access space.

Two representatives indicated greater willingness to comply with a binding maneuver obligation but stressed that such decisions would need to be made transparently based on pre-published, clear, and objective rules.

Five representatives expressed concern about the potential cost of an international STM system, but six noted value for a potential system and expected their nation would be willing to pay a reasonable amount. One representative proposed that costs should be proportional to the number of operating satellites authorized by a nation.

Representatives were much less concerned about an STM system disclosing sensitive information about their space activities. While no interviewees currently operate undisclosed satellites, several acknowledged that they might wish to avoid disclosing satellite missions or certain payload characteristics. Nonetheless, they saw little point to efforts to avoid disclosing satellite locations, noting that current technology makes it relatively easy for others to track even undisclosed satellites. One representative noted that the representative would not be concerned so much with the disclosure of SSA information, but with the potential cyber vulnerabilities of a potential STM system if it was deeply coupled with their national systems and might potentially become a target during a conflict between great powers. Four representatives indicated no concerns.

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[17] This question was not included in the first interview and was added in version 1.1. However, it was substantively addressed in all interviews.

Would you support different standards for norms compliance (i.e. post-mission disposal) across countries or actors?

Half of interviewees answering this question (seven interviewees) opposed differing standards for norms compliance. Instead they emphasized the need for attainable standards as a minimum floor that are reasonable for all to meet. Sentiments expressed in these interviews include:

- If standards are set too high, they risk restricting access to space. Having standards set through inclusive international processes by consensus is the best check to ensure they do not become exclusionary.
- Nations should be free to aspire to higher standards through voluntary or bilateral agreements.
- Capacity building can help increase the capabilities of emerging space nations and raise the regulatory floor over time.

Two interviewees favoured a weighted multi-factor approach, and three mentioned lower standards or subsidies for civil and scientific missions by emerging space nations. One interviewee specified standards should be different based on type of mission but did not specify how they should be differentiated. Three interviewees declined to address this question.

3.4 Discussion

3.4.1 What are the perspectives of representatives of emerging space nations on the design of a potential internationalized STM system, and what shapes these opinions?

This question is broken down into four sub-questions, each of which is analyzed based on the feedback included in the per-question trends and comments derived from the interviews themselves.

3.4.2 What are preferred forms of engagement to determine the design of future international STM systems?

Two main items from the interviews inform answers to this question: item 3.f (asking about venues) and item 3.g (asking about preferences for a top-down versus bottom-up approach to STM).

The overwhelming majority of interviewees support COPUOS as the place where these discussions should take place. This finding mirrors the IAA's report [15, 133], but these interviews offer further explanation for the reasoning behind this preference among emerging space nations. One interviewee summed up the reasoning, arguing that the best forum is one where everyone is invited, able to participate, and has the possibility of participating. COPUOS meets these criteria, being open to members of COPUOS, and critically, already being staffed by country representatives with at least some knowledge of space affairs. Several representatives emphasized that it is insufficient for a meeting to simply offer an open invitation to attend. Decisions are made by those who show up. Countries do not always have the budget to send a representative to attend or have an individual available with the relevant technical skill set, and space sustainability is not necessarily a top national priority for countries with emerging space capabilities and many other national challenges that compete for resources. Other venues can be useful, but play a secondary role, either serving niche situational needs, or adding various forms of additional value to a COPUOS-driven process. Should STM discussions progress to a global state conference as contemplated by the IAA [15, 133], these criteria should help guide the selection of a venue, timing, types of discussions, and selection of a secretariat.

Representatives who preferred a hybrid approach combining top-down and bottom-up approaches were generally more open to other venues and methods playing a larger role. While most participants thought of STM as involving both technical and legal/regulatory components along the lines of those described by the IAA [15], for nations without capacity to participate in the technical dialogue, there is a potential fear that the system developed, especially if it precedes a political consensus, will result in one or more of the concerns identified by respondents, potentially without an ability for them to successfully seek modifications to the developed system. This fear is not addressed in the IAA report [15, 131], which focuses on the difficulty in coordination between different entities and avoiding fragmentation/incoherence as the chief challenge associated with a bottom-up approach to STM.

The two representatives who preferred a regional and bottom-up approach were from emerging space countries that were also part of strong established regional space organizations, which perhaps explains why they did not share many of the concerns identified by nations preferring international engagement.

3.4.3 What forms of STM/SSA capability-building are most needed?

Interviewees were associated with countries with significantly varying levels of national spaceflight experience, but all are generally engaging in responsible spaceflight activities, and have set up or are setting up processes relevant to their level of national activities in space (e.g. receive conjunction warnings for countries operating spacecraft, design and execute collision avoidance maneuvers for spacecraft with propulsion). In some countries, national development of space was primarily driven by government activities, but in others interviewees anticipated that development of SSA/STM capabilities would be driven more by university and non-governmental space activities than by government-led initiatives.

While it is challenging to draw trends, the most common desire for increased national capability was for national collection of SSA data. Interest in other forms of capability building tended to relate to specific national plans for future space activities and the set of necessary enabling capabilities to carry out those activities while acting responsibly.

If an international STM system requires certain capabilities for nations or their operators to interface and use the system, building capabilities in those areas will be critical.

3.4.4 What capabilities should be provided by an international STM system?

Two questions were asked related to this question: what benefits a nation would seek to achieve from a global SSA/STM system and what functions that system should contain. The conclusions that can be drawn here are somewhat limited and highlight some of the limitations of the interview approach. While interviewees generally agreed that space sustainability was important, and that a system should be developed, there was considerably less certainty about what benefits it should provide, or what functions it should contain.

Many of the benefits cited were very high-level (e.g. "sustainable use and equitable access to space") or indirect benefits acquired from the system, but not directly related to specific system functions (e.g. avoiding conflict in space, increased mission assurance). A couple interviewees simply stated interest in access to SSA. When it came to functions, representatives with more direct experience in SSA cited specific functions and reasoning, but most either declined to answer the question or stated a preference for all options listed on the infographic.

These limitations may inadvertently highlight part of the reason why many within the space sustainability community prefer a hybrid approach that mixes bottom-up and top-down approaches: there are limits to how much top-down discourse can specify system functionality, but at the same time there are top-level concerns (equity in access, cost, retention of national control of space assets, etc.) that are impacted by technical, potentially bottom-up-driven decisions about system functions.

3.4.5 What kinds of STM requirements would constitute 'undue' cost?

This section summarizes the concerns articulated by interviewees. Not every interviewee listed every one of these (or even any) concerns. This section instead seeks to summarize the set of common concerns identified by interviewees to obtain a reasonable set of concerns to guide advice for potential STM system development.

The system needs to be affordable. Some cost is acceptable, but the cost must be reasonable and the benefits of participation must be commensurate with the cost. The financial cost structures should recognize significant variance in the extent to which nations make use of space. Different financial obligations should not translate into different status within the system.

Costs also exist in terms of impact on mission design and operations and the technical capabilities necessary to interface with the system. If the system requires increased technical capabilities from participants (relative to the status quo), the increase must be reasonable and nations must be able to practically achieve those standards. Capability building and knowledge transfer can help address these challenges.

These was disagreement about whether a system should include varied technical standards for participation. The largest camp favored uniform, but universally achievable standards, with the potential for voluntary national or bilateral commitments to do more. Other camps favored a weighted approach that took account of national experience in space, socioeconomic development, and type of mission, or an approach that included different higher standards for commercial activities. As STM-related measures develop in hard law, soft law, and hybrids of the two, this difference in philosophy will complicate negotiations and may result in divisions of view among emerging space nations.

Several representatives saw increased technical standards as a potential way for established space nations to restrict access for less-experienced actors. These representatives tended to stress the need for a consensus-driven process that would allow them to scrutinize requirements and evaluate their impact on national space activities. It would be okay for a system to organize who can be where in space, but that system should also ensure availability of slots (or space access more generally) for when a country is ready to use them. Within the STM context, there is concern that, as occurred for GEO, a first-come system would be inherently exclusionary, and an approach that explicitly seeks equity is needed.

This same concern about an STM system being leveraged to exclude actors from space showed itself in concerns about restrictions on a nation's ability to operate freely in space and the potential requirement to surrender some level of national control of space assets through participating in an STM system. Here some representatives stressed that a system should allow an operator to perform any system-directed action, rather than the system performing it automatically and that operators should be free to perform a hazard-mitigating action of their own choice rather than the system dictating a particular maneuver. To the extent rules are necessary, they need to be clear, non-biased, and treat all nations equally regardless of their size or number of spacecraft.

Representatives were generally sympathetic to the idea that a satellite might have an undisclosed mission, but skeptical of there being any gain or justification for refusing to disclose a satellite's location in orbit.

3.4.6 How do these opinions differ across interviewees and countries, and what shapes them?

Nations of those interviewed differed significantly in level of national activity in space, length of space activities, region, purpose of space program, level of national socioeconomic development, and multiple other factors.

One significant distinction present in the data relates to the level of familiarity with SSA/STM among interviewed individuals. Individuals with significant technical involvement with SSA/STM generally were more skeptical of an international STM system and tended to favor a near-term goal of SSA sharing as more realistic and achievable.

Two representatives from a particular region with strong established space institutions, but who had not been extensively engaged with work at COPUOS, provided responses that differed significantly from the rest of the cohort. Their responses were anchored in the context of this strong regional space ecosystem, and were outliers on several points including opposing stronger industry participation and one who provided the only response in favor of entirely legally binding rules for STM. Furthermore, both lacked any concerns about the potential design of an STM system. This finding is suggestive that an emerging space nation operating in an established context may have significantly different views than those outside this context.

Garnering greater insight into how opinions differ across regions, levels of national spaceflight experience, or other categories and drawing connections between the opinions expressed by interviewees and motivating factors is an exciting opportunity that should motivate further work to explore emerging space nations views on STM.

Of particular interest are the differing attitudes towards norms compliance that exist across the sample, with some respondents favoring differentiated standards and others preferring uniform universally achievable standard, but no obvious factors to explain what led each group to its perspective.

3.4.7 Preliminary Recommendations

A set of reasonable guidelines for technical work to develop STM capabilities can be derived from the concerns described above. These concerns could be addressed relatively easily in system design at the outset if appropriate recommendations are adopted as design principles. On the other hand, it would also be easy to inadvertently pursue architectural decisions that limit the ability to accommodate these concerns and lock in an architecture with only limited or expensive mitigations.

This chapter offers the following four preliminary recommendations based on these interviews:

1. **The cost of participation must be affordable, proportional, and with a clear value proposition for participation across the full spectrum of levels of national space activities.**

2. **Technical capabilities necessary to participate in the system should be identified and tracked through system design.** Capability building and knowledge transfer methods should be specifically considered. Requirements to participate should be minimized to the extent possible without impacting system effectiveness. Graduated requirements depending on national space activities and user needs may be worth investigating.

3. S**ystem designers should take great pains to ensure the system design is not exclusionary and cannot be co-opted by established system participants to exclude emerging space actors.** Designers should seek to obtain universal consensus buy-in and repeatedly consult and obtain stakeholder buy-in from nations with a variety of levels of national space capabilities throughout the development process. All nations should be treated equally by the operational system.

4. **Conversations should continue regarding the precise methods of interaction between the STM system and participant operators/satellites.** Designs that dictate a specific maneuver or perform an action automatically will face much

sharper resistance than designs that leave more freedom and flexibility to the operator. These considerations will need to be weighed against system performance and objectives.

The best way to assess adherence to these recommendations or other potential guiding principles is through consistent dialogue between the political and technical communities working on STM. Without such dialogue, there is a risk that key stakeholders will be excluded from deliberation regarding key cross-domain issues or dependencies and that architects in one domain understand guiding principles differently or make decisions based on a different set of motivating factors.

3.4.8 Validation of Preliminary Recommendations with Stakeholders

The set of four recommendations above was validated in two interviews that occurred after the initial compilation of recommendations, and with several individuals from the original interview sample who were re-approached for feedback.

Six of the original interviewees were contacted for this purpose, approximately one third of the overall sample. Four provided feedback on the recommendations. Interviewees for validation were selected based on a combination of geographic diversity, diversity of experience, and based on my intuition, informed by the dynamics of the initial interviews, about who was most likely to respond to a second survey in order to maximize the response rate. The findings were not validated with the full sample due to the significant complexity and follow-up that such an approach would entail. Validation was conducted asynchronously by email, unlike most of the original interviews. The continents represented in the revalidation set included Africa (1), Asia (1), Central America (1), South America (1), and Europe (2).

Representatives generally agreed with the recommendations presented, but several offered additional comments.

Suggestions for Additional Recommendations One recommended adding a new recommendation regarding the use of digital tools to coordinate during social-distancing and pandemic related restrictions on travel. That representative noted that while digital communications platforms can be used to make progress on international projects, there is uneven acceptance of their use among various countries. That representative also noted a distinction between technical projects, where remote meetings can be used to help reach agreements more easily, and political conversations where in-person interaction is much more important. The divergence is an important insight that may be useful to inform subsequent international work on STM and other topics in the coming months. However, this topic was not addressed in other interviews and therefore cannot be generalized as a finding.

Another individual put STM in the context of a broader need for international legal frameworks, and work on debris remediation and avoiding anti-satellite weapons testing.

Feedback on Preliminary Recommendations Representatives agreed with the first recommendation with no commenters offering significant critiques or additional comments.

On recommendation two, one representative recommended adding an explicit requirement to disseminate the technical capabilities necessary for actors to participate in the STM system. This is consistent with the intent of the recommendation, and should certainly occur. Disclosing how technical capabilities required for actors to participate change throughout the development process is important, in addition to dissemination of requirements for the ultimately implemented system. Another representative noted that capability building is hard to achieve, and that the relationship between knowledge transfer and capability building is complex and nuanced. This is true, and significant thought will be necessary to translate this recommendation into an implementable plan.

On the third recommendation, a couple representatives were confused by the phrase "buy-in," which is an idiom in American English, and thought that the recommendation referred to requiring financial contributions rather than diplomatic agreement. This recommendation is therefore recommended to be re-worded as follows for clarity, while preserving the original intention:

3. System designers should take great pains to ensure the system design is not exclusionary and cannot be co-opted by established system participants to exclude emerging space actors. Designers should seek to obtain universal consensus ~~buy-in~~ **support** and repeatedly consult and obtain stakeholder ~~buy-in~~ **assent** from nations with a variety of levels of national space capabilities throughout the development process. All nations should be treated equally by the operational system.

On the fourth recommendation, one interviewee went further than the language contained in the recommendation and argued that, as a solution to sovereignty issues, there should be a menu of options for an operator to take in response to a high-risk conjunction with the ability for an operator to elect to propose and have an alternative verified by the system. This structure certainly provides a way to address the concerns identified while preserving strong compliance. However, it is too early in the architecture definition phase and there is insufficient certainty/support among the broader interviewee pool at this time to recommend a specific solution, including the one presented by this interviewee. Another interviewee stressed the importance of flexible and agile coordination mechanisms.

Based on the results of this feedback, it appears that the interview process and associated analysis yielded a set of valid recommendations to inform future work on international STM system design.

The set of recommendations, incorporating feedback from validation is:

1. **The cost of participation must be affordable, proportional, and with a clear value proposition for participation across the full spectrum of levels of national space activities.**

2. **Technical capabilities necessary to participate in the system should be identified and tracked through system design.** Capability building and knowledge transfer methods should be specifically considered. Requirements to participate should be minimized to the extent possible without impacting system effectiveness. Graduated requirements depending on national space activities and user needs may be worth investigating.

3. **System designers should take great pains to ensure the system design is not exclusionary and cannot be co-opted by established system participants to exclude emerging space actors.** Designers should seek to obtain universal consensus support and repeatedly consult and obtain stakeholder assent from nations with a variety of levels of national space capabilities throughout the development process. All nations should be treated equally by the operational system.

4. **Conversations should continue regarding the precise methods of interaction between the STM system and participant operators/satellites.** Designs that dictate a specific maneuver or perform an action automatically will face much sharper resistance than designs that leave more freedom and flexibility to the operator. These considerations will need to be weighed against system performance and objectives.

3.5 Conclusions

At the beginning of Section 3.1, three arguments were presented, namely:

1. Representatives of emerging space nations have opinions and preferences on STM system design, even if they do not yet face space traffic coordination/management issues and do not anticipate facing them in the near future;
2. Discussions on STM should substantively involve emerging space nations from the beginning; any eventual system will be more responsive to the needs of a broader set of stakeholders if discussions include these stakeholders and their preferences from the inception of the process; and
3. Direct interviews with relevant emerging space nation stakeholders are a valuable tool for characterizing emerging space nation preferences on STM system design and associated reasoning.

The first and third arguments are hopefully self-evident based on the content of the chapter thus far. The results of this research indicate that representatives of countries with emerging space programs across a variety of levels of national space activity want to participate and do have thoughts and preferences for the design of a potential internationalized STM system and that interviews are a useful way to gather these opinions. Based on the content of these interviews, a set of high-level recommendations have been identified and validated with a subset of interviewed emerging space nation stakeholders.

In future work, these findings should be validated more broadly including with representatives of other emerging space nations and with additional representatives associated with the nations for whom an individual or individuals were interviewed for this project. More work is necessary to continue data collection across a larger set of countries, and potentially across multiple individuals per country. It may be interesting to conduct separate interviews across different groups within a country (for instance at the political level, within the leadership of a national space agency, and at a working engineering level, or comparing civilian and military perspectives). This additional data could help identify how opinions vary across different emerging space countries and why.

The second claim in the above list is normative and requires further unpacking: why should STM discussions include emerging space nation stakeholders from the start? There are two main sets of arguments that can be brought to bear on this point, each of which is sufficient. Both have been present implicitly in much of the commentary in this chapter.

The first set of arguments is intended to address a utility-motivated actor, one who wants the best, most effective STM system possible, as soon as possible, but has few other concerns. This actor might be a technical expert, or someone operating at a policy or diplomatic level, but has little interest in moral arguments for their own sake. To such an actor, the argument is as follows: the space environment is global, and space actors are growing increasingly diverse in missions, capabilities, nationalities, and objectives. For any STM system to be successful in the long run, it needs to be global in scope (whether through centralization or interoperability) and successfully coordinate and deconflict across this multiplicity of actors. To obtain this global scope, the system produced must be globally acceptable. Many STM architectures are possible, depending on the various considerations presented in Chapter 2, but not all potential architectures will meet this criterion. Furthermore, there is little reason to be confident that an architecture optimized to meet requirements in a particular national context, or in the perspective of a particular actor's interests, will be suitable for universalization (although it certainly can help inform subsequent efforts). At the same time, once an architecture is developed and implemented, the financial, bureaucratic, diplomatic, and technical costs of pivoting become much higher. Efforts to universalize an understanding developed in a national context risk disagreement at the international level that will limit the reach and effectiveness of any such system.

If a broader set of perspectives is included from the beginning, it will be much easier to universalize developed systems to achieve the necessary international scope. The recommendations above, when cast in terms of the system architecture approach discussed in the previous chapter, advocate for the treatment of emerging space nations as primary stakeholders, rather than secondary or tertiary stakeholders as presented in some of the architectures and approaches to system design. The costs of doing so, if the guidelines identified in this work are correct and representative, should be only a modest imposition. While including more actors earlier in the dialogue will take longer, one can reason from analogy and extrapolate that this additional time will be shorter overall than if additional actors are brought into the process further into development. This last claim is admittedly a supposition, rather than a certainty, but one that is certainly plausible. For instance, the late addition of additional actors was identified in multiple interviews as one of the key reasons that the development of the LTS Guidelines took such a long period of time to achieve consensus. Additional work could and should investigate this question further.

The second set of arguments is addressed to the interests of a morality or justice-motivated actor. The first sentence of the first article of the Outer Space Treaty declares that "[t]he exploration and the use of outer space...shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind" [151]. STM in any form involves efforts to coordinate and manage finite shared natural resources, and potentially the ceding of some of level of national control over national space assets (whether through norms, law, or technical coordination systems). Many critical decisions must be made to define those elements, and broad participation is necessary to ensure that the systems developed live up to this obligation. To any justice-motivated actor, it should be clear that a discussion that excludes actors based on their level of economic or scientific development, whether explicitly or tacitly, will not reflect the interests of those who were not at the table. Many potential futures for STM would do just that, whether by fostering development of standards exclusively within particular technical expert communities, by endorsing first-come first-served allocation principles, or a variety of other potential pitfalls. Those pursuing such approaches will do so not because they are ill-intentioned or immoral, but simply because well-intentioned efforts by well-meaning individuals are insufficient to overcome the inertia of structural assumptions. As above, these approaches bake in assumptions regarding allocation, capabilities, and other architectural choices. However, while the concern for the utility-motivated actor stems from impairing the efficacy of the resultant system, for the justice-motivated actor the problem is that the resulting system is illegitimate because it arises from an illegitimate process, limits access to the benefits of space technology and applications, and is unfair to certain classes of actors.

Across both types of actors—many individuals and countries will manifest both sets of concerns—the necessary path forward is clear. Ensuring a broad array of perspectives are included in international discussions to develop future STM systems from the beginning will help guarantee that those systems are more responsive to the needs of stakeholder countries. These discussions will necessarily be a long-term process, with a need to maintain incremental progress and stakeholder buy-in. Less clear are the means to do so. Undoubtedly there is a key role for technical experts and expert communities in efforts to make progress on STM. Nations will continue to research and implement national systems. International will is not present to support a top-down approach to STM, and the most likely status-quo seems to be a continued (if meandering) march towards further development of voluntary guidelines, best practices, principles, and the like. The challenge will be to harness the collective work of nations and relevant communities, while ensuring these processes are as open and inclusive as possible, and that more established actors take seriously the obligation to share their expertise, time, and resources with emerging space nations, working as equal partners and respecting the priorities and sovereignty of their collaborators. If we do so successfully, we can create a future where all people and nations can access the benefits of sustainable and safe space technologies and space applications.

This chapter closes with one additional observation that is similarly critical: there is significant coupling between, on one hand, the combination of specific political-level concerns raised by interviewees and the resulting recommendations and, on the other, the details of the mission, architecture, and concept of operations of a technical STM system. For this reason, it is critical that discussions continue to be inclusive and involve significant communication between communities discussing the technical details of a potential STM system and political level dialogues on an STM regulatory regime. If technical and policy work proceed separately, there is a significant risk that technical discussions will exclude the interests of states without the capability to participate in detailed, technical discussions and lock in choices that complicate efforts to obtain consensus at the political level.

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Chapter 4

Commercial Satellite Operator Data Sharing Stakeholder Perspectives

4.1 Introduction

It is axiomatic that timely, validated, standardized, decision-quality SSA information is a prerequisite for effective STM. Satellite operators often have better state knowledge than those collecting infrequent, non-cooperative observations due to knowledge of planned maneuvers, spacecraft characteristics (shape, attitude, etc.), and on-board sensor telemetry [116, 19]. Access to this information from operators has the potential to improve orbit propagation, reflect maneuvers soon after they happen, allow screening of maneuvers planned by one operator against the intended plans of others (rather than an assumption of non-maneuvering), and improve fidelity in conjunction screening. Because operators directly experience the consequences of on-orbit collisions, interference, and other anomalies, they have a more direct sharing incentive than other related actors, such as manufacturers and insurers. There are a variety of additional domains where information sharing by satellite operators has the potential to provide mutual benefit including RF coordination, anomaly and threat sharing, laser emissions (coordination to prevent inadvertent lasing of satellite optics), and space weather.

At the same time, there are concerns raised within the community that operators may be reluctant to share some of this information for various reasons (e.g. revealing proprietary information, the cost of developing data-sharing infrastructure, risk to mission operations). This chapter seeks to document these concerns and understand how they influence the potential design of systems for STM.

4.2 Motivation and Research Questions

There are four main research questions for this work:

1. What STM-related or adjacent domains exist where there could be significant benefit to operators or other STM stakeholders from information sharing?
2. What functions need to occur to deliver those benefits and what information do they require?
3. Are commercial satellite operators willing to share this data and what sharing-related concerns do they have?
4. What are different potential architectural forms for data sharing; what kinds of trust models do they support; and how well can those structures mitigate operator concerns about data sharing?

Answers to these questions are critical to informing the design of future STM system architectures, in particular the level of centralization versus decentralization that should exist for the various system functions and the attendant level of data sharing necessary to achieve system objectives.

4.3 Methods

To answer these research questions, a hybrid approach was selected. Section 4.4 conducts a review of existing practices, relevant SSA/STM literature, and regulatory filings before the U.S. government, while Section 4.5 presents results of a set of supplementary interviews with relevant experts and satellite operators. Experts were employed in a wide variety of settings including at non-governmental and intergovernmental organizations, within the U.S. government, at federally funded research and development centers (FFRDCs), in academia, and at commercial satellite operators or other companies within the aerospace sector.

From these sources, a list of relevant domains for consideration is developed, necessary high-level SSA/STM functions and data requirements are identified in each area, and potential data-sharing concerns are documented. Results from each of these areas are then aggregated to develop overall answers to the research questions.

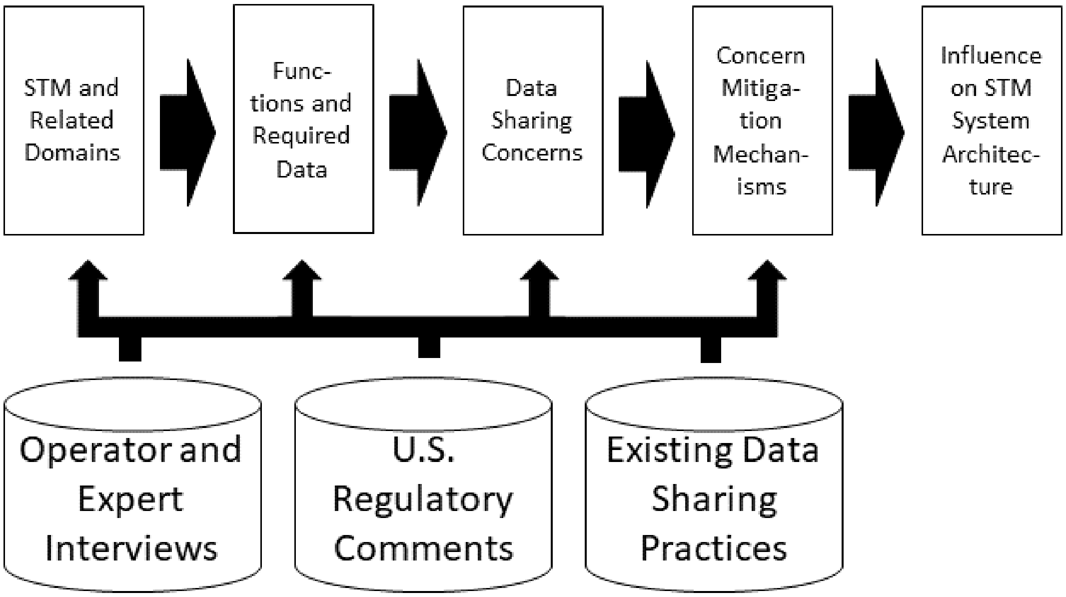

Figure 4-1: Chapter Methodology

4.3.1 Interview Protocol Development

Questions for operators were developed, informed by early interviews with SSA and STM experts. Interviews with operator representatives and non-operator SSA/STM experts were based roughly on these questions, but were tailored to their specific experiences and areas of expertise. Question topics included asking interviewees about their background and experience, their practices or understanding of practices relating to the dissemination of SSA and STM information, as well as their thoughts on potential future systems.

Questions about existing practices included how they currently disseminate SSA/STM information externally, any concerns about misuse of that information, any procedures or mechanisms they rely upon to protect that information, as well as if they have ever denied a request for information or been denied in a request they made. The questions also ask about their perception of their own practices relative to the industry and whether their willingness to share information was affected by the nationality or size of the requesting company/entity.

Questions about their perceptions included how they define SSA and STM, whether there was SSA-relevant information that they would feel uncomfortable sharing and why, their thoughts on different mechanisms to protect that information during sharing, and any difficulties relating to current data sharing for SSA and associated coordination.

Based on feedback from initial experts, earlier interviews asked specifically about maneuver coordination, RF coordination, space weather warning, and laser emission coordination as domains. Later interviews also discussed anomaly and threat sharing in response to those domains being mentioned in several early interviews. Interviewees were free to suggest whichever domains they felt were most relevant, including those not mentioned above, but I would generally follow up with questions about the listed domains if they were not raised independently by the interviewee.

4.3.2 Interview Administration

Interviewee Selection

Interviews were originally intended to be conducted in two phases. A first phase was going to involve interviews with SSA and STM experts to help scope the project and develop a set of questions for the emerging space nation and operator interviews. Interviewees in this group included NGO and trade association representatives, FFRDC employees, people at relevant U.S. government agencies and international organizations, and an academic. A second phase would involve interviewing experts from commercial satellite companies, with the goal of achieving broad representation across different orbital regimes, mission-types, and global regions in which their companies operate. In practice, the two phases overlapped significantly due to interviewees suggesting additional contacts in both groups, scheduling considerations, and evolution of the focus of the project. The resulting iterative process was more appropriate for exploratory work of this nature than the original, rigid two-phase plan. One individual with significant professional experience at various satellite operators, who was previously employed by an operator until shortly before being interviewed, was considered an operator representative despite not being employed by an operator at the time of the interview.

Potential operators were identified through various methods including membership in satellite operator organizations, attending or exhibiting at various conferences, publicly available lists of largest satellite operators by revenue, recommendations from interviewees, and connections within my professional network. To be eligible for the study, a company needed to operate at least one satellite to provide some form of remote-sensing or communications service. Companies that did not yet operate a satellite or that propose to perform other potential missions including satellite servicing, debris removal, or refueling were excluded from the sample. Individuals that work at companies that do not meet these criteria were not considered operator representatives, but were occasionally interviewed as SSA/STM experts.

Experts were identified via their relevant publications, suggestions from other interviewees, engagements at relevant events and conferences, and through general familiarity with the SSA/STM community.

Extensive outreach with repeated follow-ups was conducted to potential interviewees by phone, email, professional social media networks, and in person at MIT space-related events as well as at other major conferences like the Space Foundation's Space Symposium and Satellite, as well as to various organizations with relevant membership. Unfortunately, response rates, as well as consent rates to be interviewed among respondents, were low among operator representatives (but not experts), with more than two-thirds of companies not responding or declining to be interviewed, particularly among GEO operators. Reasons for this low willingness to participate may have included difficulty identifying a relevant interviewee within a company, low investment in responding to often-cold outreach from an unknown individual, low prioritization of participation in an academic study, sensitivity of the topics discussed, and company policies on participation in outside interviews.

4.3.3 Factors Potentially Affecting Validity

Several dimensions that impact the validity of data presented here should be noted. These include:

- The small number of actual operators interviewed, six companies (although multiple individuals were interviewed for some operators);[1]
- A bias towards the inclusion of U.S. and European operators due to differential response rates, ease of outreach, and the large number of Western operators. This trend was consistent with operator self-reported difficulty in engaging with Chinese and Russian counterparts, which was raised in multiple interviews; and
- A potential selection bias whereby larger operators and those who prioritize space sustainability were more likely to agree to be interviewed and more willing to share SSA data.

Each of these impacts the external validity of this work and the extent to which these results can be generalized.

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[1] A list is available in Appendix C.

The first concern is somewhat mitigated by the significant overlap with answers provided by operators in response to questions from U.S. regulators (in particular in comments to the FCC which are analyzed in Subsection 4.4.5), and the large number of experts interviewed. These viewpoints provide additional data from which the analysis in this chapter can proceed and the general agreement across all three sources helps provide assurance that the operator interviews are at least somewhat representative.

The second concern, a bias towards U.S. and European operators, limits the generalizability of these results but is reflective of the overall lack of American and European engagement with Russian and Chinese operators generally and the significant role of American and European operators in the global space industry. Further work should involve other global operators and would benefit from being conducted under the aegis of an international organization like the IAA or the IAASS, with the participation of authors fluent in languages other than English, ideally with a variety of nationalities.

The third concern could also limit generalizability. The FCC comments do indicate that there might be a cleavage among some very new operators versus more established operators.[2] For instance, KTi and LeoSat MA, Inc. (LeoSat), which has since ceased operations, both took more limited views regarding what information should be shared than most established operators [97, 13-14] [28].

In contrast to these limitations to external validity, internal validity is high. There is high likelihood that the domains, functions, concerns, protection models, and their applicability gathered in this work do reflect the perceptions of the operators for whom information was gathered. The interview format allows for any questions or confusion to be clarified and permits follow-up questions as necessary. Interviewees are largely experts in the topics of SSA and STM, and are familiar with the concepts being discussed with the interviewer. Similarly, interviewees have little incentive to provide false responses, with anonymity as an option for individuals unable to speak candidly with attribution. Concerns and concepts expressed by one interviewee could be validated with other interviewees.[3] In future work, validity could be further improved through a subsequent validation round with participating and new interviewees, similar to the process used in Chapter 3. Such a step would be more warranted after additional data collection to address some of the concerns regarding external validity explained above.

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[2] By established operators, I mean post-revenue companies, not the new-versus-old space dichotomy, which is frequently a counterproductive distinction.

[3] This was generally done by the interviewer only after an interviewee had provided that individual's own response to a particular question, in order to avoid influencing the original response.

4.4 Review of Public Practices, Opinions, and Relevant Organizations

This section explores relevant theoretical constructs, the current practices of various organizations across several domains relevant to the research questions in this chapter, as well as public opinions expressed by commercial operators on data sharing in U.S. regulatory filings. This information is generally derived from public sources, rather than interviews. One exception exists for Subsection 4.4.4, which is augmented with content from an interview with a representative of a space threat information-sharing organization to describe that organization's current practices and plans in greater detail than would be possible using only publicly available documentation. In another instance, an interview with a representative of Iridium is cited regarding their current operational practices around data sharing through space-track.org.

4.4.1 Types of SSA Information

STPI's 2016 report "Evaluating Options for Civil Space Situational Awareness" offers a useful taxonomy of SSA and physical-collision-relevant, non-SSA data provided by the current SSA system [116, 15-19] that serves as a useful starting point for this work with regards to data for physical collision avoidance.

The report classifies SSA data into three categories:

1. **Metric data**, which describe an object's orbital trajectory;
2. **Characterization data**, which describe aspects of the object such as "size, tumbling, composition, emissions and capabilities" [116, 15]; and
3. **Descriptive data** about the entity that launched the object, the entit(ies) that own and/or operate it, and the object's mission.

The authors further observe that metric data can be divided into various levels of processing (reproduced in Table 4.1), with data at lower levels of processing providing "greater freedom in fusing data from multiple sources, greater understanding of the data accuracy and precision, and greater flexibility in creating analytical products and services" [116, 15].

For the purpose of this project, the primary interest is ephemeris data, characterization data, and contact information for satellite operators, which is a form of descriptive data.

Level	**Description**
1-Raw sensor data	Focal plane images, radar returns
2-Observation	Location of a space object at a point in time relative to a sensor
3-Element Set	Set of variables (function) describing an object's orbital trajectory
4-Ephemeris	Predicted position of an object generated by propagating an element set over a period of time
5-Analysis Product	Information that is the result of an analysis based on element sets or observations (such as de-orbit prediction time)

Table 4.1: SSA Metric Data Levels (reproduced from [116, 16])

4.4.2 Existing SSA Data-Sharing Organizations and Practices

The SDA is an international organization dedicated to the sharing of data to support spaceflight safety. The organization's members include satellite operators, manufacturers, and government agencies [6]. The organization operates the Space Data Center (SDC), a technical system that allows for the sharing of authoritative satellite owner contact information for the purpose of collision avoidance, as well as the ingestion, verification, conversion, and screening of satellite owner/operator ephemeris data (and optionally maneuver plans) to identify and mitigate conjunctions. The organization also feeds information to the 18SPCS. Data are protected by both a legal agreement that restricts the use of shared information[4] and a technical design that only shares owner/operator ephemeris data when a conjunction has been identified [87].

The 18SPCS operates space-track.org, a website that provides SSA information to a variety of users. Members of the public can obtain basic SSA information including launch, decay, general perturbation, and other data for various space objects [35]. Operators and others can sign SSA sharing agreements with the 18SPCS to gain access to additional information including special perturbation data, satellite maneuverability information, a contact directory, and various services on a basis free from direct user fees.

ESA's Space Debris Office operates the Database and Information System Characterising Objects in Space (DISCOS), which contains characteristic and descriptive information regarding space objects' sizes, shapes, and mass, as well as fragmentation events, launches, launch sites, launch vehicle stage characteristics, engines, and initial and final orbits for

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[4] Permitted uses are "[1.]operational support, including safety of flight...[2.]RFI resolution of actual harmful interference...[3.]support for insurance underwriting...[4.]as legally required by national regulatory authorities". All other uses, including commercial purposes, to obtain orbital spectrum rights, and transfer to third parties for non-safety-of-flight applications are prohibited.

satellites [2].

Various companies publish ephemeris data or other state information for their spacecraft. This paragraph describes several companies that offer public access to their data. This list is intended to be exemplary, not exhaustive. SES SA publishes current eleven-parameter ephemeris data and TLEs [4]. Intelsat License LLC (Intelsat) provides seven day predictive ephemeris data in several formats updated on a weekly basis and when maneuvers occur [3]. Planet Labs Inc. (Planet) provides operational status, latest and historical TLEs, state vectors, and correlations between their satellite IDs and 18SPCS TLEs [5]. Spire Global, Inc. (Spire Global) now provides access to real-time TLEs derived from their own orbit determination [8]. DigitalGlobe, part of Maxar Technologies Inc., provides access to ephemeris files [1].[5] Space Exploration Technologies Corporation (SpaceX) says it provides ephemeris data and covariance information to other operators, but not the public, through space-track.org [163, 11]. Iridium similarly shares ephemeris data with other operators through space-track.org [90]. I requested further details from the 18SPCS regarding the extent of data sharing among operators with SSA-sharing agreements, but the request was not approved prior to publication of this thesis.

Existing academic writing and reports on SSA generally acknowledge there are potential national security and proprietary concerns associated with satellite information sharing, but tend to do so at a high level without sufficient specificity to inform the kind of analysis sought in this chapter. For instance, the RAND Corporation released a report in 2014 that explored using secure multiparty computation to enable the secure sharing of ephemeris data for conjunction screening without reliance on a trusted third party [60]. In describing the motivation, they note commercial businesses "view their active tracking data as proprietary information, and they fear that revealing these data would provide an advantage to their competitors," but provide little detail as to what these advantages might be, what about the information is sensitive, and how significant this fear is [60, xi].

The 2018 IAA report notes that there is a need for the system to be capable of "responding to the challenges of data assimilation and sharing, overcoming eventual constraints related to the nature of data sources or operators" and that "certain [LEO] operators may be reluctant to disclose precise satellite positions over particular regions of interests" [15, 18, 99]. It then cites unspecified ESA SSA program studies that identify three concerns relevant to commercial operators [15, 101]:

1. Ephemeris could enable the identification of exact pass times (which could be considered a security breach for some systems);

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[5] These files were out of data by approximately ten days when reviewed on August 4, 2020

2. Ephemeris would enable competitive advantages, e.g. a Earth-observing satellite could reduce its orbit to obtain sharper images than a competitor; and
3. Ephemeris might reveal sensitive information like failed maneuvers.

No further information is provided about how widespread each of these potential concerns is, and requests to ESA Space Debris Office for access to the underlying study in question were not returned.

Rendleman notes, in an example typical of the way SSA data-sharing sensitivities are described in the literature, that "commercial operators usually desire to limit exchanges of information that could give competitors insight into sensitive proprietary information relating to the capabilities, health, and life of their satellites" [127, 854].

Oltrogge [118, 6] offers a long list of potential concerns, cautioning

> SSA frameworks predicated on wide open, free data sharing ignore the realities of commercial and government entities needing to protect sensitive or proprietary data. Unintentional release of such data can place data contributors at risk of liability, degraded national security, conflicts of interest, unfair competitive advantage and adverse impacts to mission, revenues and the customer base.

It is worth placing this comment in the context of his role as program manager for the Space Data Center which uses legal and technical protection mechanisms to limit data sharing to a need-to-know basis. Like the above instances, it does not explain which forms of data sharing would lead to each of these potential harms and under what circumstances. In another part of the same article, he states that "the commercially-proprietary, competition-sensitive and at times highly-protected nature of operator data on its systems" includes "ephemerides, station-keeping maneuver strategies, spacecraft dimensions, RF characteristics, system performance/capabilities and spacecraft fleet specifications and definition" but does not map these data sources to the concerns identified earlier [118, 15]. In this second instance, he identifies two additional concerns, the creation of conflicts of interest and the potential for increased insurance rates.

Space Policy Directive 3 directs the creation of an open architecture data repository and mandates the inclusion of "measures to safeguard proprietary or sensitive data, including national security information" [114].

4.4.3 Anomaly Sharing

Work has been ongoing for several years to discuss the development of a comprehensive database of satellite anomalies more detailed than current efforts. A search identified two main sources discussing operational concerns regarding the creation of a satellite anomaly database (many more sources discuss techniques to use data derived from such a database).[6] Both sources agree that there would be significant value for operators and researchers from the creation of an anomaly database, but note that operator concerns about data sharing exist and would need to be addressed. The sources reach different conclusions regarding how to accommodate these privacy concerns, with one considering the application of specific cryptographic techniques and the other calling for unspecified data obfuscation methods.

In 2014, the RAND Corporation published the results from a study for the Defense Advanced Research Projects Agency on the benefits of creating a satellite anomaly database and how cryptographic techniques could be used to enable secure sharing of satellite anomaly information [54]. The report found that the creation of such a database could assist with anomaly attribution (e.g. distinguishing between a satellite-specific anomaly and an environmental hazard experienced by multiple satellites) as well as improve the speed and reduce the cost of anomaly investigation. At the same time, it noted two main barriers to creating such a database in the first place:

1. Commercial operators may be hesitant to reveal their technical issues to competitors or investors; and
2. Establishing such a database would require both a trusted organization to operate it and funding to support its operations.

The report notes that there are two basic privacy problems:

1. Concerns from placing sensitive information into a trusted database; and
2. Concerns from users accessing the database.

The first concern, they argue, can be mitigated by having an organization trusted by participants administer the database, or through the use of secure multiparty computation, a computational technique that allows multiple users to share individually held data and perform calculations to obtain results without gaining access to the underlying data. The second concern could be addressed through the application of another technique known as differential privacy, which adds small amounts of noise to query results to prevent the

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[6] The discussion of these two sources should not be read as implying the lack of an extensive history of work within the space safety community to facilitate greater sharing of anomaly information. For instance, Darren McKnight regularly organizes the Space Systems Anomalies and Failures (SCAF) Workshop, which includes efforts to encourage greater sharing and standardize methodologies and reporting. Rather, it is to describe two models for sharing and the concerns explicitly mentioned.

use of multiple queries to infer information about an individual element of a data set from reported aggregated statistics.

During a meeting at the European Space Weather Week in November 2017, interested parties met to discuss the creation of a satellite anomaly database [57]. The meeting summary contains several useful details and largely corroborates the concerns and architectures discussed in the RAND report. Commercial stakeholders described various concerns with anomaly sharing including:

- Anomaly sharing could publicize weaknesses in company operations in a way that hurts the company's competitiveness;
- Attribution could raise liability issues; and
- The customers of commercial satellite operators might be sensitive to anomaly reporting.

The participants discussed two approaches: a "curated pool" and a "standardized share." In the first approach, operators provide unredacted information to a trusted third party under a non-disclosure agreement, which can then conduct analysis and share findings back to operators in such a way that obfuscates the original proprietary data. In the second, operators obfuscate data themselves before sharing, at the cost of potential limitations on analysis since no party has the full unredacted data set and because operators might apply obfuscation inconsistently. The representatives agreed that creation of a pool using publicly available anomaly data would be useful to demonstrate the value of the database and test methods for data obfuscation.

4.4.4 Threat Information Sharing

The Space Information Sharing and Analysis Center (Space ISAC) is a new organization, launched in April 2019, to support collaboration between companies in the space sector and the U.S. government relating to vulnerabilities, incidents, and threats [7]. The Information Sharing and Analysis Center (ISAC) model was created by Presidential Decision Directive-63 in 1998 [10], and more than 20 ISACs now operate for industries including automotive, real estate, and oil and natural gas. A representative from the organization indicated that it is scheduled to reach initial operational capacity by the end of summer 2020 [89]. The organization's activities will include programming such as workshops or webinars, exercises, an annual summit, collaborative working groups, and a secure digital platform for sharing threat information online [89].

The Space ISAC will cover "all-threats security information" and enable sharing among members, as well as with various U.S. government entities in a protected but unclassified environment [89]. In order to gain access, new members must go through a vetting process. When submitting information into the threat-sharing portal, the submitting entity is responsible for conducting any desensitization or anonymization it views as necessary (although some will also be conducted automatically by the portal software) [89]. It also is able to chose which entities will receive the information [89]. Limitations on sharing or disclosure of the shared information are legally protected by the Cybersecurity and Information Sharing Act of 2015 (6 U.S.C. § 1503), contractually protected by the Space ISAC membership agreement, and through technical protection measures that will be included in the threat sharing portal [89]. The ability to query non-desensitized or less sanitized information through protection techniques such as differential privacy is uncertain and will depend on the technical capabilities of the software solution procured by Space ISAC for the sharing portal [89]. Space ISAC board members have specified that securing the portal against compromise by external actors is a top priority [89].

4.4.5 Operator Viewpoints in the FCC Record

Within the United States, laws passed by Congress are usually written in a high-level manner that requires significant detail to be defined to enable actual implementation and enforcement. This is generally done by administrative agencies within the Executive Branch. The Administrative Procedure Act (5 U.S.C. § 500-596) regulates the process by which executive departments and independent agencies exercise this discretion and imposes various obligations regarding solicitation and consideration of feedback from the public as part of rulemaking and public notification of agency actions and decisions.

Actions by the FCC, and the public comments provided by operators during the rulemaking process, are a useful and instructive source of information on commercial satellite operator perspectives on SSA data sharing. Two dockets are particularly helpful: "Update to Parts 2 and 25 Concerning Non-geostationary, Fixed-Satellite Service Systems and Related Matters" (IB docket No. 16-408) [51] and "Mitigation of Orbital Debris in the New Space Age" (IB Docket No. 18-313) [52]. All dockets following the Iridium-Cosmos collision in 2009 with the word "ephemeris" present in one or more comments were examined, but most did not include responsive content that addressed commercial satellite operator concerns about ephemeris sharing.[7]

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[7] The topic is briefly mentioned in "In the matter of streamlining licensing procedures for small satellites" (ID docket No. 18-86) [17, pars. 57-58] by a few commenters, but these brief comments are further developed

I further reviewed comments filed in response to the DoC's "Request for Information on Commercial Capabilities in Space Situational Awareness Data and Space Traffic Management Services" (Docket ID DOC-2019-0001) [46]. Several organizations responded to both agencies, and the content responsive to the goals of this chapter was essentially identical. Among organizations responding uniquely to the DoC's request for information, many commenters addressed the technical infrastructure of the repository and noted a need for sophisticated access controls with details unspecified. Two commenters offer additional information relevant to technical protection measures for data. Providence Access Company and Analytical Graphics, Inc. filed a joint comment arguing that the open sharing of data raises concerns relating to "protection of intellectual and competition-sensitive property, proprietary data, being accountable for data misuse, and a legal framework" [44, 5-6]. ConsenSys offered a comment describing a blockchain-based network as a platform for an STM system to avoid requiring trust of a single overseeing entity [65].

The first FCC docket, 16-408, proposed and ultimately expanded to additional spectrum bands a pre-existing, periodic, ephemeris-sharing requirement for satellites in non-geostationary satellite orbits (NGSOs) providing fixed satellite service[8] under the rationale that satellite location data are necessary for the spectrum sharing mandated by the FCC [13, pars. 56-58]. Many commercial satellite operators (including The Boeing Company (Boeing), WorldVu Satellites Limited (OneWeb), Planet, Spire Global, Keplerian Technologies Inc. (KTi), SpaceX, Telesat Canada (Telesat), and SES Americom, Inc. and O3b Limited (SES)) all supported the ephemeris-sharing requirement, and Boeing went so far as to argue "there is no indication in the record that NGSO system operators may be inclined to withhold such data, or make it difficult for other NGSO system operators to access" [25, 20]. However, there was significant disagreement regarding the best method to share such information. The FCC ultimately imposed a format-agnostic requirement to share data in a "mutually acceptable" manner. In joint comments, Planet and Spire Global provided a set of four fundamental questions for the FCC to consider regarding the sharing of ephemeris data, which are worth reproducing here to help guide consideration of ephemeris sharing in the next docket: "(i) how often ephemeris data should be shared, (ii) with whom it must be shared, (iii) what are permissible formats and sharing techniques, and (iv) whether the Commission or another government agency should provide an index or location for the sharing as a minimum/default option for operators" [132, 4]. From the record, it appears that the broad cross-section of NGSO operators and manufacturers who responded found

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by each of these organizations in the "Mitigation of Orbital Debris in the New Space Age" proceeding.

[8] Fixed satellite service is one of numerous categories of satellite service identified and allocated frequencies by the ITU and national laws.

no particular sensitivity with sharing ephemeris information, but that significant questions remain on the best ways to do it.[9]

The scope of the "Mitigation of Orbital Debris in the New Space Age" docket is much more sweeping. In November of 2018, the FCC proposed to update rules on orbital debris mitigation from 2004, with new rules in a variety of areas including risk quantification, post-mission disposal, proximity operations, and others. The 2004 rules [11] largely consisted of a series of disclosure requirements around whether an operator has engaged in analysis related to best practices to limit the amount and probability of debris generation contained in the 2001 U.S. Government Orbital Debris Mitigation Standard Practices [14, 3,15-16].

Several of the new proposals addressing data sharing by commercial satellite operators are relevant to the objectives of this chapter. These include:

- An obligation to share initial deployment, ephemeris data, and planned maneuver information with the 18SPCS or a successor civilian agency [14, 15];
- An obligation to share ephemeris information with other operators with whom an operator's spacecraft have a risk of collision [14, 26];
- An obligation, upon receiving a conjunction warning, to take all possible steps to mitigate the conjunction including directly "sharing ephemeris data and other appropriate operational information" with other involved operators [14, 15-16];
- An obligation to disclose information related to multi-satellite deployments [14, 16];
- An obligation to disclose the extent of satellite maneuverability (e.g. number of anticipated collision avoidance maneuvers, means of collision avoidance during operational lifetime and post-mission, and disclosure requirements for differential drag and other newer technologies for maneuverability) [14, 16]; and
- An obligation to disclose spacecraft capabilities and intention to perform rendezvous or proximity operations (RPO) [14, 24-25].

This list is not exhaustive and excludes various other information disclosure requirements that are closely linked to data sharing with the FCC for the purpose of its public-interest determination during licensing, e.g. a requirement to provide justification for choosing an orbit over 650 km for an NGSO satellite constellation deployment.

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[9] The authors of the joint comments [132, 4] do speculate that providers who host (presumably national security) government payloads could potentially be prohibited by the U.S. government from sharing ephemeris data, but do not object to sharing on their own account.

Table 4.2 maps these requests to the STPI SSA data types and different levels of sharing. Notably, the docket does not ask about many forms of potential sharing, including direct public sharing (although data shared with the FCC would generally be public by default unless confidentially were to be granted either on a case-by-case basis or as a general policy).

	Shared With				
Information (type)	18SPCS or a successor civilian agency	Other operators (with a potential conjunction risk)	Other operators (upon receipt of a conjunction warning)	The FCC (either with public disclosure or under seal)	The public
Initial deployment (metric)	1			4	
Ephemeris (metric)	1	2	3		
Planned maneuver information (metric)	1				
Maneuverability (characterization)			3?	5	
RPO capability/intent (characterization)				6	

Table 4.2: FCC Questions Mapped to STPI Information Type and Sharing Audience

Before discussing the specific comments and opinions contained in the record, it is important to note that an operator's opposition to an FCC rule mandating sharing of a form of information is not necessarily equivalent to opposition to sharing that information. Even if a piece of information is innocuous, operators might fear compliance costs associated with FCC verification of their sharing, limited flexibility imposed by a specific FCC-defined sharing methodology, and whether the shared information will be used to justify subsequent and potentially more burdensome regulations.

In discussing the comments in the record, this section will examine each data type and opinions about sharing that data with each of the groups identified in Table 4.2, rather than following the structure contained in the FCC proceeding. This review is current as of June 5, 2020, and does not consider comments made after this date. While I reviewed and coded all comments contained in the full record, only comments addressing the SSA data-sharing fields identified in this section are recorded in Table F.1. This understates the total level of assent, as comments are biased towards mentioning topics that have a strong impact on the core businesses of commenters, especially topics where they disagree with proposed FCC action. For instance, Viasat Inc. does not mention ephemeris sharing in its comments, although it is unlikely the SDA member opposes NGSO operators sharing ephemeris data with their orbital neighbors, similar to behavior the GEO operator already engages in voluntarily [108].

I also wish to note there is some level of subjectivity and interpretation inherent in the comment coding process; another reader might code some of these entries differently.

Several of the companies who filed comments are no longer in business, including LeoSat. OneWeb is undergoing bankruptcy restructuring. Nevertheless, their comments are still useful in assessing the breadth of opinions across the industry.

Ephemeris Data

Seventeen commenters supported mandating the sharing of ephemeris data with the 18SPCS. Three supported voluntary rather than mandatory sharing, without articulating any particular concern about the sharing of ephemeris information. Lockheed Martin Corporation (Lockheed Martin) uniquely argued that the compromise of access to tracking data or ephemeris data would mean “NGSO system operations would be vulnerable to direct attack or subversion” [75, 12]. Given the widespread ability of adversary countries to track even classified U.S. satellites, it is hard to understand how this would be the case. The fact that no other commenter repeated this claim helps corroborate that this perception may be an outlier.

There was again widespread support for sharing of ephemeris data with operators of spacecraft at potential risk of a conjunction. Nine commenters supported the proposal. Several offered caveats: for instance, that some operators may not have quality ephemeris data to share [160, 18], that sharing might be better accomplished bilaterally than through a centralized system [27, 18-19], that generalized sharing should be voluntary rather than mandatory [134, 9], and that a sharing mandate may be unnecessary since there is already private sector coordination [125, 12]. Lockheed Martin objected again, considering ephemeris to be “highly sensitive and proprietary data” [75, 17].

In response to a proposed requirement to take all possible steps to mitigate conjunctions, there was similar widespread support, with a few commenters proposing to require all appropriate versus all possible steps [146, 8] [115, 5-6], [75, 12]. Lockheed Martin again was alone in positing that there may be situations "where it is impossible or inappropriate to share ephemeris data or operational information with another operator" [75, 12].

KTi, a satellite transponder technology company, argued in all three cases that the data generated by spacecraft and transponders is "confidential and proprietary" information, that should be protected by only requiring the sharing of "three-dimensional position and velocity data" to protect their business model [97, 14]. No operator supported this view in the record.

Across all three forms of ephemeris data sharing (with the 18SPCS, among operators with a shared potential risk of conjunction, or in response to a conjunction notification), there did not seem to be any concern by commercial satellite operators expressed in the record about the sharing of satellite ephemeris. There were however, several reservations regarding the nature of a governmental sharing mandate. Because the FCC did not specifically inquire about public sharing of ephemeris data, the topic was only addressed in passing in the record.

Initial Deployment

There were fewer comments that addressed an obligation to share information regarding initial deployment. Boeing opposed this obligation as unnecessary and out of scope for the FCC [26, 24] [27, 30-31]. KTi would presumably also have objected to this sharing based on their overall stance on SSA sharing. ORBCOMM Inc. strongly supported the requirement, devoting significant space in their comments to a prior issue relating to coordination with an aggregator for a launch into an overlapping orbit [144, 14-16]. Telesat supported sharing initial deployment information with 18SPCS, but asked that issues around multi-satellite deployments be left for consideration by a launch licensing agency, not the FCC [115, 5-6]. Spaceflight, Inc., a launch broker, commented on the logistical challenge of asking an operator for detailed launch information at the time of filing, but did not object in principle to sharing deployment information [61]. No commenters expressed any further proprietary or other concerns regarding initial deployment information.

Planned Maneuver Information

This subsection considers maneuver plans independently from ephemeris data because a maneuver plan is actually a slightly lower level form of metric data than ephemeris data. While it is possible to recover some level of information about satellite maneuvers by comparing ephemeris data to a nominally propagated object, subject to various assumptions about the satellite, planned maneuver data allows for improved situational awareness. Among the operators that addressed planned maneuvers distinctly from ephemeris data, opinions remained correlated. Lockheed Martin once again preferred voluntary sharing to a mandate [75, 11-12] and KTi implicitly opposed maneuver sharing as it is an additional data product beyond six-element state information. In this case they were joined by Tyvak Nano-Satellite Systems, Inc., which seemed to fear that a requirement to disclose planned maneuvers (but presumably not predictive ephemeris data) would be unduly burdensome to its freedom to operate [16]. While several commenters opposed a sharing mandate, major commercial satellite operators were all supportive or silent.

Maneuverability

This topic inspired significantly more disagreement, in part because the FCC's original document combined multiple distinct disclosures relating to maneuverability. These included asking about mandating a disclosure of the estimated number of collision avoidance maneuvers necessary over the life of the spacecraft, although several operators responded regarding the operational sharing of maneuverability status for collision-avoidance coordination.

Several operators considered sharing maneuverability information to be problematic. Global NewSpace Operators, a coalition of several companies that submitted a group filing, supported some level of maneuvering capabilities sharing, but "only to the extent that disclosure does not reveal proprietary information about the applicant's system" [160, 10]. Boeing similarly noted "the actual techniques employed to complete satellite maneuvers is [sic] often highly proprietary" [27, 28] and LeoSat asserted "[s]pecific information relating to satellite maneuverability is proprietary and competitive in nature" [28, 5].

A number of other commenters supported the proposal in some form. The Aerospace Corporation approved of sharing maneuverability information as part of conjunction mitigation [106, 12]. The Commercial Smallsat Spectrum Management Association (CSSMA) supported collected and aggregated sharing of maneuverability information [134, 10] and proposed a category-based approach to differentiate between propulsion, differential drag, and non-maneuverability as a potential compromise position. Iridium [105, 6-8], SES [156, 3], Telesat [115, 6], and SpaceX [162, 12-13] all supported maneuverability information sharing as useful for conjunction mitigation. OneWeb provided additional specificity, arguing that maneuverability information should feature "information detailing the satellite's maneuvering capabilities, including achievable conjunction separation distances based upon decision lead time and the process by which an applicant intends to assess conjunctions and execute required evasive maneuvers" [47, 13].

RPO Capability/Intent

The FCC requested feedback on the intention of operators and the ability of their spacecraft to perform RPO. Some operators expressed concerns that the disclosures were redundant and would be contained in existing FCC submissions [106, 18][27, 40]. Global NewSpace Operators supported such sharing, while noting inherent limits due to "export control or proprietary information" [160, 17]. This same potential trade-off is present in the "CONFERS Guiding Principles for Commercial RPO and OOS and Recommended Design and Operating Practices" that are referenced in the SWF submission [158, 6-7].

Other Comments

Several companies commented on other data-sharing preferences that are worth highlighting outside of these specific categories.

Boeing and CSSMA opposed disclosure of spacecraft propellant characteristics due to proprietary concerns [27, 13] [134, 9].

Eutelsat SA opposed disclosure of precise TT&C frequencies due to jamming concerns [30, 8-11].

SpaceX argued for the sharing of unspecified satellite health information [162, 12-13] in addition to maneuverability and ephemeris data.

The FCC ultimately chose to require disclosure of plans for whether an operator (including for amateur and experimental satellites) would share initial deployment, ephemeris data, and planned maneuvers with the 18SPCS and other operators, but not to impose a specific sharing requirement. They reasoned that a separate certification adopted in the rulemaking process, to require operators to commit to take all possible steps to assess and mitigate collision risk upon receiving a conjunction warning, implicitly included sharing ephemeris data and other necessary information. [19, pars. 67-75].

Conclusions from FCC Filings

Based on the filings, there appears to be limited commercial operator concern about the sharing of ephemeris data or planned maneuvers with the 18SPCS or other operators (either generally or upon receipt of a CDM). There is less clarity in the record regarding a mandate for public sharing of ephemeris data (although some operators do share ephemeris data publicly). There is more divergence relating to satellite maneuverability status or RPO capabilities, in large part due to a lack of definition over what such a disclosure would entail.

Table F.1 summarizes comments from the record that addressed the sensitivity of sharing various types of information. Comments that oppose a regulatory mandate or governmental collection of data due to regulatory mistrust or a preference for voluntary sharing are coded as part of the other comment category if they do not express any specific concerns about data sharing and just prefer voluntary methods to a regulatory mandate.

4.4.6 Status of Available Information on Commercial Operator Data Sharing

The information available in the record and included in this review is helpful, but not comprehensive or sufficient to address the research questions identified for this chapter, which seek to understand potential data sharing domains, functions, information requirements, protection mechanisms, and implications for STM system design. Drawing from the FCC record, it is evident that some operators see value to data sharing for collision avoidance and RFI mitigation (addressed indirectly in the FCC record). However, these domains are not necessarily exhaustive. Across each of the discussed domains, specific functions and information requirements to achieve those functions are present only somewhat implicitly, with varying levels of specificity. The set of concerns raised for different kinds of data sharing is helpful, if again somewhat superficial. Data sharing structures and protection mechanisms are mentioned only somewhat in passing.

There are various structural influences inherent in gathering data on these questions from the FCC record that provide further limitations. In particular, the context of the FCC record, gathered voluntarily as part of a notice of proposed rulemaking, leaves multiple holes relevant to the research questions of this chapter. Some specific topics were not discussed. For instance, many GEO operators did not provide opinions on ephemeris data sharing (since the FCC's proposal focuses on NGSO operators) and most operators did not discuss thoughts on public ephemeris data sharing (since it was not raised by the FCC). There are also biases in the responses that arise from the format. Commenters were likely to focus their comments on the topics most critical to their businesses, especially those where they disagreed with the FCC's proposals. This approach maximized impact while minimizing cost and effort associated with composing comments. An absence from mention may mean neutrality or disinterest, or it could be a sign of lukewarm support. Answers were also generally composed, or at least vetted, through regulatory experts, who sometimes have views differing from technical individuals within the same companies.

The data-sharing organizations and concepts described elsewhere in this section provide several point solutions for potential data-sharing constructs, but analysis and interviews are needed to understand what circumstances different constructs are appropriate for, and to generalize this list of point solutions to a potential tool set available for data sharing across each domain.

Interviews with SSA/STM experts and commercial space operators provide a way to dig deeper into each of the research questions identified for this chapter, as well as verify and validate the content gathered in this review.

4.5 Results, Analysis, and Synthesis

This section is divided into three subsections: domains and relevant functions, concerns, and protection mechanisms. Except where otherwise indicated, the results of the first two subsections are derived from the interviews. The third section is synthetic of both the interviews and review in Section 4.4. Section 4.6 draws from both data sources. Results are described in more general terms than in the preceding chapter. This is done for two main reasons. First, the smaller number of interviewees, especially in some of the subclasses of satellite operators (e.g. LEO remote-sensing operators), potentially enable the identification of a responding company if isolated individually. Secondly, the interviews, while semi-structured, varied much more widely given the differences between companies and the backgrounds of responding individuals. A list of interviewees is provided in Appendix C Table C.2. Eighteen total interviews were conducted, with two interviews featuring multiple representatives (Planet, and another LEO operator who requested anonymity).

Representatives with connections to six operators were interviewed, as summarized in Table 4.3.[10] Five operate LEO satellites. One operates GEO satellites. Three primarily provide communications services, and two are focused on Earth observation. Three operate constellations, one operates a large constellation as part of a planned mega-constellation, and one operates a non-constellation architecture. All are based in the United States or United Kingdom.

4.5.1 Domains and Relevant Functions

This category describes the domains raised by interviewees where potential information sharing might be needed by an SSA or STM system and the functions that information sharing would enable.

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[10] One operator asked to not be identified beyond operating in LEO. That operator is excluded from all other counts and descriptions in this paragraph. One interviewee is a former employee of an operator, speaking in a personal capacity.

Operator	Orbit Regime	Mission Type	Current Fleet Structure	Headquarter Location
Anonymous Operator	LEO			
DigitalGlobe, part of Maxar Technologies Inc.	LEO	Earth Observation	Non-Constellation	U.S.A.
Inmarsat	GEO	Communication	Constellation	U.K.
Iridium Communications Inc.	LEO	Communication	Constellation	U.S.A.
OneWeb (former employee, speaking in personal capacity)	LEO	Communication	Megaconstellation	U.K./U.S.A.
Planet Labs Inc.	LEO	Earth Observation	Constellation	U.S.A.

Table 4.3: Characteristics of Operators Connected to Interviewees

Radio Frequency

Interviewees described the RF domain as important, with desired functions of coordinating to prevent interference as well as geolocating interference when it occurs. RF information sharing was mentioned in nine of 18 interviews. Attendees were, with one exception, not RF experts but distinguished between static information often contained in public regulatory findings such as transmit and receive frequencies, bandwidth, power, encoding, packet ID information (if implemented), etc., and active, real-time information about RF emissions as distinct from what is authorized. Two interviewees distinguished other more detailed RF information that is not commonly shared but that would be helpful including polarization across transponders, channel-switching strategies, antenna parameters, and beam patterns/coverage maps from more public license information. One representative believed that RF interference was largely solved at GEO through better industry coordination, and not yet a huge issue in LEO. Another agreed that LEO RF coordination was currently not a problem. An individual noted that the SDA began work to implement more automated systems for interference identification and geolocation, but determined that the wide variety of potential antenna configurations made data collection too onerous versus more manual coordination between operators when required. Further fidelity would improve both of these functions, but a basic level of interference prevention and geolocation of interference sources is possible with public RF information.

Functions	Information Inputs
Interference prevention	• Public info (tx and rx frequencies, bandwidth, power, encoding, packet ID) • [Active real time information] • [Detailed RF information (e.g. transponder polarization, channel switching strategies, antenna parameters, beam patters/coverage maps)]
Interference geolocation	• Public info (tx and rx frequencies, bandwidth, power, encoding, packet ID) • [Active real time information] • [Detailed RF information (transponder polarization, channel switching strategies, antenna parameters, beam patters/coverage maps)]

Table 4.4: RF Domain Functions and Information Inputs (bracketed information is useful but not obligatory)

Safety of Flight/On-Orbit Collision Avoidance

Safety of flight came up in essentially every interview, and was the domain more closely tied to both SSA and STM for interviewees. Key functions include conjunction screening, conjunction assessment, collision-avoidance maneuver generation, and coordination/execution. Conjunction assessment requires ephemeris data, with co-variance being helpful to inform miss-distance calculations. Naturally, timely, standardized, and verified owner/operator ephemeris data are superior to that gathered by third parties through non-cooperative measurements. One interviewee noted that covariance information was more important for smaller objects, but that the interviewee's organization tended to consider miss distances a more helpful metric for larger and generally better characterized objects. Two interviewees noted that covariance information was hampered by a lack of standardization in the mechanisms used to calculate it and potentially limited realism under certain circumstances.

Conjunction assessment requires the same information as conjunction screening, but can be additionally augmented by size, mass, attitude, and maneuverability/health for additional fidelity. One operator described using the historical magnitude of station-keeping by secondary objects to inform worse case risk and necessary collision avoidance maneuver magnitude when it was unable to make contact with the operators of the secondary object. One interviewee noted that size, mass, and attitude information is really only needed by whichever entity is tasked with propagating orbits, and that the contribution of attitude information for collision avoidance was an unnecessary level of precision whose usefulness was swamped by other forms of error. Mass may be useful for severity calculation as an input to risk assessment.

Collision-avoidance maneuver and coordination/execution can be improved by the explicit exchange of maneuver plans in addition to the planned ephemeris data, which requires contact information for flight dynamics teams at the second operator if coordination is to occur. Maneuverability and health information helps inform if and how each spacecraft should maneuver. One operator described coordination with another operator in overlapping orbits, whereby thruster position constraints prevented its satellites from conducting retrograde burns without imposing a service outage, and prograde burns were limited by the size of their satellite control box and a need for atmospheric drag to return them to their nominal orbit (during a time of a low solar minimum). Exchange of satellite health and maneuverability information allowed the other operator, who had fewer operational constraints, to conduct collision avoidance between the two companies satellites' until a design update in subsequent satellites allowed the first operator to mitigate the original maneuver constraint. Several operator interviewees treated ephemeris data as essentially equivalent to maneuver plans for their purposes and expressed confidence in their ability to operationally infer maneuvers from ephemeris data. While coordination is critical for satellite-on-satellite conjunctions, one interviewee stressed that collision risk is a relatively small component of overall mission risk, that the threat to missions from trackable objects (approx. 4% of collision risk) is swamped by LNT objects (approx. 96%), and that satellite-on-satellite conjunctions are a small portion of overall collision risk (approx. 10% of trackable risk, or 0.4% of overall collision risk).

Functions	**Information Inputs**
Conjunction screening	• Ephemeris • [Covariance]
Conjunction assessment	• Ephemeris • [Covariance] • [Size, mass, attitude] • [Maneuverability/health]
Collision avoidance maneuver generation	• Ephemeris • [Maneuver plans] • [Covariance] • [Maneuverability/health]
Coordination/maneuver execution	• Ephemeris • Maneuver plans • Operator contact information • [Maneuverability/health]

Table 4.5: Safety of Flight/On-Orbit Collision Avoidance Domain Functions and Information Inputs (bracketed information is useful but not obligatory)

Launch and Re-entry (including deployment information)

Launch and re-entry was mentioned in five interviews (although one interviewee said it should be separate from an STM system, in part to mirror the American jurisdictional split between the FAA and the FCC/DoC). While many of these functions involve physical collision avoidance, this domain is broken out to distinguish it from collision avoidance during nominal orbital operations. Key functions during ascent include collision avoidance during ascent (requiring ephemeris information), integration with the national airspace (which is complicated and was not addressed in detail by interviewees, but might include information such as ephemeris data, break-up modeling, and reliability assessments of launch vehicles), and identification of small-satellite payloads when many payloads are deployed from a single rocket. Key information to be shared include ephemeris data and payload manifests/deployment plans. During re-entry, the key function is collision avoidance with other satellites, air vehicles, and those on the ground. Information needs include ephemeris data, disposal strategies (controlled or uncontrolled), and potentially casualty risk.

Space Weather

Space weather was mentioned in four interviews. Potential functions include in-situ measurements of atmospheric drag experienced (to enable scientific research and better orbit propagation), which would require ephemeris data and inferred drag measurements (or parameters to enable calculation of inferred drag measurements), as well as space weather warnings, which would require operator contact information and potentially susceptibility information regarding how robust or vulnerable a satellite is to space weather (to enable relevant warnings). Anomaly sharing, including relating to space weather events is considered separately. Space weather was not considered a major issue for commercial operators or something operators were particularly interested in being featured in a potential STM system.

Near-Earth Objects

No interviewee had significant comments regarding NEOs or described desired functions for an SSA/STM system relating to NEOs.

Laser Emissions

Laser deconfliction was mentioned in three interviews with non-operator experts. Each acknowledged laser coordination as a necessary area, but did not consider it to currently be

Functions	**Information Inputs**
Collision avoidance during ascent	• Ephemeris
Integration with national airspace	• Ephemeris • [Break-up modeling] • [Reliability assessments of launch vehicles]
Identification of small-satellite payloads	• Ephemeris • Payload manifests • Deployment plans
Re-entry collision avoidance	• Ephemeris • Disposal strategies • [Casualty risk]

Table 4.6: Launch and Re-entry (including deployment information) Domain Functions and Information Inputs (bracketed information is useful but not obligatory)

Functions	Information Inputs
In-situ atmospheric density measurement	• Ephemeris • Inferred drag
Space weather warning	• Operator contact information • [Spacecraft susceptibility information]

Table 4.7: Space Weather Domain Functions and Information Inputs (bracketed information is useful but not obligatory)

Functions	Information Inputs
Laser deconfliction	• Ephemeris • Laser information • [Satellite susceptibility information]

Table 4.8: Laser Emissions Domain Functions and Information Inputs
Laser Emissions Domain Functions and Information Inputs (bracketed information is useful but not obligatory)

a major concern for operators. No operator mentioned laser emissions. Potential functions include sharing of satellite ephemeris data (to identify when a satellite would be in the field of view of a planned laser emissions), information about the laser and emission, and susceptibility information or maximum parameters for the laser emission that will not harm a particular satellite. While laser emission information was not described in detail during the interviews, an example of such information enumerated to an operational level of detail can be found at the Laser Clearinghouse on space-track.org [78].

Cyber and Other Threat Information Sharing

Threat information sharing was mentioned by one operator, as well as by the representative of Space ISAC (which focuses on the sharing of threat information). Potential information to be shared includes descriptions of threats, incidents, and vulnerabilities as well as alerts, recommendations, and standards to enable other operators to:

1. Be aware of potential threats; and
2. Develop and implement best practices to improve system security

Functions	**Information Inputs**
Increase awareness of threats	• Threats • Alerts • Incidents • Vulnerability information
Develop and share best practices	• Threats • Alerts • Incidents • Vulnerability information • Recommendations • Standards

Table 4.9: Cyber and Other Threat Information Sharing Domain Functions and Information Inputs

Anomaly Sharing

Anomaly sharing was mentioned by four interviewees. Potential functions include:

- Validating environmental models (particularly non-trackable debris flux models) and satellite vulnerability models,
- Enhancing mission assurance;

- Facilitating the development of space capabilities by emerging space actors in a faster and safer manner (since they do not need to experience failures themselves to learn from them;
- Speeding up, reducing cost, and improving accuracy of root cause attribution investigations; and
- Reducing ambiguities during geo-political tensions.

Information requirements are similar across these five categories and include an unambiguous timeline of events, lowest possible component attribution, clear trigger/failure root cause, and details regarding the investigation process methodology and cause/effect analysis.

One operator expressed significant skepticism regarding the usefulness of shared anomaly information for operators. The representative saw three potential benefits from anomaly sharing (using a different grouping than proposed in this section):

1. Competitive intelligence;
2. Operational safety (coordinating in response to a specific safety issue induced by an anomaly, e.g. a satellite drifting out of its assigned GEO slot); and
3. Industry-wide education to reduce orbital failures and improve resiliency.

That representative noted that competitive intelligence is a possible, but undesirable use of such information. While operational safety is an important use, it requires only limited and targeted sharing of information. That representative also claimed that the industry-wide benefit from anomaly sharing is too diffuse and long-term to motivate most operators and accrues primarily to others, not the sharing entity. Any sharing sufficient to achieve this third aim, the representative argued, would all but ensure identifiability. Less-sensitive aggregated information would not be useful.

4.5.2 Concerns

This section describes concerns identified by interviewees with the categories of data identified in Subsection 4.5.1. In some cases, topics were not discussed in sufficient numbers of interviews or interviewee opinions did not identify specific concerns. In these instances, I have tried to extrapolate potential concerns based on the comments made in interviews and contained in the literature, and marked these with an asterisk (*).

Functions	**Information Inputs**
Validate environmental and vulnerability models	• Unambiguous timeline of events • Lowest possible component attribution • Clear trigger/failure root cause • Details regarding investigation process methodology and cause/effect analysis
Enhance mission assurance	• Same as above
Enable emerging actors to develop space capabilities faster/safer	• Same as above
Speed up, reduce cost, and increase accuracy of root cause attribution	• Same as above
Reduce ambiguities during geo-political tensions	• Same as above

Table 4.10: Anomaly Sharing Domain Functions and Information Inputs

Radio Frequency

No operator considered information already disclosed in public regulatory filings to be sensitive. A communications operator noted that more detailed RF information would be considered confidential as it is the product of a considerable amount of engineering work and sharing it could provide another company with a commercial advantage.

Another remote sensing operator noted that real time emissions information could be used to infer data priority by monitoring downlinks, and that the location of ground stations is potentially commercial sensitive as an indicator of business strategy. That operator also noted that if a company had a client with a direct downlink site, sometimes those clients might object to disclosure of the fact they were downlinking data for their own business strategy or security reasons.

Information Inputs	**Concerns**
• Public info (tx and rx frequencies, bandwidth, power, encoding, packet ID)	• None
• Active real time information	• Infer data priority, reveal customers or information about customers
• Detailed RF information (e.g. transponder polarization, channel switching strategies, antenna parameters, beam patters/coverage maps)	• Reveal company's engineering practices and/or business strategy

Table 4.11: RF Domain Concerns

Safety of Flight/Collision Avoidance

Ephemeris Data Most interviewed individuals described a shift over time to considering ephemeris data to be either minimally sensitive or non-sensitive for sharing. Several interviewees described generalized concerns about using spacecraft ephemeris data or maneuver information to infer system capabilities (e.g. propulsion, maneuverability, attitude control precision/accuracy), properties (e.g. size, mass), operational plans and remaining fuel, or reverse engineering proprietary geostationary station-keeping strategies, but none indicated that these concerns were a major issue from their perspective (although some thought others would feel that these were). One operator noted that ephemeris data could be used to infer satellite health, which could be of concern to an operator of a mega-constellation by disclosing what portion of their satellites were dead on deployment.

One non-operator relayed a story regarding an operator who was reluctant to share high-quality ephemeris data out of a fear that such information could be used to target their spacecraft for deliberate physical interference. However, the interviewed representative considered this concern to be technically unfounded and noted that the operator eventually agreed to share data in another format with arguably lower fidelity. One operator described a reluctance to share information about the position of geosynchronous spacecraft due to non-cooperative close approaches by state-operated spacecraft. Another individual described the opposite approach whereby an operator uncomfortable with close approaches by state-operated spacecraft shared its ephemeris information with that state in the form of a letter with a request to encourage that state to avoid collisions with its spacecraft.

One operator described a reluctance to publicly share ephemeris data due to its inclusion as part of several products sold to other businesses, as well as additional value-added verification that goes into packaging ephemeris data as a product for those users. That operator also noted that publication of ephemeris data without restrictions could potentially give other operators more lead time to file complaints with the FCC regarding large maneuvers. However, that operator commented that neither of these concerns was an absolute, and that if it did not require significant engineering effort to publicly share ephemeris data and if there were a good reason to do so versus sharing with only other operators, it would probably do so.

Covariance One interviewees noted that covariance data was of minimal value because calculation approaches have not been standardized and it can be hard to know if the value provided by another entity is realistic. One operator noted that releasing information about covariance calculation methods can potentially reveal the capabilities of in-house flight dynamics software, or parameters of a satellite restricted from dissemination by the satellite's manufacturer due to competitiveness concerns.

Maneuver Plans Multiple interviewees described maneuver plan sharing practices as inconsistent across operators, but noted that maneuvers could be inferred from predictive ephemeris files. No operator indicated that it considered maneuver plans to be of increased sensitivity as compared to predictive ephemeris data.

Operator Contact Information No operator considered contact information to be particularly sensitive. Several individuals noted that the major challenge was keeping information up to date. One operator noted a distinction between sharing information widely with other operators and publicly. That operator worried that publication might result in saturation of a critical phone line for an ops floor, either inadvertently by members of the public (seeking technical support, etc.) or maliciously by rogue actors. The individual did not have similar concerns for email or other communication mechanisms.

Spacecraft Health and Maneuverability Two operators noted that companies tend to be reluctant to make failures public immediately due to a potential impact on stock prices or customer perspectives, and expressed a preference to announce failures at a next shareholder meeting. One of these operators stressed that it would still share information with other operators upon request for collision avoidance purposes. Only a limited number of later interviewees were specifically prompted with a question about maneuverability, but none of those operators objected to either sharing a boolean true/false for maneuverability, or capability relative to a certain threshold displacement per unit time. One operator noted that for high interest conjunctions they frequently need to confirm health and maneuverability with the other party due to uneven operator update cadences on space-track.org, but that operators are forthcoming when asked for safety of flight applications.

Spacecraft Size and Mass No operator expressed concern about sharing spacecraft mass or general size, but one interviewee thought others in the industry might.

Attitude Multiple remote sensing operators noted that they considered attitude data sensitive because it could be used to recover information about tasking of satellite sensors. No non-remote sensing operator considered attitude information to be particularly sensitive, but several interviewees did note that they did not use attitude information for other spacecraft as part of their conjunction screening or assessment calculations, particularly at an initial screening stage.

Information Inputs	Concerns
• Ephemeris	• Infer system capabilities/properties, remaining fuel/operational plans, station-keeping, harassment by states/actors, sold as product, state-actor threat
• Covariance	• Covariance methodology may reveal internal systems, manufacturer's proprietary bus information
• Maneuver plans	• None beyond concerns shared regarding ephemeris data sharing
• Operator contact information	• Public saturation of critical contact lines (either accidental or malicious) • None for non-public sharing
• Spacecraft health	• Impact on stock prices if published, reduced customer confidence
• Maneuverability	• None specified for binary of maneuverability, or maneuverability relative to some threshold displacement per time value
• Size, mass	• None for approximate figures • More specific values may be sensitive
• Attitude	• Can infer tasking for imaging and potentially other remote sensing operators

Table 4.12: Safety of Flight/Physical Collision Domain Concerns

Launch and Re-entry (including deployment information)

No operator expressed concerns about the sharing of launch ephemeris data. Launcher size information is generally public. However, one interviewee noted that the probabilities of collision during ascent are so low that the calculations are not done for many commercial launches, and that launch collision avoidance is much less of an issue than airspace coordination. Integration into the national airspace was not discussed in depth in any interviews, but potential dynamic keep-out windows are designed based on potential debris dispersion in case of an accident.

Multiple interviewees who shared LEO orbits where many smallsats have been deployed expressed a concern about the identification of small satellites following deployment. No smallsat operators indicated that they would consider the sharing of deployment information to be sensitive.

Re-entry information sharing with a regulator was not considered sensitive, but in a few interviews where re-entry was discussed in more detail, operators felt there was not much benefit to any public disclosures beyond what is already required for licensing.

Space Weather

Because space-weather-induced anomalies have considerations similar to other anomalies, this aspect of the topic is considered under anomaly sharing rather than in this section. One non-operator interviewee indicated that from their experience, operators (who, unlike some NASA or DoD satellites, do not have exquisite scientific instruments on-board) would ignore space weather alerts, and would be unlikely to wish to share space weather vulnerability information. Only a limited number of interviewees addressed the in-situ measurement function, but no interviewee thought that operators would be particularly motivated to invest the effort to contribute to in-situ sensing and sharing of atmospheric density information. Certain aspects of ephemeris data sensitivity may be lessened if the density measurement work is conducted in a time-lagged way that does not require current ephemeris data. It also may depend on whether data are made public, or used as an input into research to help calibrate a model and only shared with a particular researcher or set of researchers with specific terms of use.

Near-Earth Objects

No interviewee indicated any concerns about sharing NEO data or addressed the topic at any length beyond acknowledging it.

Information Inputs	**Concerns**
• Launch ephemeris	• None
• Break-up modeling	• Not discussed. Potential proprietary system details, limited need to know other than regulator/air traffic control*
• Reliability assessments of launch vehicles	• Not discussed. Potential embarrassment/reluctant to disclose true estimate of own reliability. Limited need to know other than regulator/air traffic control*
• Payload manifests	• None
• Deployment plans	• None
• Disposal strategies	• None. Not discussed in most interviews.*
• Casualty risk	• Limited need to know other than regulator • Potential proprietary system design details revealed by re-entry modeling • Potential backlash if taken out of context by public

Table 4.13: Launch and Re-entry (including deployment information) Concerns (* = extrapolation)

Information inputs	Concerns
• In-situ atmospheric density measurement	• Same low-level concerns as ephemeris sharing, potentially less given that information is not required in real-time*
• Space weather warning	• Contact information is not particularly sensitive. • Operators unlikely to want to share susceptibility information given limited perceived benefits from the project

Table 4.14: Space Weather Concerns (* = extrapolation)

Laser Emissions

Three interviewees noted that there was no need to share susceptibility/vulnerability information, as general deconfliction through the 18SPCS Laser Clearinghouse is adequate for current laser activity. Two noted that there might be more concern in the future if the amount of laser activity increases.

Information Inputs	Concerns
• Ephemeris	• Same low-level concerns as ephemeris data sharing. Also dependent on who shared with.*
• Laser information	• Not explored. Sharing is currently limited to U.S. government/18SPCS, so presumably limited.*
• Satellite susceptibility information	• General reluctance to share vulnerability information and no clear need.

Table 4.15: Laser Emission Concerns (* = extrapolation)

Cyber and Other Threat Information Sharing

Only one operator discussed cyber sharing and did so more as a desired capability rather than as a described sharing plan. Space ISAC indicated that members generally do not wish to be identified when sharing information and they control both the shared information and dissemination list to ensure non-attribution. Because cyber and threat sharing is a newer domain and active sharing through Space ISAC has not yet begun, most comments from interviewees primarily discussed information sharing as something desirable, but not yet implemented. The concerns listed in this table are all extrapolations.

Anomaly Sharing

One non-operator expert noted that the lack of existing operator sharing (other than very controlled sharing with space insurers and bus manufacturers) made operators less forthcoming for the time being, due to concerns similar to those around disclosing satellite failures. These include the attribution of non-resolved technical anomalies or operational errors reflecting poorly on the competency/reliability of the company, impact on either stock prices or customer demand/confidence, and associated disclosure of technical or process information in a way that might reveal proprietary information or confer a business advantage on a competitor. One operator described sharing non-fatal impact data with a government agency under non-attribution terms for a combination of these reasons. Another operator argued that the lack of direct benefit to operators drove generalized opposition to sharing. That operator representative distinguished between SSA sharing, where benefit primarily accrued to the sharing operator by reducing that operator's collision risk, and anomaly sharing, where the primary beneficiary is others.

4.5.3 Protection Mechanisms

Various mechanisms exist to address operator concerns, such as those above. This section talks about several general mechanisms and some of their benefits and disadvantages. This section presents original analysis rather than explicitly reporting outcomes of the interviews, but is informed by commonalities and trends identified in the sharing instances and perceptions shared by interviewees.

Norms

Even if operators have concerns about sharing information, industry norms of behavior may be sufficient to persuade them that sharing is acceptable and that self-interested norms com-

Information Inputs	**Concerns**
• Threats	• May inform threat actor behaviors, cause change in tactics, reveal methods or sources*
• Alerts	• May inform threat actor behaviors, cause change in tactics, reveal methods or sources*
• Incidents	• May inform threat actor behaviors, cause change in tactics, reveal methods or sources, cause additional targeting of the targeted entity or similar entities, adverse customer reaction, legal liability*
• Vulnerability information	• May encourage exploitation of vulnerability, other similar vulnerabilities*
• Recommendations	• May inform threat actor behaviors, cause change in tactics, highlight vulnerabilities*
• Standards	• Least likely to be sensitive. Potential for exploitation of gaps or transition time to new standards by threat actors*

Table 4.16: Cyber and Threat Information Sharing Concerns (* = extrapolation)

Information Inputs	Concerns
• Unambiguous timeline of events	• Financial risk from adverse stockholder reaction • Time-consuming to conduct investigation and to share results • Public investigation result increases anomaly publicity • Sharing investigation results or process will disclose proprietary information about the satellite or company business or security vulnerabilities. • Legal or export control controls associated with information sharing • Perception of lack of need for investigation or disclosure if a workaround is found • Culture discourages sharing • Attribution published is wrong and results in harm to reputation for company or third parties • Liability risk from admitting findings or from third-parties impacted by root cause attribution or errors • Reputational risk to company from anomaly
• Lowest possible component attribution	• Same as above
• Clear trigger/failure root cause	• Same as above
• Details regarding investigation process methodology and cause/effect analysis	• Same as above

Table 4.17: Anomaly Sharing Concerns (* = extrapolation)

pliance will keep other actors from misusing the information. For instance, while operators might have concerns about congestion of phone contact lines for their operations floor, industry norms (as well as self-interest) keep operators from misusing that information. Multiple interviewees mentioned the importance of norms for information sharing in both more established areas such as ephemeris data and in newer domains like anomaly sharing. Norms seem to be particularly helpful when there are potential minor or hypothetical harms from sharing of data that cannot be readily addressed through other means and violations of norms are clearly identifiable. Norms may be easier to develop among groups that perceive a shared identity and have a longer period of time to gradually develop them. Norms also tend to be more flexible than some of these other mechanisms and may provide a better vehicle for the gradual evolution of behaviors as entities become more comfortable with sharing.

Legal Protections

The force of the law can help make operators more comfortable sharing information. This can take the form of either protections in law that authorize something, indemnify an operator, or prohibit a behavior through legally enforceable contracts. The Space ISAC relies on legal restrictions on sharing of information present in federal law. The SDA has a binding and enforceable contract to prevent misuse of shared ephemeris information. The important aspect for legal protections is having clear standards which are enforceable and provide a credible mechanism to address potential breaches. Developing legal norms can impose a barrier to entry, especially if done on a peer-to-peer basis rather than through shared participation in a trusted third-party body with a common agreement. Depending on the nationalities and natures of the entities involved, legal methods may be more or less enforceable. If harms from misuse are significant enough (both in likelihood and consequence) to raise major concerns for operators, legal mechanisms may be inadequate if misuse cannot be readily detected by other parties. Legal protection mechanisms may work less well if cooperation involves multiple entities that do not share a common supervising legal entity that both submit to, or involves cooperation between companies and states (especially if those states lack independent judiciaries or block use of the country's own legal system to compel corrective action by the government).

Trusted Third Party

The use of a mutually trusted third party is a special form of access control, worth specific mention due to its widespread use. The use of a trusted third party helps reduce the number of entities with which sensitive information needs to be shared under nominal conditions, potentially better aligns incentives between the sharer and the receiver of the information, has the potential for the development of specialized knowledge and value-added capabilities as well as network effects, and the ability to redistribute information on a need-to-know or desensitized basis. The SDA uses a trusted-third-party model that provides some information like contact information freely, but only shares ephemeris data when operators have a demonstrable need to know. A trusted third-party structure requires there to exist a party that is mutually acceptable to all participating entities, and with adequate capability and funding to support sharing. These criteria can be challenging under some circumstances.

Data Desensitization/Anonymization

In some cases data can be made non-sensitive or less sensitive through the redaction of certain information. Space ISAC members will be responsible for applying any redaction they consider necessary before sharing information through the planned electronic portal, such as removing information that would allow the identification of the submitting company. The cost of data desensitization is that it can make the information less useful for other parties with whom it is shared. For instance, it might be more helpful to know if a particular model of gyroscope experiences a particularly high failure rate rather than just that multiple gyroscopes have experienced a failure recently, because it allows an operator to check if their satellites use that particular part. Desensitized sharing can also be difficult to do without the aid of a trusted third party if the identity of the sharing company or entity is a sensitive piece of information that needs to be protected.

Technical Protection Methods (access controls, cryptographic techniques)

Various technical protection methods can provide addition safeguards. These include access controls that restrict who can see certain data or the circumstances under which they can see them. For instance, as mentioned previously, the SDA only allows members to view each others' ephemeris data when a conjunction has been detected. One additional form of access control that offers theoretical potential but was not mentioned in any of the interviews is the strategic assignment of responsibilities to the more sensitive entity in cases where one entity is willing to share information and the other is not. As long as both entities trust the ability of the more sensitive entity to carry about a function, e.g. a collision avoidance maneuver, this can help mitigate some instances with issues about data-sharing sensitivity. This is explored at a conceptual level by the NASA Ames team [109].

Cryptographic techniques can provide additional security or flexibility in sharing architectures. For instance, secure multiparty computation could be used to identify conjunctions without operators sharing their ephemeris data directly with each other, while still avoiding the need to identify a trusted third party [60]. Differential privacy provides a framework to allow richer analysis of a database containing sensitive information about particular companies or satellites, while still providing rigorous protections against disclosure of information about individual entities [54]. If the host of a database is not trusted by entities querying the database, private information retrieval protocols could be used to prevent the database operator from being able to tell what information was retrieved [54]. Across the interviews, there was less enthusiasm for these methods than I had originally expected. The engineers at companies working on most of the problems considered in this chapter generally do not have extensive training in cryptography, making the solutions somewhat unfamiliar. They also seem generally happy to trust a professionally run third party with access to their semi-sensitive information. Where information is particularly sensitive, such as in the anomaly or threat sharing cases, there seems to be much more comfort with sanitized sharing, even at the cost of some potential utility, over the more complex and difficult to implement, but theoretically more useful possibility presented by something like a differential-privacy-based approach.

4.6 Discussion

This section seeks to integrate the concerns raised in the record, as well as the interviews conducted as part of this study, and identify what kinds of sharing structures could support the functions identified in each domain while addressing operator concerns.

4.6.1 Radio Frequency

Basic RF information already disclosed in regulatory filing is not particularly sensitive to any operator, but there are challenges to standardizing and sharing information in ways useful for geolocation and interference detection. Efforts to implement Carrier ID will also be helpful. More extensive and more detailed RF information sharing, including real time emissions information sharing, may be helpful in the future, but no operator felt that sharing such information currently would produce enough of a benefit to deal with the technical challenges or potential proprietary issues. Detailed RF information is highly proprietary for many operators, particularly communications operators. If operators judge that the benefits would justify the creation of more automated systems for more extensive sharing,

Protection Mechanism	**Benefits**	**Disadvantages**
Norms	• Powerful • Least burdensome • Can evolve more naturally than more formal mechanisms	• Hard to develop • Culture and group specific • Does not directly prevent misuse
Legal protections	• Strong enforceability if certain conditions hold • Can be clear and unambiguous if properly drafted • Can be low-friction if standard language is already drafted	• Enforceability depends on participants • May be less suited to instances where detection of misuse of information is hard • Can be high friction if a new agreement must be drafted, or if agreements drafted on a bilateral basis
Trusted third party	• Can add value without downsides of full sharing of data • Off-loads some administrative/technical burden of data sharing • Has neutral third-party arbiter to assist with disputes	• Need party trusted by all • Excludes sharing with those outside the protected sharing environment
Data desensitization or anonymization	• Increases confidence and reduces risk for sharing organization • Potentially allows public or broader sharing	• May reduce value/utility of shared data • Challenging to disclose data while avoiding attribution without trusted third-party or cryptographic methods
Technical protection methods (access controls, cryptographic techniques)	• Increases confidence and reduces risk for sharing organization, especially if data must be shared with untrusted parties • Potentially allows public or broader sharing	• Costly and complex to implement technical protection mechanisms for sharing • Solutions may be fairly domain specific

Table 4.18: Summary of Benefits and Disadvantages of Various Protection Mechanisms

a trusted protected environment like the SDA is a natural vehicle to accommodate that sharing.

4.6.2 Safety of Flight/Collision Avoidance

In this domain, interviews provided significant additional detail and insight, largely consistent with the FCC record but with more information on why operators consider particular types of data sharing to be sensitive or not.

Four necessary functions were identified: conjunction screening, conjunction assessment, collision-avoidance maneuver generation, and maneuver coordination and execution.

Ephemeris sharing to enable these functions is critical, but also an area where operator attitudes towards sharing have evolved to be at least somewhat permissive. Nonetheless, there appear to be some inhomogeneities in operator attitudes towards ephemeris sharing depending on company with some being willing to publish ephemeris (often in addition to sharing through more restricted settings such as the SDA or space-track.org), while others are only willing to publish in those settings. Both forms of sharing add value for different reasons. Among operators who preferred sharing only in a restricted setting, there was a perception that the benefits from publication would be minimal. The distinction in stance generally does not seem to be a result of orbital regime or business, but rather a function of individual attitudes and company culture. Several concerns were raised regarding public sharing, but none of the companies interviewed raised particularly strong objections. Two companies did note the selling of ephemeris data as part of a value-added product as a reason to avoid publication, but both noted (one explicitly and one implicitly) that safety of flight outweighs any proprietary interest and that they would publish their ephemeris data if there were a clear way it would improve orbital safety over more restricted sharing.

Some comments in the record distinguished between maneuver plans and ephemeris data, but in my interviews, operators with spacecraft propulsion noted that maneuvers could be inferred from ephemeris data and did not distinguish between their perceptions of the sensitivity of the two pieces of information.

While ephemeris and even covariance data (although not methodology) do not seem to be particular sensitive, several fields were identified that allow for higher fidelity operations that are sensitive to at least some users. These include attitude, maneuverability, and health information. Existing practice seems to already involve exchanging some of these parameters in response to a particular high-interest event, which means data sharing is less frequent and generally needs to be only bilateral rather than system-wide (at least until a final mitigation plan is devised). At the same time, some of the sensitivities around use, particularly for attitude and Boolean characteristic information (operative/non-operative) or other health data, make it unlikely that such information could be published even while companies are increasingly willing to publish ephemeris data. One operator noted that those in the SSA community frequently ask for all possible information about spacecraft for use in their analysis, even when it is potentially sensitive and offers minimal additional benefit. That representative expressed a hope that the community would come to a better consensus on what information was actually useful and focus effort on providing that at the highest levels of accuracy, chiefly ephemeris data, covariance, and contact information.

From an architecture design perspective, restricted sharing with a trusted third party or third parties to perform conjunction screening seems to be adequate to address operator needs and concerns while still enabling conjunction screening. There are strong network effects, and the consolidation of screening within a single or limited number of such organizations enhances the efficacy of screening for all, while minimizing technical burden associated with developing and maintaining data interfaces and validating and standardizing data formats. Nonetheless, vesting all these functions in a single organization is likely unrealistic in the short to medium term, and maybe ever. Having more entities with incomplete access to high fidelity data means screening by each will be based on a less unified operational picture and the accuracy of screening will decrease as certain entities without access to data from certain operators will need to fall back on less accurate information. For this reason, public sharing of such data has value in a fragmented conjunction screening environment, but operationally ingesting, validating, and standardizing such data poses significant challenges. Cryptographic techniques may be helpful, but there is low familiarity with the underlying technologies among flight dynamics engineers at the companies interviewed, and a general attitude that the current system of a trusted third party works sufficiently well that no interviewee seemed particularly interested in exploring alternatives.

There is no indication that any operators object to sharing of ephemeris data for safety of flight purposes, or have refused a request for ephemeris data with a legitimate need to know or been refused in making such a request (after successfully making contact). There are significant challenges associated with contacting other operators, especially the interviewed operators trying to contact those from Russia and China.

There is insufficient data from interviews to determine if operators would be willing to publicly share mass, size, or covariance information, although one may tentatively conclude the answer is yes if enough operators begin to use such information operationally to decide such sharing adds value. From interviews to date, this level of additional fidelity is sometimes used in semi-manual processes for assessment of high-risk conjunctions, but generally not as part of initial screenings. Accordingly, this function would be compatible with either ingestion into a trusted third party's system for use in initial screening, or with sharing among operators only during coordination for a particularized high-interest event. Neither of these is likely to raise significant concern among operators, although further technical work will be necessary to achieve broader standardization of covariance methodologies. The precise description of such methodologies during exchanges may raise more objections than simply a mutual assurance that both operators are following a particular standard or standards. The level of fidelity of both mass and size information that is operationally useful and that operators would be willing to share is a topic that deserves further investigation. In practice, it is likely that order-of-magnitude information about mass would be adequate as an input into risk calculations during initial conjunction screening or even during conjunction assessment. Hard-body radius information is useful as a lowest level of fidelity, especially in an initial screening stage, but a bounding prism of satellite hard-body area combined with attitude could allow higher-fidelity calculations. While remote sensing operators objected to publication of attitude information, sharing in a restricted setting upon an actual event requiring coordination would likely be acceptable. Significant improvements in state knowledge and error reduction may be necessary before some of this information is no longer dominated by other sources of error. Information about spacecraft operational status and maneuverability is not sensitive for some operators, typically those who have a large number of low-value small satellites that they replace on a regular basis. For operators with a few satellites, especially large, high-value satellites, disclosing information about operational or maneuverability failures is much more of a significant issue with potential impact on customer confidence and stock prices. Disclosures in a protected structure upon an actual conjunction requiring assessment and coordination is likely to be acceptable. Alternatively, such disclosures could happen from operators to the trusted third-party system, to determine if coordination is necessary (if both could move). If the architecture were to assign maneuver responsibility, it could potentially assign maneuver responsibility to the maneuverable spacecraft without revealing the status of the other craft (and the first operator would not know if this was because of limited maneuverability, operational constraints, generalized equity concerns, a system failure, or random chance).

The sharing of contact information is necessary to facilitate maneuver coordination, and in practice maneuver assessment and avoidance maneuver generation are likely to occur iteratively as part of the coordination process. No operator indicated an objection to sharing contact information with other operators, although maintaining updated contact information, especially in centralized directories, was described as a challenge with varying levels of conscientiousness across operators. One operator did note a desire to restrict sharing of the most critical contact information, phone numbers for its ops floor, from the public. A trusted third-party sharing environment, or even a more generalized phone number that would allow company administrative staff to provide the flight floor contact information upon a credible request, would address this concern. There are again significant network effects from the gathering of updated information on a per-object basis in a standardized format in a central repository as compared to operators posting such information on their own websites in different locations/formats that require manual investigation during a conjunction.

As the frequency of conjunctions requiring collision-avoidance maneuvers increases, future STM architectures will need to enable the above steps in a more automated manner. This poses technical challenges, but as long as coordination happens through existing trusted third parties (ideally with a combination of legal and technical protection mechanisms), there do not appear to be any significant unresolvable impediments.

4.6.3 Launch and Re-entry

No operator interviewed, or company in the record, indicated that launch ephemeris data is sensitive. This should be confirmed in future work through discussions with launch operators. Integration with air traffic is a significant technical challenge, and one that potentially involves significant sensitive data and analysis. However, the functions that require these data result in fairly non-sensitive outputs. Given the centralized nature of national regulators and air traffic control system administration, there would likely be little need to share sensitive data with other air space users or the public and that sharing with governments and air space control system administrators is unlikely to produce concerns. This could be further verified by discussions with launch providers, which would be much more directly involved in such conversations than satellite operators procuring launches.

No operator opposed better deployment mechanisms and sharing of deployment plans. Several across the FCC comments and these interviews noted problems with delayed or difficult identification to the extent that it was impacting their operations. Nevertheless, there are open questions about the preferred means to facilitate more rapid identification and the responsibilities of launch aggregators and launch providers. Best practices have not yet solidified around the coupled questions of deployment and identification technologies and procedures. An interview with a representative from the FAA/AST highlighted that they are aware of the issue, but looking for industry to further develop best practices prior to acting [88]. A launch provider commenting in the FCC record seemed open to sharing deployment information and conducting conjunction screening for deployment plans, but this should be confirmed in future work by interviews with additional launch aggregators and providers. This is an area where there is a data sharing, standardization, and practices problem, but one that does not seem to involve much of a data-sharing sensitivity constraint.

4.6.4 Space Weather

There was limited appetite for the development of any functions relating to space weather. While commercial spacecraft could potentially feed into work to measure atmospheric drag using satellites as in-situ sensors, the benefits of improved atmospheric models seem too indirect to motivate operators. Operators perceive a minimal enough benefit from additional space-weather-warning infrastructure, especially more automated infrastructure, to motivate work to develop system interfaces or share susceptibility information. This was surprising, given the numerous mentions of space weather information as part of architectures considered in Chapter 2.

4.6.5 Near-Earth Objects

No operator had comments on any functions regarding NEOs. While the topic was mentioned by several experts, the inclusion of NEOs in the term STM is more a philosophical construct than something that has any bearing on these questions.

4.6.6 Laser Emissions

Operators did not seem to feel that there were any pain points with existing laser emissions. In the future, if laser emissions become much more widespread and if satellite optic susceptibility varies significantly, setting per-object susceptibility limits rather than a single overall limit may make sense. No operators or the FCC's docket (for obvious jurisdictional reasons, as well as a lack of practical need) were particularly interested.

4.6.7 Cyber and Other Threat Information Sharing

This is a particularly interesting and challenging topic. Companies gain from understanding each other's and the government's experience with threats, vulnerabilities, and incidents as well as alerts and sets of developed recommendations and standards. At the same time, there are many significant pitfalls if an operator's vulnerabilities or incidents are identified. Publication of threat information may reveal methods or sources, and change the behaviors of threat actors. A company might be embarrassed by being named in an incident or vulnerability report. It might face exploitation of those vulnerabilities, suffer reputational and financial harm or potentially liability, and see further targeting of a company's infrastructure.

The Space ISAC model relies on dissemination scoping and desensitization by the threat submitter in addition to legal and technical protections. This greater level of control could potentially make companies more willing to share information that if compromised has potentially much greater downsides than safety-of-flight information. These more significant downsides may also explain why the organization chose to rely on data distribution controls and anonymization in addition to legal protections against outside disclosure. Without further insight to shared data, it is hard to know how much potential value, if any, is lost by these access controls and data desensitization processes. Further insight into the level of both data sanitation and restriction on dissemination that occurs within Space ISAC would be instructive for future work.

Threat-sharing information is more sensitive than anomaly information because it presupposes the existence of an adversary who would learn from public disclosures in ways that reduce the utility of shared information and increase risk for both the sharer and other users. Accordingly, threat information is unlikely to ever be made public, at least at a level of operational detail. Standards and best practices, however, may be publicized when they emerge from the experiences of organizations like Space ISAC, particularly if they chose to make recommendations that become adopted by the U.S. government as best practices either recommended or mandated for members of industry.

4.6.8 Anomaly Sharing

Much of the calculus for anomaly sharing is similar to cyber and threat information sharing: there are certainly concerns about reputational risk, financial consequences, and liability (from incidents, as well as from potentially misidentifying the root cause of an error). However, there is disagreement in the community about how dire these consequences are, and if a cultural shift towards a shared safety culture, more similar to what exists for the aviation industry (which while more advanced, is still imperfect) would enable the more candid sharing of anomaly information than what currently occurs.

As a first step, one expert recommended the public sharing of anomaly information in a standardized format that lists the generic component that experienced the anomaly (e.g. phased array antenna), the satellite class (CubeSat, smallsat, larger satellite), and orbital regime (LEO, MEO, GEO) as a tool to gradually shift culture and demonstrate value while avoiding many of the above concerns. Because of the challenges associated with disclosing information anonymously, this would likely necessitate the existence of a trusted third party to accept submissions and then disseminate the database.

This generic database might be helpful, but offer less utility than the fuller sharing of a timeline, lowest possible component attribution, root cause, and investigation process data. Such information, that expert suggested, might be shared on a reciprocal basis, whereby operators would commit to providing their anomaly data to gain access to that of others. Such an approach would help build communication and cooperation towards a shared goal and vision to make data sharing between contributing entities more sustainable.

While more elaborate access structures could be put in place, mimicking either an SDA or Space ISAC model, this restricted sharing undermines many of the benefits of such data sharing in the first place. Academics and researchers can build better environmental and vulnerability models, new operators can learn from other's experiences, root cause investigations can improve, and actors can gain confidence to distinguish natural anomalies from malicious intervention. However, all of these functions are predicted on widespread access to fairly specific anomaly data by entities other than just participating operators.

Others were more skeptical about the point of anomaly sharing, the benefits that could be achieved through sharing of various levels of information, how to feasibly prevent misuse, and the basic viability of such sharing. Some saw the potential benefit of sharing, but also recognized significant associated challenges.

Overall, operator attitudes were less favorable than the documents surveyed in Subsection 4.4.3.

4.7 Conclusions

The work in this chapter has improved explicit knowledge of operator concerns about data sharing for SSA/STM and related purposes through both original data collection and systematic review of primary sources filed with U.S. regulators. The contents consider data sharing across a variety of domains more systematically and with greater specificity than prior work.

Across many of these areas, it becomes clear that information sharing is occurring, and can occur, in spite of various concerns around data sensitivity, so long as operators see a benefit from doing so. As one interviewee described it, data sharing requires truth, trust, and traceability to occur and be useful. If operators see sufficient benefit, they will likely be able to achieve information sharing in each of these domains, although several, in particular anomaly and threat sharing, are relatively nascent for the time being. A critical determinant, as described by one operator, is the extent to which shared information provides insight into a system's operational status and capabilities. The more insight is provided, the more sensitive sharing will become and bigger benefits will need to be to motivate sharing.

The analysis in this chapter demonstrates that data-sharing concerns do exist, but these concerns are manageable and do not appear to be a serious impediment to the development of future STM systems, at least among established American and European commercial communications and remote sensing satellite operators to whom these results can be reasonably generalized in the core domains of safety of flight/collision avoidance and RF. At the same time, there are several concerns that are present for at least some operators and domains that mean that public information sharing is unlikely to occur for some potentially useful types of information and STM systems will need to be designed to accommodate these restrictions, or more provocatively and perhaps unnecessarily to compel operators to publicly share data they consider sensitive in spite of their concerns. This finding, that data sensitivity concerns can be managed, and the various suggestions about how to potentially do so, is a useful and encouraging consequence for future work on STM architecture design.

Beyond these specific results, there are several more general conclusions that may be drawn:

- Attitudes about data sharing are driven by culture and individuals and can and do shift over time. The presence of a single individual at a company in the relevant position can prevent or enable sharing. Attitudes among commercial operators have shifted towards greater sharing of positional data following the Iridium-Cosmos collision in 2009, but there are still limits to willingness to share, not all of which are rooted in well-justified rationales. Higher fidelity sharing of information in the future (e.g. attitude, threat information, and anomalies) will require and be facilitated by shifting perceptions of risk and benefit as well as practices among operators. Interviewed operators seem to believe there is considerable heterogeneity in attitudes in the industry, including voices more conservative than those interviewed in this sample. This heterogeneity influences both shared information and acceptable sharing structures and data protection techniques.

- The absence of concerns about sharing is not enough to ensure it happens. Implementing sharing takes engineering resources and may involve some level of risk that, while not sufficient to prevent sharing under any circumstance, can dissuade sharing with a marginal value proposition. A generalized paranoia may exist for some operators, where even innocuous information may be withheld from sharing due to a concern that competitors might find ways to derive commercially useful insights from the shared data. Operators are motivated to share even sensitive information if they perceive a clear and direct benefit for doing so. For instance, this self-interest led to the creation of the SDA. Many companies have recognized that space sustainability is in their own long-term interest and have taken very forward-leaning steps in engineering and data-sharing practices for the sake of space sustainability. Work around threat and anomaly sharing is less developed, and there has not yet been a similar cultural shift within the industry.

- Pain points remain in sharing. Further work is needed to develop systems for identification of small satellites following deployment, to scale collision avoidance to larger numbers of spacecraft and smaller objects, integrate higher fidelity information, and bridge cultural and national barriers when it comes to even the basics of collision avoidance coordination.

The implications of the results of this chapter vary for different stakeholders.

For regulators, it is evident that governmental STM services must provide a clear value proposition to operators sharing data and build trust over time. Data security, traceability, and integrity will be important architectural drivers as identified in many of the concepts in Chapter 2. There are multiple potential domains and functions for the scope of an STM system, and information-sharing requirements depend heavily on the particular domains and functions included. While it may be possible to coerce industry participation without persuading operators participation is in their self-interest, engagement will suffer and operators may be driven towards other regulatory regimes depending on the severity of the imposition.

For academics, this chapter provides insight into commercial operators' willingness to share various types of information. This willingness, or lack thereof, has a strong influence on the practicality of proposed systems and analysis techniques. Understanding these attitudes may help inform and motivate future work relating to STM system functions, utilized data, and data protection methods. For those interested in corporate behavior as a topic of inquiry, STM provides an example of sharing potentially competitively sensitive data for mutual gain. Various techniques have, are, and could be used to manage this prisoner's dilemma and reduce the likelihood and harms associated with defections. This may be interesting for comparison with other businesses in different industries faced with similar dynamics.

For operators themselves, this analysis may spur reflection on what data is actually sensitive or not and why, particularly given implications for system-wide safety. It also provides an opportunity for comparison and bench-marking of company and individual attitudes around data sharing. The results may additionally help inform future discussions on data sharing, especially for more complex and developing domains such as threat and anomaly information sharing.

For a system architect, this work hopefully helps distill a list of domains, functions, and data types for potential inclusion in an STM system, and flag some of the concerns about potential data-sharing structures and their implications for commercial operators and associated operator organizations. The need for operator-perceived benefit from sharing that outweighs concerns can be conceptualized as a constraint, either at the system level, or for commercial satellite operator stakeholder satisfaction.

4.8 Future Work

Further work should be conducted in several areas to explore stakeholder views not adequately captured by the work in this chapter. Among established American and European commercial communications and remote-sensing satellite operators, more focused interviews with RF experts would be helpful to understand the state of RF coordination, anticipated future trends, data sensitivity, and the potential value of greater data sharing in further detail. Interviews should also be conducted to more fully characterize opinions on launch and re-entry functions and data sharing.

The work conducted in this chapter should be repeated at a greater set of companies, especially companies that are newer or have been less publicly committed to space sustainability, with operators from the Middle East, Africa, and Asia, and among national actors with both civil and national security missions. Operators from countries with emerging space programs would be a particularly valuable perspective, and it would be quite useful to understand how perspectives of such operators compare with those of established operators.

Other sets of space users with newer classes of missions may have opinions that differ from commercial communication and remote-sensing operators. In particular, companies engaging in RPO/OOS may have different attitudes regarding maneuver sharing. This was hinted at in some of the FCC filings made by relevant companies. Interviews should also be conducted with launch providers, launch aggregators, and smaller scale smallsat operators, to understand their thoughts on data sharing relating to deployment plans. Data sharing by commercial SSA data and service providers is another interesting and tricky area, one that in many ways mimics earlier and ongoing debates about the ingestion of commercial weather data by the National Weather Service.

A broader survey of ISACs, as well as deeper access into the future operations of Space ISAC, would enable a better understanding of the trade-offs involved with that chosen sharing infrastructure. Interviews with attendees at spacecraft-anomaly-sharing workshops, including the SCAF Workshop, would enable a deeper look at how perceptions of anomaly sharing are shifting over time and the impact of potential sharing architectures.

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Chapter 5

Conclusions

5.1 Chapter Summaries

The flow of this thesis has been as follows:

Chapter 1: Introduction Chapter 1 introduced key concepts and background and described the research questions, methods, and organization of the thesis.

Chapter 2: Review of Proposed Systems Architectures for STM Chapter 2 described the system architecture analysis framework, explained how to apply it to STM, and used it to review a set of different potential architectures, frameworks, and other proposals for STM in the literature. Using the system architecture analysis framework, a set of key differences among the architectures was identified to help the reader "concentrate on the critical few details and interfaces that really matter and not to become overloaded with the rest" [101, 26]. These differences included:

- System objectives, especially which phases of flight and problem domains are included, and whether economic or national security objectives are considered;
- Whether architectures are conceived of as a national or international system and whether a top-down, bottom-up, or hybrid approach is used to achieve eventual internationalization;
- What role private sector stakeholders have in both system definition and operation;
- System boundaries, and whether they include technical/operational elements, regulatory aspects, or both, as well as scope and enforceability;

- How potential groups and sub-groups of stakeholders are defined; and
- How data-sharing and information security concerns are understood and influence allocation of functions to forms.

Across the surveyed architectures, gaps were identified regarding consideration of emerging space nation stakeholders and the characterization of commercial space operator data-sharing concerns at a level of specificity sufficient to inform architecture choices in each relevant domain. The perspectives of emerging space nation operators were posited to be important for efforts to internationalize potential STM systems and encourage widespread adoption. Descriptions of data-sharing sensitivities were repeatedly present in the literature, but architectures were either defined in response to concerns understood by the authors without being explicitly articulated or commercial operator data-sharing concerns were presented in overly generalized manners (e.g. proprietary concerns, national security reasons).

Chapter 3: Emerging Space Nation Stakeholder Perspectives on STM Chapter 3 discussed the views of emerging space nations on STM. It is, to my knowledge, the first academic work specifically examining views of representatives from emerging space nations on STM. It examines viewpoints expressed in discussions at COPUOS and its subcommittees and the opinions of relevant national experts from emerging space nations gathered through original interviews. To conduct these interviews, a set of questions and interview protocol were developed and administered. The methodology was justified and validity considerations were discussed, including a recognition that the results of interviews do not necessarily imply a national stance for the nation of an interviewed individual consistent with their perspective. Results were collected and reported qualitatively and quantitatively. A set of recommendations for future internationalized STM system development efforts was then derived from the interviews and validated with a subset of interviewees.

Some of the findings include: representatives of emerging space nations have perspectives on STM, want a system to be developed, and want to be included in ongoing discussions. There is strong (but not unanimous) preference for COPUOS as the venue for these conversations to take place. The reasons for interest in an STM system vary widely and there is not yet consensus on the forms, functions, or objectives for such a system. Many interviewees, but not all, have concerns about a potential STM system's cost, technical requirements, and whether such a system could be wielded by established actors to exclude new entrants.

Efforts by self-interested actors, who stand the most to gain from STM capabilities in the short run, will likely lead to the development of STM systems, but these systems will not necessarily reflect the interests of all space actors. In particular, bottom-up processes exclude those who lack capacity.

Based on interview results, a set of four guidelines was developed:

1. **The cost of participation must be affordable, proportional, and with a clear value proposition for participation across the full spectrum of levels of national space activities.**

2. **Technical capabilities necessary to participate in the system should be identified and tracked through system design.** Capability-building and knowledge-transfer methods should be specifically considered. Requirements to participate should be minimized to the extent possible without impacting system effectiveness. Graduated requirements depending on national space activities and user needs may be worth investigating.

3. **System designers should take great pains to ensure the system design is not exclusionary and cannot be co-opted by established system participants to exclude emerging space actors.** Designers should seek to obtain universal consensus support and repeatedly consult and obtain stakeholder assent from nations with a variety of levels of national space capabilities throughout the development process. All nations should be treated equally by the operational system.

4. **Conversations should continue regarding the precise methods of interaction between the STM system and participant operators/satellites.** Designs that dictate a specific maneuver or perform an action automatically will face much sharper resistance than designs that leave more freedom and flexibility to the operator. These considerations will need to be weighed against system performance and objectives.

These recommendations address STM system cost, technical capabilities required for actors to participate in the system, the importance of an inclusive system development process, and the level of control ceded to the STM system by participating operators. STM development processes that heed these recommendations will be more palatable to emerging space nations and yield more equitable and just systems. These guidelines were supported by those with whom they were validated, although many of the validators had additional suggestions for recommendations beyond these four.

Future work is described to develop and extend the results of the work in Chapter 3. These proposals include more interviews with representatives of additional emerging space nations to further explore how and why views differ across nations. Similarly, more interviews should be conducted per nation with different stakeholders to help assess differences across national organizations and individual perspectives and potentially report results in an individually anonymized, but country-attributed manner.

With more interviews, it may also be possible to derive additional helpful recommendations for STM system design.

Another interesting task would be to engage with those working to build operational SSA/STM systems to explore how these principles could be implemented in their processes. Further lessons could also be learned from national efforts to implement the LTS Guidelines over the coming years.

Lastly, a normative assertion was made that a more inclusive process for STM development is in the interest of established as well as emerging space nations. Expressed in terms of the systems architecture framework, emerging space nations should be treated as primary rather than secondary or tertiary stakeholders. Doing so, it was argued, would accelerate adoption and increase participation in an eventual STM system at minimal additional cost. There is negligible moral downside to doing so, and any practical delays to initial implementation are likely to be compensated by faster international adoption and broader participation. Further work should be conducted to explore this assertion.

Chapter 4: Commercial Satellite Operator Data Sharing Stakeholder Perspectives Chapter 4 analyzed commercial satellite operator perspectives on data sharing for SSA and related purposes, providing additional traceability from specific data types to particular concerns about sharing as compared to the more generalized concerns present in the literature. It reviewed current SSA and related domain data-sharing practices, as well as the record before U.S. regulators to study views articulated by commercial operators on relevant data sharing.

New data collection was found to be necessary. Practices of some organizations were not sufficiently described in public documents. Operator concerns explained in the public record were not always articulated in sufficient detail to support this project, and views were expressed on specific topics but not in a manner that was exhaustive across all domains and functions.

An interview protocol was developed, and interviews were conducted with SSA/STM experts and representatives from commercial satellite operators. A limited number of operator representatives consented to participate in the study, and viewpoints were largely restricted to American and European operators.

Based on both the review of existing literature and new data collection, a set of data-sharing domains was identified. Potential system functions in each domain were then enumerated, along with the information necessary to perform each function. These domains included RF, safety of flight/on-orbit collision avoidance, launch and re-entry (including deployment information), space weather, near-Earth objects, laser emissions, cyber and other threat information sharing, and anomaly sharing. While space weather, near-Earth objects, and laser emissions were considered part of at least some definitions of STM, actual operator enthusiasm for including such domains in an STM system was minimal. In the case of space weather, expert interest was significantly higher than actual operators. Operator views on the sensitivity of data to enable functions in each domain were collected, as well as expert perceptions of operator concerns. Concerns were traced to specific types of shared information and were generally consistent with the general categories identified in Chapter 2, although with more specificity. These concerns included revealing data about companies' customers, capabilities/processes and impacting stock prices, customer confidence, and companies' commercial competitiveness. Operators were asked about potential mechanisms to mitigate concerns and their perceptions of these options, including norms, legal protections, use of a trusted third party, data de-sensitization/anonymization, and technical protection mechanisms. Legal protections were generally seen as most important, but technical protections were helpful especially when layered on top of legal protections. In part due to a lack of interviewee familiarity, there was limited enthusiasm for complex technological protection mechanisms that rely on cryptographic techniques like differential privacy.

Analysis was then conducted to understand the implications of commercial satellite operator data-sharing concerns for STM system architecture. Across all of the domains, operator concerns were informed by potential benefits of data sharing. In the RF and safety of flight/collision-avoidance domain there is clear potential benefit. This benefit has already motivated both protected and unprotected sharing between operators, and may motivate further sharing of potentially sensitive data in the future. There is a need for sharing data in the launch and re-entry domain, especially regarding small satellite deployment information during aggregated launches, but there does not seem to be a particular data sensitivity concern about sharing this data. Cyber and other threat information sharing and anomaly sharing are more challenging topics due to greater sensitivity surrounding the information to be shared, as well as less clear direct benefits to an operator from sharing.

In domains where operators perceive sufficient benefit from sharing, there are no inherent architectural barriers to achieving such sharing. Where they do not, sharing will be slower and may be limited unless attitudes shift.

Several broader conclusions were drawn. These include recognition that concerns about sensitivity are subjective and vary between and within operators and companies, in part based on their particular missions and culture and partly based on individuals. These attitudes can and do evolve over time. Furthermore, a lack of concern about sharing is insufficient to ensure sharing will happen. Operators will only self-organize sharing if enough perceive a direct benefit from doing so. Pain points continue to exist for data sharing, and further evolution of data sharing systems is necessary.

The understanding of potential SSA/STM functions, required data types, and operator willingness to share various types of information has informed work by the SSR definition team to determine the kinds of data-sharing practices and collision avoidance capabilities that the SSR should reward among operators. Inclusion in the SSR may help motivate additional operator data sharing, both when operators are simply agnostic to sharing and when the rationale for sharing is primarily a community-wide benefit rather than direct gain to the sharing operator.

Future work on this topic should involve interviews with representatives from more operators, especially operators from places other than the United States and Europe and those less involved in space sustainability efforts. It would also be useful to follow the activities of Space ISAC and study the data-sharing model and reactions from members during early operations. While the work of this thesis has been premised on exploring operator preferences, it could be informative to explore if there are STM domains or functions where there is sufficient societal or industry-wide benefit to consider regulatory coercion for data sharing even if operators would not engage in a particular form of data-sharing on their own. If such domains do exist, understanding operator attitudes about such coercion and best practices to maximize benefit and minimize concerns would be valuable.

Work could also be conducted to characterize attitudes of national security actors related to data sharing across these domain, and analyze how they compare to commercial actors. It would additionally be useful to explore attitudes of operators engaged in RPO/OOS, ADR, and other novel mission classes to see if their attitudes differ significantly from the communications and remote sensing operators interviewed in this work.

5.2 The Findings of this Thesis in the Systems Architecture Framework

Section 5.1 summarized the findings of this thesis. In this section, these findings are placed in the context of systems architecture.

Chapter 2 reviewed a set of architectures proposed in the literature to identify architecturally relevant differences that serve as trade-offs for consideration in a potential STM system.

Chapter 3's set of recommendations can be viewed as a set of constraints on the process of STM system development and the resulting system. The fulfillment of these constraints significantly increases the likelihood of emerging space nation stakeholder participation and satisfaction. For the purpose of architecture definition and operation, the chapter argues that emerging space nations should be treated as primary rather than secondary or tertiary stakeholders.

Chapter 4 identified a series of domains for potential system objectives, functions to fulfill objectives in each domain, their data requirements, and mechanisms to address operator concerns about data sharing. As such, it is best viewed as a set of system-level or stakeholder-level satisfaction constraints for commercial satellite operators. Various data protection strategies imply a certain allocation of functions to forms, for instance the use of a trusted third party for conjunction assessment relies on the allocation of conjunction assessment to that particular entity as the form. This chapter discusses these concerns in greater detail and more systematically than previous treatments. It provides meaningful analytical breakdowns showcasing the differing levels of concerns different operators have regarding sharing different kinds of SSA/STM data and how these concerns can be addressed by different solutions and potential STM architectures.

Viewing these recommendations in terms of systems architecture helps explain the implications of the results from each chapter is a more abstract and context-independent manner for future potential STM system design and consideration.

5.3 Closing Remarks

As part of Chapter 1 of this thesis, there was discussion of the extent to which definitions of SSA and STM differ across stakeholders. In this thesis, this spectrum has been explored through three perspectives: that of system architects in Chapter 2, that of emerging space nations in Chapter 3, and that of commercial satellite operators in Chapter 4. This section provides a few concluding remarks to help unify these lenses and position the work of this thesis in its own proper context.

First, STM is a necessary but not sufficient capability to ensure space safety and sustainability in the long term. STM addresses the threat of collisions between maneuverable space objects, and will be increasingly critical in a denser future space environment where spacecraft-on-spacecraft conjunctions will dominate spacecraft-on-debris conjunctions. Nevertheless, action is and will continue to be needed to better understand the space environment, limit the generation of future debris, and to remediate the debris already in orbit. Likewise, better SSA is a necessary prerequisite to support STM. The topics addressed in this thesis are necessarily longer-term and these findings should be updated in light of new efforts to build systems for SSA data sharing and fusion and to implement the LTS Guidelines.

Second, like many domains, system architecture is not neutral in STM. STM architectures can and will impose processes, obligations, and limitations on users, whether they are countries, companies, or citizens. These aspects will be potentially long-lived and more difficult to change the longer they are in operation. Thoughtful and careful work to understand system stakeholders, their needs and desired outcomes, and trade-offs in fulfilling these needs and desired outcomes in a context focused on justice will yield more resilient and equitable systems that better achieve the internalization requisite for effective STM.

Third, system scope and data-sharing requirements for STM significantly depend on the domains and functions included in the architecture of the potential system. Numerous types of data pose potential sharing concerns for commercial operators and numerous system design features raise concerns for emerging space nations. Commercial operator attitudes to sharing data depend on the benefits they perceive they will receive from such sharing and emerging space nation perceptions depend heavily on the process used to develop the system. If operators believe the benefits they directly receive, not just the aggregate societal benefit, outweigh the potential concerns about sharing, then various legal and technical structures can be used to great effect. If emerging space nations believe their perspectives and concerns are heard and accommodated, most will happily do their part to ensure a sustainable future space environment. Careful consideration of both these tests will go a long way to addressing this super wicked problem.

Appendix A

Acronyms and Abbreviations

Term	**Definition**
18SPCS	18th Space Control Squadron
ADR	Active Debris Removal
AIAA	American Institute of Aeronautics and Astronautics
AMOS	Advanced Maui Optical and Space Surveillance Technologies Conference
API	Application Programming Interface
CAS	Conjunction Assessment Suppliers
CCSDS	Consultative Committee for Space Data Systems
CNES	National Centre for Space Studies/Centre National d'Etudes Spatiales
COPUOS	Committee on the Peaceful Uses of Outer Space
CPR	Common Pool Resource
CSSMA	Commercial Smallsat Spectrum Management Association
DISCOS	Database and Information System Characterising Objects in Space
DoC	Department of Commerce
DoD	Department of Defense
DoS	Department of State
DoT	Department of Transportation
EASA	European Union Aviation Safety Agency
ESA	European Space Agency
EuroControl	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration

(*table continues*)

Term	**Definition**
FAA/AST	Federal Aviation Administration Office of Commercial Space Transportation
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
GEO	Geosynchronous Orbit
HEO	Highly Elliptical Orbit
IAA	International Academy of Astronautics
IAASS	International Association for the Advancement of Space Safety
IADC	Inter-Agency Space Debris Coordination Committee
ICAO	International Civil Aviation Organization
ISAC	Information Sharing and Analysis Center
ISSC	International Space Safety Center
ISU	International Space University
ITU	International Telecommunications Union
KTi	Keplerian Technologies Inc.
LAPAN	National Institute of Aeronautics and Space/Lembaga Penerbangan dan Antariksa Nasional
LEGEND	LEO-to-GEO Environment Debris Model
LEO	Low Earth Orbit
LNT	Lethal Non-Trackable
LSC	Legal Subcommittee
LTS	Long-term Sustainability
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MEO	Medium Earth Orbit
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NGO	Non-governmental Organization
NGSO	Non-geosynchronous
NSS	National Security Space
OADR	Open Architecture Data Repository
OOS	On-orbit Servicing
OOSA	Office for Outer Space Affairs
ORDEM	Orbital Debris Engineering Model

(*table continues*)

Term	**Definition**
OSTR	Outer Space Traffic Rules
OSTTS	Outer Space Traffic Technical Standards
RF	Radio-frequency
RFI	Radio-frequency Interference
RPO	Rendezvous and Proximity Operations
RSO	Resident Space Object
S3	STM Service Supplier
SAIC	Science Applications International Corporation
SARPS	Standards and Recommended Practices
SCAF	Space Systems Anomalies and Failures
SDA	Space Data Association, Space Domain Awareness, Space Development Agency
SDC	Space Data Center
SDS	Supplemental Data Suppliers
SIMS	Spaceflight Information Management System
SSA	Space Situational Awareness, SSA Suppliers
SSN	Space Surveillance Network
SSO	Sun-synchronous orbit
SSR	Space Sustainability Rating
STCM	Space Traffic Coordination and Management
STM	Space Traffic Management
STPI	Science and Technology Policy Institute
STSC	Scientific and Technical Subcommittee
SWF	Secure World Foundation
TLE	Two-line element set
UAS	Unmanned Aircraft Systems
UN	United Nations
UTM	Unmanned Aircraft Systems Traffic Management
WEF	World Economic Forum

Table A.1: List of Acronyms

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Appendix B

Summary of Reviewed STM-related Concepts and Architectures

Table B.1: Summary of Reviewed STM-related Concepts and Architectures

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
ISU 2007	Architecture, traffic rules, implementation plan	Avoiding harmful interference (physical)	International	Coordination	International org.	Yes	Top-down international.
Jakhu et al. 2011	Architecture and Framework	Safety, efficiency, sustainability, minimal burden	International	Coordination of standards	International org.	National	Standards, with organizational structure to strongly encourage national adoption

(*table continues*)

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
STPI 2016	Concepts	Unspecified. Related to “oversight, coordination, regulation, and promotion of space activities” [116, 81]	Options from analogous domains a) International top-down b) Semi-privatized bottom-up c) Bottom up national to international d) National, decentralized across agencies	1) Regulation by space licensing authorities 2) Private bottom-Up 3) Civil middle of the road 4) Civil top-down control	1) Gov., but not necessary any operational system 2) Private, but not necessarily an operational system	1) None? 2) None? 3) None or Private? 4) Government	1) Regulation 2) Voluntary best practices 3) Mandatory rules and penalties 4) Mandated movements

(*table continues*)

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
SAIC 2016	Architectures and frameworks	1) Space safety 2) National security space interests 3) Economic vitality of space domain	National	1) Private bottom-up 2) Military data sharing 3) Civil/ public-private partnership (bottom-up) 4) Civil middle of the road 5) Civil top-down control	1) Private 2) DoD 3) Public or public/ private partnership 4) Public 5) Public	1) Private 2) DoD 3) Public or public/ private partnership 4) Public 5) Public	1) Industry-led, weak informal gov. role 2) Status quo 3) Gov. facilitates bottom-up industry best practices/ guidelines/ standards 4) Gov.-led in collaboration with industry 5) Gov.-imposed

(*table continues*)

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
ESA 2017	Architecture (suborbital focus)	Safety, integration with European Air Traffic Management System and Infrastructure	Pan-European	Control	Public entity	Yes	Yes
AIAA 2017	Agenda for future research and consensus-building	Space safety	N/A	N/A	N/A	Probably	All actors
Oltrogge 2018	Architecture	Flight safety (all-phase)	Private or multinational to eventually global	Coordination	Public/ private partnership or multilateral org.	Public/ private partnership or multilateral org.	Complex bottom-up ecosystems involving various actors
Skinner 2018	Architecture	Flight safety (orbital focus, but launch and re-entry included in definition)	National	SSA and services	Public	Yes	No

(*table continues*)

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
NASA ARC 2018-2019	Architecture and initial prototype with example use case	1) Safety coordination 2) Promote commercial STM services (semi-implicit)	National	Coordination	Public/ private hybrid	Yes	Relies upon, but outside scope of system
IAA 2018	Roadmap	Implicit	1) Top down (international first) 2) Bottom up (domestic/ commercial norms and national to international)	Not yet determined	Not yet determined	Not yet determined	1) Subject to discussion in international fora 2) Yes, but formulation, application, verification, and harmonization challenging

(*table continues*)

Author/ Organization & Year	**Type**	**System Objectives**	**National or International**	**Level of Involvement**	**System Owner**	**Operational System?**	**Norms/ Reg./ Standards**
IAASS 2019	Problem statement/ concepts	Various (avoid physical/ RF interference, SSA for safety, space operations assurance, fulfilment of community demand signals, API-architecture for on-orbit physical de-confliction, standards development)	Varies by concept	Standards development, coordination (depending on concept)	Public/ private partnership Others unspecified	Varies	In some concepts
CNES 2020	Architecture	Coordination, safety, sustainability, regulatory harmonization, interference mitigation	Flexible/ hybrid. Public entity for coordination.	Coordination	Public entity	Yes	Yes

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Appendix C

Interviewee List

Table C.1: List of Emerging Space Nation Interviewees

Name	**Title**	**Country**
Anonymous Interviewee		Argentina
Weimar Quiroga	Coordinator in Regulation and O&F, Agencia Boliviana Espacial	Bolivia
Cristian Puebla	Advisor of Academic Extension on Space Affairs, Chilean Air Force	Chile
Victoria Valdivia Cerda	Political Advisor, Subdirectorate of Space Affairs, Operations Directorate, Chilean Air Force	Chile
Giovanni Corredor	Advisor, Vice-presidency of Colombia	Colombia
Paul Lias	Expert in Space Technologies and Policy, Economic Development Department, Ministry of Economic Affairs and Communications	Estonia
Robertus Heru Triharjanto	Director, Center for Aerospace Policy Studies, National Institute of Aeronautics and Space (LAPAN)	Indonesia
Andrew Nywade		Kenya
Adrian Malacz	Vice Chairman, Polish SSA System Establishment Task Force	Poland
Anonymous Interviewee		Romania
Pontsho Maruping	Chairperson, South African Council for Space Affairs Head of Commercialisation, South African Radio Astronomy Observatory	South Africa
Thagoon Kirdkao	Director of Space Affairs Division, Royal Thai Air Force	Thailand
Wasanchai Vongsantivanich	Satellite Systems Engineer, Geo-informatics and Space Technology Development Agency	Thailand
Fatheya Sharji	Senior Space Legislative Specialist, United Arab Emirates Space Agency	United Arab Emirates
Dao Ngoc Chien	Deputy Director-General, Department of High Technology, Ministry of Science and Technology	Viet Nam
Anonymous Interviewee		
Anonymous Interviewee		

Table C.2: List of Commercial Space Operator and SSA STM Expert Interviewees

Name	**Title**	**Company Organization**
Mark Skinner	Senior Project Leader, Space Traffic Management	The Aerospace Corporation
Timothy Maclay	Chief Executive Officer	Celestial Insight, Inc.
Darren McKnight	Tech Director	Centauri
Megan Wood	Senior Director of Corporate Strategy	DigitalGlobe, a Maxar Technologies company
Stephen Earle	Space Traffic Program Lead	Office of Commercial Space Transportation, U.S. Federal Aviation Administration
Mark Dickinson	Vice President, Satellite Operation Chairman (at time of interview)	Inmarsat Space Data Association
Diane Howard	Executive Secretary Non-resident Scholar	International Institute of Space Law Strauss Center for International Security and Law, University of Texas School of Law
Ryan Shepperd	Mission Planning and Orbital Analysis, SSA Lead	Iridium Communications Inc.
Anonymous Interviewee		Planet Labs Inc.
Vivek Vittaldev	Lead, Mission Planning & Scheduling, Mission Systems	Planet Labs Inc.
Therese Jones	Senior Director of Policy	Satellite Industry Association
Brian Weeden	Director of Program Planning	Secure World Foundation
T.S. Kelso	Operations Manager, Space Data Center	Space Data Association
Daniel L. Oltrogge	Program Manager, Space Data Center	Space Data Association

(*table continues*)

Name	**Title**	**Company/ Organization**
Erin Miller	Vice President, Operations	Space Information Sharing and Analysis Center
Niklas Hedman	Chief of Committee, Policy and Legal Affairs Section	United Nations Office for Outer Space Affairs
Jason Y. Kim	Senior Policy Analyst	Office of Space Commerce, U.S. Department of Commerce
Anonymous Interviewee		Anonymous LEO Operator
Anonymous Interviewee		Anonymous LEO Operator
Anonymous Interviewee		Anonymous Organization

Appendix D

Emerging Space Nation Interview Protocol

This section contains the protocol used for interviews in chapter 3. The formatting in this version is different than as administered. The original was typeset in Microsoft Word, while this version is typeset by LaTeX.

D.1 Key Definitions

Space Sustainability the ability of all humanity to continue to use outer space for peaceful purposes and socioeconomic benefit over the long term.[1]

Space Situational Awareness (SSA) the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.[2]

Space Traffic Management (STM) the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.[3]

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[1] Definition from the Secure World Foundation. https://swfound.org/our-focus/space-sustainability/.

[2] Definition from National Space Council, "Space Policy Directive-3, National Space Traffic Management Policy." 2018.

[3] Definition from National Space Council, "Space Policy Directive-3, National Space Traffic Management Policy." 2018.

D.2 Future Scenarios (referenced in question 3.a)

D.2.1 Scenario 1: ICAO for Space (International) [4]

An international organization develops rules, procedures, and standards to ensure safe operations. It offers traffic control rules for launch, orbit, and re-entry to protect the public, prevent interference and collisions between spacecraft and other air/space users. National authorities implement and certify safety against international standards.

D.2.2 Scenario 2: Private STM (Private)

A private non-governmental non-profit Space Traffic Management Association provides coordination and management of on orbit traffic on a voluntarily basis for operators who choose to become members. Launch and re-entry continue to be handled by national governments. Rules, procedures, and standards are developed by members of the organization.

D.2.3 Scenario 3: United States (or other nation) STM Open to Others (De Facto)

The United States (or another nation) develops an STM system, building on existing national regulatory structures for launch, re-entry, and a new system for on-orbit coordination and management. Operators from other countries can voluntarily participate in the system. Other nations can mandate the participation of their traffic or arrange bilateral integration with other national systems. Nations share voluntary best practices through an international inter-governmental or non-governmental organization.

D.3 Questions

1. About the Interviewee:
    (a) Please describe your current position and responsibilities.
    (b) How much does space sustainability affect your daily work?
2. About the country:
    (a) What do believe are your nation's priorities in space?

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[4] Based on concept from R. S. Jakhu, T. Sgobba, and P. S. Dempsey, The Need for an Integrated Regulatory Regime for Aviation and Space: ICAO for Space?, no. 7. New York: SpringerWienNewyork, 2011.

(b) Have you done work or engaged in dialog on any space sustainability topics? Please describe.

(c) Are you aware of any engagement on space sustainability topics by your country's government, space program, or other individuals/organizations? Please describe.

(d) To your knowledge, have space sustainability concerns had a significant impact on any of your country's space activities?

(e) [Added in v1.1] The United Nations Committee on the Peaceful Use of Outer Space recently adopted Guidelines for the Long-term Sustainability of Outer Space Activities [hyperlinked to `http://www.unis.unvienna.org/unis/en/pressrels/2019/unisos518.html`]. Is your country planning to review national laws against these guidelines or otherwise implement them? Can you describe any such planned efforts?

(f) Which of these areas does your country have experience in? Where do you have less experience? Do you believe your country has plans to increase capability in any of these areas? Do you think it should increase capabilities in any of these areas?

  i. Space Situational Awareness Data Collection and Sharing
  ii. Conjunction Screening
  iii. Conjunction Assessment
  iv. Collision Avoidance Maneuver Design
  v. Maneuver Coordination
  vi. Spacecraft Design for Demise
  vii. Other Space Sustainability Topics

(g) Please describe how you would like to engage in international discussions on STM. What capabilities and strengths does your country bring to global discussions on STM?

3. Thoughts about international SSA/STM:

  (a) Would you like to see the development of a global SSA/STM system? Do you have preferences among the 3 scenarios (mentioned on the previous page) or others?

    i. [added in v1.2] Would you want the system development process to use consensus, a voting-based decision-making processes, or a hybrid? Why?

    ii. [added in v1.2] Would you prefer binding rules, non-binding rules, or a hybrid? Why?
    iii. [added in v1.2] What do you believe should be the role for industry participants? Should they participate through their authorizing states or directly?

(b) What benefits would your nation seek to achieve from a global SSA/STM System?

(c) What functions would you like that system to perform? Alternatively, what objectives should it fulfill (see graphic [replicated in Figure D-1])?

(d) [Added in v1.1] What capabilities do you believe are needed for SSA and STM at the national or regional vs. international level?

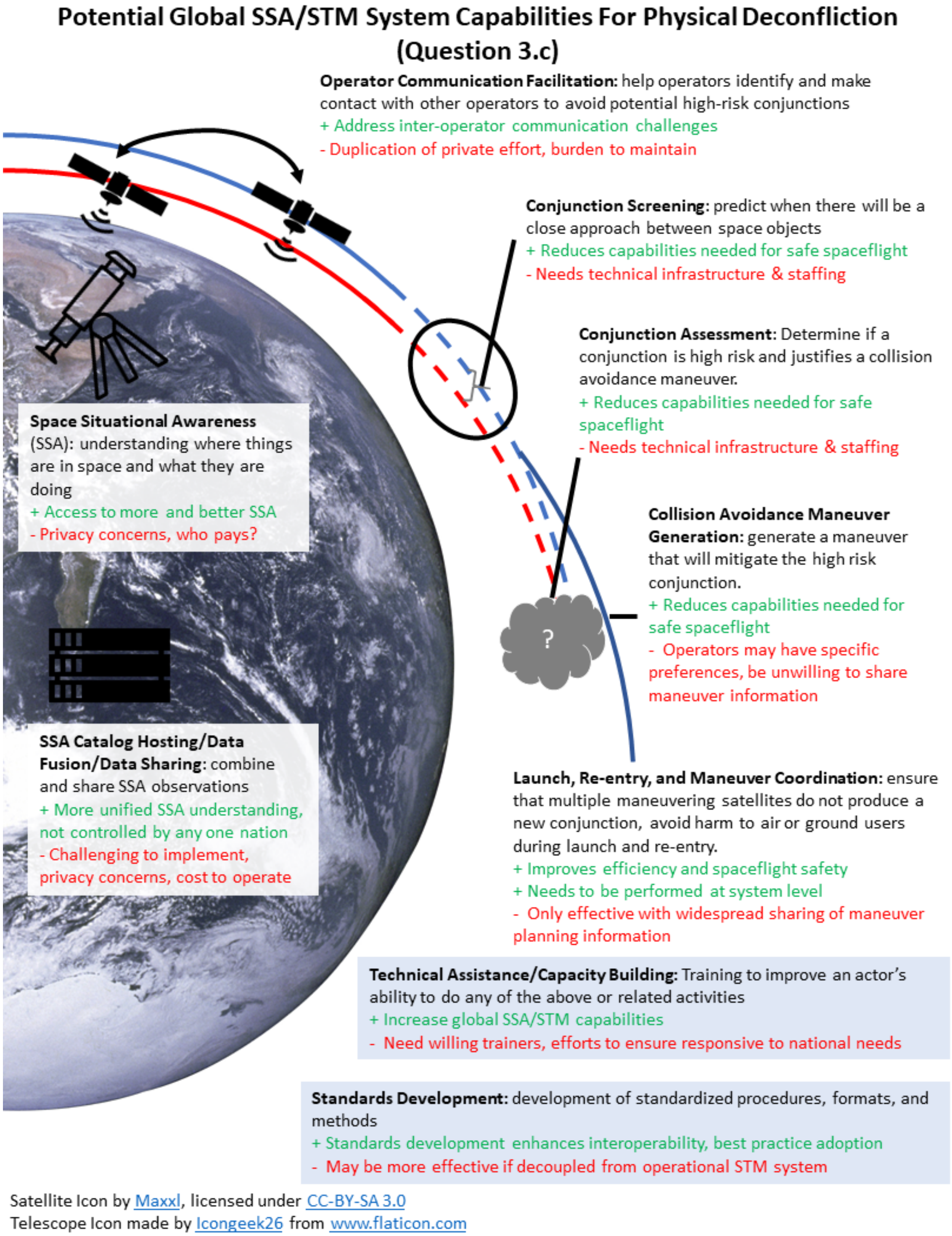
(e) Would you participate in the development of that system? How do you think representatives of your country would prefer to provide input into the potential design of a future international SSA/STM system?

(f) What venues and methods do you think representatives of your country would prefer to provide input into the potential design of a future international SSA/STM system? Can you rank the importance? Why? What are different venues most useful for?
    i. COPUOS, Subcommittees, and Working Groups
    ii. Combined with Capacity Building Workshops
    iii. Bi-lateral Discussions between Countries
    iv. International NGO (e.g. Space Data Association).
    v. International Intergovernmental Organizations (e.g. Inter-Agency Space Debris Coordination Committee (IADC))
    vi. Standards Development Bodies
    vii. Academic and Technical Conferences/Expert Exchanges
    viii. Commercial and Private Sector Associations
    ix. All of the Above
    x. Others

(g) [Added in v1.1] Do you have thoughts on whether STM should be organized from the top down (starting from international discussions among countries) or from the bottom up (with national frameworks and discussions among private actors)? If you prefer a mix of the two approaches, what elements should be developed through each approach?

   (h) [Added in v1.1] Do you think your country would likely participate in an international SSA/STM system? What factors would influence the decision?
   (i) [Added in v1.1] Do you have any concerns about the potential consequences/impacts of an international space traffic management system? What do you believe would constitute an 'undue' cost (monetary, or otherwise) for such a system?
      i. STM system requirements increasing cost of participation
      ii. STM system requirements increasing level of technical sophistication necessary for space activities
      iii. STM system requirements restricting my nation's ability to operate freely in space
      iv. STM system giving some control over national space assets to a foreign entity
      v. STM system disclosing sensitive information about space assets/activities to others
      vi. No concerns
   (j) Would you support different standards for norms compliance (i.e. post-mission disposal) across countries or actors based on:
      i. Type of mission (civil, commercial, national security)
      ii. Level of national experience in space
      iii. Level of national socioeconomic development

4. Collaboration
   (a) Are there other stakeholders within your country's government with whom you would recommend I speak?
   (b) [added in v1.2] Are there any best practices you would like to see enacted to promote greater involvement of emerging space actors in SSA/STM system design and operation?
   (c) Is there anything else you want to tell us about your country's engagement on space sustainability?



Potential Global SSA/STM System Capabilities For Physical Deconfliction (Question 3.c)

Operator Communication Facilitation: help operators identify and make contact with other operators to avoid potential high-risk conjunctions
+ Address inter-operator communication challenges
- Duplication of private effort, burden to maintain

Conjunction Screening: predict when there will be a close approach between space objects
+ Reduces capabilities needed for safe spaceflight
- Needs technical infrastructure & staffing

Conjunction Assessment: Determine if a conjunction is high risk and justifies a collision avoidance maneuver.
+ Reduces capabilities needed for safe spaceflight
- Needs technical infrastructure & staffing

Space Situational Awareness (SSA): understanding where things are in space and what they are doing
+ Access to more and better SSA
- Privacy concerns, who pays?

Collision Avoidance Maneuver Generation: generate a maneuver that will mitigate the high risk conjunction.
+ Reduces capabilities needed for safe spaceflight
- Operators may have specific preferences, be unwilling to share maneuver information

SSA Catalog Hosting/Data Fusion/Data Sharing: combine and share SSA observations
+ More unified SSA understanding, not controlled by any one nation
- Challenging to implement, privacy concerns, cost to operate

Launch, Re-entry, and Maneuver Coordination: ensure that multiple maneuvering satellites do not produce a new conjunction, avoid harm to air or ground users during launch and re-entry.
+ Improves efficiency and spaceflight safety
+ Needs to be performed at system level
- Only effective with widespread sharing of maneuver planning information

Technical Assistance/Capacity Building: Training to improve an actor's ability to do any of the above or related activities
+ Increase global SSA/STM capabilities
- Need willing trainers, efforts to ensure responsive to national needs

Standards Development: development of standardized procedures, formats, and methods
+ Standards development enhances interoperability, best practice adoption
- May be more effective if decoupled from operational STM system

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Telescope Icon made by Icongeek26 from www.flaticon.com

Figure D-1: Interview Graphic Prompt Regarding Potential SSA/STM System Functions

Appendix E

Emerging Space Nation STM Results

Question (number)	**Number of Responses Per Option**										
Capabilites to contribute (2.g)	Peacekeeper/Broker	Contribute SSA/Location	Data Processing	Services							
	1	6	1	1							
Which STM Scenario?(3.a)	Scenario 1 (UN)	Scenario 2 (Private)	Scenario 3 (Nat. System)	Hybrid (Scen. 2/3)							
	10	0	4	1/1							
Decision process for system (3.a.i)	Consensus	Voting	Hybrid								
	3	0	4								
Binding or non-binding rules? (3.a.ii)	Hard	Soft	Hybrid								
	1	0	5								
Role of Industry Participants (3.a.iii)	Direct Participation	Through Industry Association/Organization	Through States								
	6	1	2								
Desired benefits from STM sys.? (3.b)	Access to Space	Avoid Conflict	Promote collab	SSA Info	Sustainability	Econ. Dev	Equity/ Better Mgmt.	Pub. Outreach			
	6	2	1	2	2	1	4	1			
What functions performed by STM system? (3.c)	All	Comm. Facilitation	Conj. Screening	Conj. Assessment	COLA Man. Gen.	Man. Coord.	Cap. Build.	Standard Dev.	SSA Coll.	SSA Data Fusion	Other
	5	7	8	7	7	8	8	7	6	8	4
What venues to provide input into STM design? (3.f)	COPUOS	Cap. Build. Workshops	Bi-lats	Int. NGO	IGO	Standards Dev. Bodies	Acad. & Tech. Conf. and Expert Exchange	Comm./Priv. Assoc.	All of the Above	Others	
	10	2	2	0/2	4/1	0	0	0	0	0	
How should STM be organized? (3.g)	Top-Down	Bottom-Up	Hybrid								
	4	2	7								
Would you participate? Why? (3.h)	Yes	Cap. Build.	Be Good Actor	Intl. Accept. of Sys.	Foreign Invest.	Understand Sys.	Keep Nat. Control	Mission Assurance	Budget-Friendly	Cost-benefit	Treats All Equally
	14	2	2	1	2	1	1	1	1	2	1
What concerns do you have? (3.i)	Cost	Tech Reqs.	Freedom of Ops.	Cede Control to For.	Info. Disclosure						
	5	7	6	4	2						
Varied standards for compliance? (3.j)	Type of Mission	Level of Econ. Dev.	Weight of factors	Attainable Universal Norms							
	4	1	2	7							

Figure E-1: Summary of Emerging Space Nation Interview Results
Cells with two values indicate (primary/secondary choice)

Appendix F

Data Sharing Concerns Present in the “Mitigation of Orbital Debris in the New Space Age” FCC Docket

Table F.1: Relevant Comments and Concerns (+ = support, O = other comment, P = proprietary, E = export control, S = security, B = burden).

Company	**Ephemeris Sharing (18SPCS)**	**Ephemeris Sharing (with CA Risk)**	**Ephemeris Sharing (with CDM)**	**Ephemeris Sharing (public)**	**Initial Deployment (metric)**	**Planned Maneuvers**	**Maneuverability**	**RPO**	**Other**
The Aerospace Corporation	+	+	+		O		+	O	
Global NewSpace Operators[1]	O	O	O		O		P	P/E	
AT&T									S
The Boeing Company (Comments)	+	+	+		U	+	P	O	P
The Boeing Company (Reply Comments)	+	O			U		P	O	P
The Consortium for Execution of Rendezvous and Servicing Operations								+	
Commercial Smallsat Spectrum Management Association (Comments)	O	O	O	O		O	+		

(*table continues*)

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[1] Astroscale Holdings, Altius Space Machines, Inc., Nanoracks LLC, OrbitFab, Inc., Roccor, LLC, SpaceBridge Logistics, Inc., Space Exploration Engineering, LLC, SpaceNav, LLC

Table F.1: Relevant comments and concerns (+ = support, O = other comment, P = proprietary, E = export control, S = security, B = burden).

Company	**Ephemeris Sharing (18SPCS)**	**Ephemeris Sharing (with CA Risk)**	**Ephemeris Sharing (with CDM)**	**Ephemeris Sharing (public)**	**Initial Deployment (metric)**	**Planned Maneuvers**	**Maneuverability**	**RPO**	**Other**
Commercial Smallsat Spectrum Management Association (Reply Comments)	+		+	+			+		P
Eutelsat S.A.									S
Intelsat License LLC	+	+	+		+	+		+	
Iridium Communications Inc.	+	+				+	+		
Keplerian Technologies Inc.	P	P	P	P	P	P	P	P	
LeoSat MA, Inc.	+		+				P		
Lockheed Martin Corporation	O	S/P	S/P		O	S/P			O
Maxar Technologies Inc.	+								
WorldVu Satellites Limited (OneWeb)	+	+	+			+	+		
ORBCOMM Inc.	+	+	+		+				
SES Americon, Inc., O3b Limited	+						+		
Satellite Industry Association			O						
Sirius XM Radio Inc.	+								

(*table continues*)

Table F.1: Relevant comments and concerns (+ = support, O = other comment, P = proprietary, E = export control, S = security, B = burden).

Company	**Ephemeris Sharing (18SPCS)**	**Ephemeris Sharing (with CA Risk)**	**Ephemeris Sharing (with CDM)**	**Ephemeris Sharing (public)**	**Initial Deployment (metric)**	**Planned Maneuvers**	**Maneuverability**	**RPO**	**Other**
Space Logistics, LLC								+	
Spacefilght, Inc.					O				
Space Exploration Technologies Corp.	+	+	+				+		+
Swarm Technologies Inc.	+								
Secure World Foundation	O							O	
Telesat Canada	+	+	O		+	+	+		
Tyvak						B			
University Small-Satellite Researchers (Reply Comments)	+	O	+						

Bibliography

[1] Digital Globe Ephemeris. URL: `https://partner.digitalglobe.com/ephemeris/`.

[2] DISCOSweb. URL: `https://discosweb.esoc.esa.int/`.

[3] Ephemeris | MyIntelsat. URL: `https://my.intelsat.com/ephemeris/public#/`.

[4] Ephemeris Data. URL: `https://extranet.ses.com/Ephemeris/`.

[5] Planet Labs public orbital ephemerides. URL: `http://ephemerides.planet-labs.com/`.

[6] SDA Overview. URL: `http://www.space-data.org/sda/about/sda-overview/`.

[7] Space ISAC - Space Information Sharing and Analysis Center. URL: `https://s-isac.org/`.

[8] Spire - Open TLE Service. URL: `http://tle.spire.com/`.

[9] UNOOSA Meetings Audio. URL: `https://www.unoosa.org/oosa/audio/v2/meetings.jsp?lng=en`.

[10] Presidential Decision Directive 63 on Critical Infrastructure Protection: Sector Coordinators, 8 1998. URL: `https://www.govinfo.gov/app/details/FR-1998-08-05/98-20865/summary`.

[11] Report and Order, 6 2004. URL: `https://www.fcc.gov/ecfs/filing/5511437972`.

[12] National Space Policy of the United States of America, 6 2010. URL: `https://www.space.commerce.gov/policy/national-space-policy/`.

[13] Report and Order and Further Notice of Proposed Rulemaking, 2017. URL: `https://www.fcc.gov/document/updated-rules-facilitate-non-geostationary-satellite-systems`.

[14] Notice of Proposed Rulemaking and Order on Reconsideration, 2018. URL: `https://www.fcc.gov/ecfs/filing/11190043203850`.

[15] Space Traffic Management - Towards a Roadmap for Implementation. Technical report, International Academy of Astronautics, Paris, France, 2018.

[16] Comments of Tyvak, 2019. URL: `https://www.fcc.gov/ecfs/filing/1040649399024`.

[17] Streamlining Licensing Procedures for Small Satellites Report and Order, 8 2019. URL: `https://www.fcc.gov/ecfs/filing/08020582709488`.

[18] Notice of Proposed Rulemaking, 2020. URL: `https://www.fcc.gov/ecfs/filing/11190043203850`.

[19] Report and Order and Further Notice of Proposed Rulemaking, 2020. URL: `https://www.fcc.gov/ecfs/filing/04240586604013`.

[20] AIAA Space Traffic Management Working Group. Space Traffic Management (STM): Balancing Safety , Innovation , and Growth. Technical Report November, AIAA, 2017. URL: `https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/position-papers/stmpapernovember2017.pdf`.

[21] Air Force Space Command. Geosynchronous Space Situational Awareness Program. URL: `https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/730802/geosynchronous-space-situational-awareness-program-gssap/`.

[22] Air Force Space Command. Space Based Space Surveillance. URL: `https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/249017/space-based-space-surveillance-sbss/`.

[23] Salvatore Alfano and Daniel Oltrogge. Probability of Collision: Valuation, variability, visualization, and validity. *Acta Astronautica*, 148:301–316, 7 2018. `doi:10.1016/j.actaastro.2018.04.023`.

[24] Audrey L. Allison. *The ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century*. Springer, Cham, 2014. URL: `https://link.springer.com/book/10.1007/978-3-319-05314-1`, `doi:10.1007/978-3-319-05314-1`.

[25] Audrey L. Allison and Bruce A. Olcott. Reply Comments of the Boeing Company, 2017. URL: `https://www.fcc.gov/ecfs/filing/10411162757647`.

[26] Audrey L. Allison and Bruce A. Olcott. Comments of the Boeing Company, 2019. URL: `https://www.fcc.gov/ecfs/filing/10405203725521`.

[27] Audrey L. Allison and Bruce A. Olcott. Reply Comments of The Boeing Company, 2019. URL: `https://www.fcc.gov/ecfs/filing/1050656163821`.

[28] Joseph C. Anders. Comments of LeoSat MA, Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/104051333319010`.

[29] AK Anilkumar, Satoru Aoyama, Ben Baseley-Walker, Karl Bilimoria, Cian Curran, Karina Drees, Donato Giorgi, Evelyne Greneche, R. Brogan Hetrick, Munchun Jing, Richard B. Leshner, Xuejun Liao, Kenta Maruyama, Ricardo Marvao, Lex Meijer, Xavier Michalski, Ayako Ono, Angeline Asangire Oprong, Sascha Pillokeit, Kevin Shortt, Tim Smallhorn, Erin Tegnerud, Antonio Yukio Ueta, Meritxell Vinas Tio, Brian Weeden, Weibin Gao, Weiguo Shen, Ole Kristian Western, Guangming Zhang, and Jhony Zavaleta. Space Traffic Management Final Report. Technical report, International Space University, Beijing, China, 2007.

[30] Fabrice Barbedette and Carlos M. Nalda. Comments of Eutelsat S.A., 2019. URL: `https://www.fcc.gov/ecfs/filing/104062948620632`.

[31] Christophe Bonnal, Laurent Francillout, Monique Moury, Ursula Aniakou, Juan-Carlos Dolado Perez, Julien Mariez, and Sylvain Michel. CNES Technical Considerations on Space Traffic Management. *Acta Astronautica*, 167:296–301, 2 2020. `doi:10.1016/j.actaastro.2019.11.023`.

[32] Owen Brown, Travis Cottom, Michael Gleason, Matthew Hallex, Andrew Long, Edgar Rivera, David Finkleman, Moriba Jah, David Koplow, and Ray Sedwick. Report on Space Traffic Management Assessments, Frameworks and Recommendations. Technical report, SAIC, 2016. URL: `http://www.spacepolicyonline.com/pages/images/stories/OrbitalTrafficMgmtreportfromSAIC.pdf`.

[33] Bryce Space and Technology. Start-Up Space: Update on Investment in Commercial Space Ventures. Technical report, Bryce Space and Technology, Washington D.C., 2020. URL: `https://brycetech.com/reports/report-documents/Bryce_Start_Up_Space_2020.pdf`.

[34] Jannuel V. Cabrera, Sreeja Nag, and David Murakami. An Initial Analysis of Automating Conjunction Assessment and Collision Avoidance Planning in Space Traffic Management. *Advances in the Astronautical Sciences*, 168:3071–3090, 2019.

[35] Combined Force Space Component Command. Documentation: SSA Sharing & Orbital Data Requests. URL: `https://www.space-track.org/documentation#/odr`.

[36] Committee on the Peaceful Uses of Outer Space. Report of the Committee on the Peaceful Uses of Outer Space Fifty-eighth session (10-19 June 2015). Technical report, United Nations, Vienna, Austria, 2015.

[37] Committee on the Peaceful Uses of Outer Space. Report of the Committee on the Peaceful Uses of Outer Space Fifty-ninth session (8-17 June 2016). Technical report, United Nations, Vienna, Austria, 2016.

[38] Committee on the Peaceful Uses of Outer Space. Report of the Committee on the Peaceful Uses of Outer Space Sixtieth session (7-16 June 2017). Technical report, United Nations, Vienna, Austria, 2017.

[39] Committee on the Peaceful Uses of Outer Space. Report of the Committee on the Peaceful Uses of Outer Space Sixty-first session (20–29 June 2018). Technical report, United nations, Vienna, Austria, 2018.

[40] Committee on the Peaceful Uses of Outer Space. Report of the Committee on the Peaceful Uses of Outer Space. Technical report, United Nations, Vienna, Austria, 2019.

[41] Edward Crawley, Bruce Cameron, and Daniel Selva. *System Architecture : Strategy and Product Development for Complex Systems*. Pearson Education, 2016.

[42] Edward Crawley, Oliver de Weck, Steven Eppinger, Christopher Magee, Joel Moses, Warren Seering, Joel Schindall, David Wallace, Daniel Whitney, O Weck de, Steven Eppinger, Christopher Magee, Joel Moses, Warren Seering, Joel Schindall, David Wallace, and Daniel Whitney. The Influence of Architecture in Engineering Systems, 2004.

[43] John W. Creswell and Dana L. Miller. Determining Validity in Qualitative Inquiry. *Theory Into Practice*, 39(3):124–130, 8 2000. `doi:10.1207/s15430421tip3903{\_}2`.

[44] Andrew R. D' Uva, Alexander Purves, and Travis Langster. Office of Space Commerce RFI Response of Providence Access Company and Analytical Graphics Inc, 5 2019. URL: `https://www.regulations.gov/document?D=DOC-2019-0001-0035`.

[45] Joel A. Dennerley. Emerging space nations and the development of international regulatory regimes. *Space Policy*, 35:27–32, 2016. `doi:10.1016/j.spacepol.2016.02.003`.

[46] Department of Commerce. Request for Information on Commercial Capabilities in Space Situational Awareness Data and Space Traffic Management Services, 2019. URL: `https://www.regulations.gov/docket?D=DOC-2019-0001`.

[47] Mariah Dodson Shuman, Brian Weimer, Douglas Svor, and Samuel Swoyer. Comments of Worldvu Satellites Limited, 2019. URL: `https://www.fcc.gov/ecfs/filing/1040650203789`.

[48] Frans G. von der Dunk and Fabio Tronchetti. *Handbook of Space Law*. Edward Elgar Publishing, Cheltenham, UK, 2015.

[49] Sandra Erwin. Space Fence surveillance radar site declared operational. *SpaceNews*, 3 2020. URL: `https://spacenews.com/space-fence-surveillance-radar-site-declared-operational/`.

[50] European Space Agency. Space Debris User Portal. URL: `https://sdup.esoc.esa.int/`.

[51] Federal Communications Commission. Update to Parts 2 and 25 Concerning Non-geostationary, Fixed-Satellite Service Systems and Related Matters, 2016. URL: `https://www.fcc.gov/ecfs/search/filings?proceedings_name=16-408`.

[52] Federal Communications Commission. Mitigation of Orbital Debris in the New Space Age, 2018. URL: `https://www.fcc.gov/ecfs/search/filings?proceedings_name=18-313`.

[53] Gregory P. Fonder, Peter J. Hack, and Matthew R. Hughes. AN/FSY-3 Space Fence System - Sensor Site One/Operations Center Integration Status and Sensor Site Two Planned Capability. In *Technical Proceedings from the 18th Annual Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, Maui, HI, 9 2017. Maui Economic Development Board.

[54] David A. Galvan, Brett Hemenway, William Welser IV, and Dave Baiocchi. Satellite Anomalies: Benefits of a Centralized Anomaly Database and Methods for Securely Sharing Information Among Satellite Operators. Technical report, RAND Corporation, Santa Monica, CA, 2014. URL: `https://www.rand.org/pubs/research_reports/RR560.html`.

[55] Roy Gardner, Elinor Ostrom, and James M. Walker. The Nature of Common-Pool Resource Problems. *Rationality and Society*, 2(3):335–358, 1990. `doi:10.1177/1043463190002003005`.

[56] Bill Gillham. *Case Study Research Methods*. Continuum, London, U.K., 2000.

[57] J. C. Green, Y. Y. Shprits, E. Haggarty, T. Onsager, and I. Zhelavskaya. Summary of Stakeholder Inputs on Development of a Satellite Anomaly Database from the European Space Weather Week. *Space Weather*, 16(4):343–344, 2018. `doi:10.1029/2018SW001823`.

[58] Camilo Guzman Gomez and Yinet Cordoba A. The Equitable Access to the Geo for Developing Countries: A Pending Challenge. In *Proceedings of the 64th International Astronautical Congress*, Beijing, China, 2013. International Astronautical Federation. URL: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2960223`.

[59] Garrett Hardin. The Tragedy of the Commons. *Science*, 162(3859):1243–1248, 12 1968. `doi:10.1126/science.162.3859.1243`.

[60] Brett Hemenway, William Welser IV, and Dave Baiocchi. Achieving Higher-Fidelity Conjunction Analyses Using Cryptography to Improve Information Sharing. Technical report, RAND Corporation, 2014.

[61] Kristina Hloptsidis. Comments of Spaceflight, Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/10405412027037`.

[62] International Academy of Astronautics. Cosmic Study on Space Traffic Management. Technical report, International Academy of Astronautics, 2006.

[63] International Telecommunications Union. Managing the radio-frequency spectrum for the world, 12 2019. URL: `https://www.itu.int/en/mediacentre/backgrounders/Pages/itu-r-managing-the-radio-frequency-spectrum-for-the-world.aspx`.

[64] ISO/TC 20/SC 14. Space systems — Avoiding collisions with orbiting objects (ISO/TR 16158). Technical report, Geneva, 2013. URL: `https://www.iso.org/standard/55739.html`.

[65] Brian Israel, Chris Lewicki, and David Hyland-Wood. Ex Parte Presentation in re: Request for Information on Commercial Capabilities in Space Situational Awareness Data and Space Traffic Management Services, 2019. URL: `https://www.regulations.gov/document?D=DOC-2019-0001-0043`.

[66] Ram S. Jakhu, Tommaso Sgobba, and Paul Stephen Dempsey, editors. *The Need for an Integrated Regulatory Regime for Aviation and Space*, volume 7 of *Studies in Space Policy*. Springer Vienna, Vienna, 2011. `doi:10.1007/978-3-7091-0718-8`.

[67] Adam Jonas, Armintas Sinkevicius, Simon Flannery, Benjamin Swinburne, Patrick Wellington, Terence Tsui, Rajeev Lalwani, James E. Faucette, Brian Nowak, Ravi Shanker, Kai Pan, Eva T. Zlotnicka, Nigel Coe, Brian Essex, Craig Hettenbach, Katy L. Huberty, Tetsuro Tsusaka, Keith Weiss, Carmen Hundley, Alex Straton, Jonathan Lanterman, Shaked Atia, Lisa Nekrasova, and Ethan C. Ellison. Investment Implications of the Final Frontier. Technical report, Morgan Stanley Research, 2017.

[68] Christine Joseph. A Micro- and Macro- Analysis of Human-Machine Interfaces and Systems in Space. Master's thesis, Massachusetts Institute of Technology, 2019. URL: `https://dspace.mit.edu/handle/1721.1/122681`.

[69] Yaniv Kazansky, Danielle Wood, and Jacob Sutherlun. The Current and Potential Role of Satellite Remote Sensing in the Campaign against Malaria. *Acta Astronautica*, 121:292–305, 4 2016. `doi:10.1016/J.ACTAASTRO.2015.09.021`.

[70] D. J. Kessler, N. L. Johnson, J.-C. Liou, and M. Matney. The Kessler Syndrome: Implications to Future Space Operations (AAS 10-016). In *33rd Rocky Mountain Guidance and Control Conference*, volume 137, pages 47–62, Breckenridge, CO, 2010. American Astronautical Society.

[71] Donald J. Kessler and Burton G. Cour-Palais. Collision frequency of Artificial Satellites: The Creation of a Debris Belt. *Journal of Geophysical Research*, 83(A6):2637, 1978. `doi:10.1029/JA083iA06p02637`.

[72] G. Michael Koltiska, Han Du, Dan Prochoda, and Kevin Kelly. AN/FSY-3 Space Fence System Support of Conjunction Assessment. In *Technical Proceedings from the Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2016.

[73] Parimal Kopardekar, Joseph Rios, Thomas Prevot, Marcus Johnson, Jaewoo Jung, and John E. Robinson III. UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations. *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016. `doi:10.2514/6.2016-3292`.

[74] Rafał Kopeć. Geostationary Belt – State's Territory or Province of Mankind? *Review of Nationalities*, 8(1):167–178, 2 2019. `doi:10.2478/pn-2018-0011`.

[75] Scott A. Kotler. Comments of Lockheed Martin Corporation, 2019. URL: `https://www.fcc.gov/ecfs/filing/10405091397740`.

[76] Holger Krag, Stijn Lemmens, and Letizia. Space Traffic Management Through the Control of the Space Environment's Capacity. In *1st IAA Conference on Space Situational Awareness*, Orlando, FL, 2017. International Academy of Astronautics.

[77] Bhavya Lal, Asha Balakrishnan, Becaja M Caldwell, Reina S Buenconsejo, and Sara Carioscia. Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM). Technical report, Science & Technology Policy Institute, Washington D.C., 2018.

[78] Laser Clearinghouse Team. Laser Clearinghouse (LCH). URL: `https://www.space-track.org/documentation#/lch`.

[79] Margaret D. Lecompte and Judith Preissle Goetz. Problems of Reliability and Validity in Ethnographic Research. *Review of Educational Research*, 52(1):31–60, 1982.

[80] Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Legal Subcommittee on its fifty-fourth session, held in Vienna from 13 to 24 April 2015. Technical report, United Nations, Vienna, Austria, 2015.

[81] Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Legal Subcommittee on its fifty-fifth session, held in Vienna from 4 to 15 April 2016. Technical report, United Nations, Vienna, Austria, 2016.

[82] Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Legal Subcommittee on its fifty-sixth session, held in Vienna from 27 March to 7 April 2017. Technical report, United Nations, Vienna, Austria, 2017.

[83] Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Legal Subcommittee on its fifty-seventh session, held in Vienna from 9 to 20 April 2018. Technical report, Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space, Vienna, Austria, 2018.

[84] Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Legal Subcommittee on its fifty-eight session. Technical Report A/AC.105/1203, Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space, Vienna, Austria, 2019.

[85] Francesca Letizia, Stijn Lemmens, Benjamin Bastida Virgili, and Holger Krag. Application of a debris index for global evaluation of mitigation strategies. *Acta Astronautica*, 161(February):348–362, 8 2019. `doi:10.1016/j.actaastro.2019.05.003`.

[86] Francesca Letizia, Stijn Lemmens, and Holger Krag. Environment capacity as an early mission design driver. *Acta Astronautica*, 173:320–332, 2020. `doi:https://doi.org/10.1016/j.actaastro.2020.04.041`.

[87] Christine Leurquin. Introduction to the Space Data Association, 2011. URL: `https://swfound.org/media/52875/christine_leurquin.pdf`.

[88] Miles Lifson. Interview with Stephen Earle, 2019.

[89] Miles Lifson. Interview with Erin Miller, 2020.

[90] Miles Lifson. Interview with Ryan Shepperd, 2020.

[91] Miles Lifson and Danielle Wood. Implications of Emerging Space Nation Stakeholder Preferences for Future Space Traffic Management System Architecture (IAC-19 E3.4), 2019.

[92] J.-C. Liou. An Active Debris Removal Parametric Study for LEO Environment Remediation. *Advances in Space Research*, 2011. `doi:10.1016/j.asr.2011.02.003`.

[93] J.-C. Liou and Nicholas L. Johnson. A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO. *Acta Astronautica*, 64(2-3):236–243, 1 2009. `doi:10.1016/J.ACTAASTRO.2008.07.009`.

[94] J.-C. Liou, N.L. Johnson, and N.M. Hill. Controlling the Growth of Future LEO Debris Populations with Active Debris Removal. *Acta Astronautica*, 66(5-6):648–653, 3 2010. `doi:10.1016/j.actaastro.2009.08.005`.

[95] J.-C. Liou, M. Matney, A. Vavrin, A. Manis, and D. Gates. Project Review: NASA ODPO's Large Constellation Study. *Orbital Debris Quarterly News*, 22(3), 9 2018. URL: `https://www.orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i3.pdf`.

[96] Lockheed Martin Corporation. Space Fence Now Actively Monitors Orbital Debris as Small as a Marble, 2020. URL: `https://www.lockheedmartin.com/en-us/news/features/2020/space-fence-now-actively-monitors-orbital-debris-as-small-as-a-marble.html`.

[97] Andrew Long and Robert Feconda. Comments of Keplerian Technologies Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/10405184706997`.

[98] Laura Delgado López. Space Sustainability Approaches of Emerging Space Nations: Brazil, Colombia, and Mexico. *Space Policy*, 37:24–29, 2016. `doi:10.1016/j.spacepol.2015.12.004`.

[99] Michael Lucibella. Air Force Restrictions Impact Adaptive Optics, 10 2009. URL: `https://www.aps.org/publications/apsnews/200910/optics.cfm`.

[100] Tim Maclay and Darren Mcknight. Space Environment Management: Framing the Objective and Setting Priorities for Controlling Orbital Debris Risk. In *Proceedings of the 70th International Astronautical Congress*, pages 21–25, Washington, D.C., 10 2019. International Astronautical Federation. URL: `https://www.oneweb.world/assets/news/media/Space-Environment-Management-Framing-the-Objective-and-Setting-Priorities-for-Controlling-Orbital-Debris-Risk.pdf`.

[101] Mark W. Maier. *The Art of Systems Architecting.* CRC Press, Boca Raton, 2nd edition, 2000. `doi:10.1201/9781420058529`.

[102] Tanja L Masson-Zwaan and Mahulena Hofmann. *Introduction to Space Law.* Wolters Kluwer, Alphen aan den Rijn, The Netherlands SE, 4 edition, 2019.

[103] Jonathan C McDowell. The Edge of Space: Revisiting the Karman Line. *Acta Astronautica*, 151:668–677, 10 2018. `doi:10.1016/j.actaastro.2018.07.003`.

[104] Darren McKnight. A Practical Perspective on Space Traffic Management. *Journal of Space Safety Engineering*, 6(2):101–107, 6 2019. `doi:10.1016/j.jsse.2019.03.001`.

[105] Maureen C. McLaughlin. Comments of Iridium Communications Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/104050570315757`.

[106] Theodore J. Muelhaupt, William H. Ailor, Josef S. Koller, Marion E. Sorge, Alan B. Jenkin, and Roger C. Thompson. Comments of the Aerospace Corporation, 2019. URL: `https://www.fcc.gov/ecfs/filing/10307212587227`.

[107] David Murakami, Sreeja Nag, Miles Lifson, and Parimal Kopardekar. Space Traffic Management with a NASA UAS Traffic Management (UTM) Inspired Architecture. *AIAA Scitech 2019 Forum*, (January):1–27, 2019. `doi:10.2514/6.2019-2004`.

[108] Christopher Murphy, Daryl T. Hunter, John P. Janka, and Elizabeth R. Park. Comments of Viasat, Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/10405682711799`.

[109] Sreeja Nag, David Murakami, Miles Lifson, and Parimal Kopardekar. System Autonomy for Space Traffic Management. In *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*, pages 1–10. IEEE, 9 2018. `doi:10.1109/DASC.2018.8569343`.

[110] Sreeja Nag, David D. Murakami, Nimesh A. Marker, Miles T. Lifson, and Parimal H. Kopardekar. Prototyping Operational Autonomy for Space Traffic Management. In *Proceedings of the 70th International Astronautical Congress*, Washington, D.C., 2019. International Astronautical Federation.

[111] NASA. Orbital Debris Engineering Model (ORDEM), Version 3.1.1.1. URL: `https://software.nasa.gov/software/MSC-25457-1`.

[112] NASA Orbital Debris Program Office. LEGEND : 3D/OD Evolutionary Model. URL: `https://orbitaldebris.jsc.nasa.gov/modeling/legend.html`.

[113] National Research Council. *Orbital Debris: A Technical Assessment*. National Academies Press, Washington, D.C., 6 1995. `doi:10.17226/4765`.

[114] National Space Council. Space Policy Directive-3, National Space Traffic Management Policy, 2018. URL: `https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/`.

[115] Elisabeth Neasmith. Comments of Telesat Canada, 2019. URL: `https://www.fcc.gov/ecfs/filing/1040662931484`.

[116] Emily S Nightingale, Bhavya Lal, Brian C Weeden, Alyssa J Picard, and Anita R Eisenstadt. Evaluating Options for Civil Space Situational Awareness (SSA). 2016.

[117] Daniel Oltrogge. Testimony of Mr. Daniel Oltrogge at “Space Situational Awareness: Key Issues in an Evolving Landscape”, 2 2020. URL: `https://science.house.gov/imo/media/doc/OltroggeTestimony.pdf`.

[118] Daniel L. Oltrogge. The “We" Approach to Space Traffic Management. In *SpaceOps Conference*, pages 1–21, Marseille, France, 2018. `doi:10.2514/6.2018-2668`.

[119] Daniel L Oltrogge, Thomas M Johnson, and Andrew R. D’Uva. Sample Evaluation Criteria for Space Traffic Management Systems. In *1st IAA Conference on Space Situational Awareness*, Orlando, FL, 2017.

[120] Elinor Ostrom. *Governing the Commons: The Evolution of Institutions for Collective Action.* Cambridge University Press, Cambridge, 2015. `doi:DOI:10.1017/CBO9781316423936`.

[121] Ufuoma Ovienmhada. Earth Observation Technology Applied to Environmental Management: a Case Study in Benin. Master's thesis, Massachusetts Institute of Technology, 2020.

[122] William Pasmore, Stu Winby, Susan Albers Mohrman, and Rick Vanasse. Reflections: Sociotechnical Systems Design and Organization Change. *Journal of Change Management*, 19(2):67–85, 2019. `doi:10.1080/14697017.2018.1553761`.

[123] Sebastian M. Pfotenhauer, Danielle Wood, Dan Roos, and Dava Newman. Architecting Complex International Science, Technology and Innovation Partnerships (CISTIPs): A Study of Four Global MIT Collaborations. *Technological Forecasting and Social Change*, 104:38–56, 2016. `doi:10.1016/j.techfore.2015.12.006`.

[124] M. Rathnasabapathy, D. Wood, M. Jah, M. French, C. Christiansen, A. Schiller, F. Letizia, H. Krag, S. Lemmens, N. Khlystov, and M. Soshkin. Space Sustainability Rating: Towards an Assessment Tool to Assure the Long-Term Sustainability of the Space Environment. In *70th International Astronautical Congress*, Washington, D.C., 2019. International Astronautical Federation.

[125] Blake E. Reid, Allen Magnusson, Frederick Steimling, and Jordan Regenie. Reply Comments of University Small-Satellite Researchers, 2019. URL: `https://www.fcc.gov/ecfs/filing/105062044904107`.

[126] J. Reid, C. Zeng, and D. Wood. Combining Social, Environmental and Design Models to Support the Sustainable Development Goals. In *2019 IEEE Aerospace Conference*, pages 1–13, 2019. `doi:10.1109/AERO.2019.8741623`.

[127] James D. Rendleman and Sarah M. Mountin. Responsible SSA Cooperation to Mitigate On-orbit Space Debris Risks. In *RAST 2015 - Proceedings of 7th International Conference on Recent Advances in Space Technologies*, pages 851–856. Institute of Electrical and Electronics Engineers Inc., 8 2015. `doi:10.1109/RAST.2015.7208459`.

[128] Lucie Reymondet. A Framework for Sense-Making of Complex Sociotechnical Systems. Master's thesis, Massachusetts Institute of Technology, 2016. URL: `http://seari.mit.edu/documents/theses/SM_REYMONDET.pdf`.

[129] Horst W. J. Rittel and Melvin M. Webber. Dilemmas in a General Theory of Planning. *Policy Sciences*, 4(2):155–169, 1973. `doi:10.2307/4531523`.

[130] Per Runeson and Martin Höst. Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2):131–164, 2009. `arXiv:9809069v1`, `doi:10.1007/s10664-008-9102-8`.

[131] Russian Federation. Further Ideas on a Set of Goals for Achieving the Vienna Consensus on Space Security and the Need for Thorough Reflection on the Modalities of Addressing the Complex Issues Associated with Space Traffic Management and the Justifiability of the High Expect. 2016.

[132] Mike Safyan, Jonathan Rosenblatt, and George John. Joint Comments of Planet Labs Inc. and Spire Global, Inc., 2017. URL: `https://www.fcc.gov/ecfs/filing/10228859518563`.

[133] Victoria Samson. Possible SSA Futures : A Report of the 2017 AMOS Dialogue. In *4th Annual STM Conference, "Seeking Sustainable Solutions"*, Daytona Beach, FL, 2018. ERAU, Secure World Foundation. URL: `https://swfound.org/media/206065/vsamson_erau_stm_jan_2018.pdf`.

[134] Craig Scheffler. Reply Comments of the Commercial Smallsat Spectrum Management Association, 2019.

[135] Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Scientific and Technical Subcommittee on its fifty-third session, held in Vienna from 15 to 26 February 2016. Technical report, United Nations, Vienna, Austria, 2016.

[136] Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Scientific and Technical Subcommittee on its fifty-fourth session, held in Vienna from 30 January to 10 February 2017. Technical Report February, United Nations, Vienna, Austria, 2017.

[137] Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Scientific and Technical Subcommittee on its fifty-sixth session, held in Vienna from 11 to 22 February 2019. Technical report, United Nations, Vienna, Austria, 2019.

[138] Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space. Report of the Scientific and Technical Subcommittee on its fifty-seventh session, held in Vienna from 3 to 14 February 2020. Technical report, United Nations, Vienna, Austria, 2020.

[139] Alan Scott, Craig Haley, and Neil Rowlands. Flexible Next-Generation Space-Based SSA Payload. In *Advanced Maui Optical and Space Surveillance Technologies Conference*, Maui, HI, 2014. Maui Economic Development Board. URL: `http://www.amostech.com/TechnicalPapers/2014/Space_Systems/SCOTT.pdf`.

[140] Secure World Foundation. Summary of the 2017 AMOS Dialogue. URL: `https://swfound.org/media/206083/2017-amos-dialogue-report.pdf`.

[141] Secure World Foundation. Capacity-building for Space Sustainability: The Role of Government, Industry and Civil Society, 2020. URL: `https://swfound.org/events/2020/capacity-building-for-space-sustainability-the-role-of-government-industry-and-civil-society`.

[142] Michael Sheetz. The Space Industry will be Worth Nearly $3 trillion in 30 Years, Bank of America Predicts, 10 2017. URL: `https://www.cnbc.com/2017/10/31/the-space-industry-will-be-worth-nearly-3-trillion-in-30-years-bank-of-america-predicts.html`.

[143] Mark Skinner. Conceptual Development of a Civil Space Traffic Management (CSTM) Capability. In *Advanced Maui Optical and Space Surveillance Technologies Conference*, Maui, HI, 2018. URL: `https://amostech.com/TechnicalPapers/2018/Poster/Skinner.pdf`.

[144] Walter H. Sonnenfeldt and Stephen L. Goodman. Comments of ORBCOMM Inc., 2019. URL: `https://www.fcc.gov/ecfs/filing/1040634711630`.

[145] Space-Track.Org. Frequently Asked Questions. URL: `https://www.space-track.org/documentation#/faq`.

[146] Tom Stroup. Comments of the Satellite Industry Association, 2019. URL: `https://www.fcc.gov/ecfs/filing/104052764611227`.

[147] E. L. Trist and K. W. Bamforth. Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System. *Human Relations*, 4(1):3–38, 1951. `doi:10.1177/001872675100400101`.

[148] R. Tüllmann, C. Arbinger, S. Baskcomb, J. Berdermann, H. Fiedler, E. Klock, and T. Schildknecht. On the Implementation of a European Space Traffic Management System - III. Technical Requirements. Technical report, DLR, 2017. URL: `https://elib.dlr.de/112204/`.

[149] R. Tüllmann, C. Arbinger, S. Baskcomb, J. Berdermann, H. Fiedler, E. Klock, and T. Schildknecht. On the Implementation of a European Space Traffic Management System-I. A White Paper. Technical report, DLR, 2017. URL: `http://elib.dlr.de/112148/`.

[150] R. Tüllmann, C. Arbinger, S. Baskcomb, J. Berdermann, H. Fiedler, E. Klock, and T. Schildknecht. On the Implementation of a European Space Traffic Management System-II. The Safety and Reliability Strategy. Technical report, DLR, 2017. URL: `https://elib.dlr.de/112163/`.

[151] United Nations General Assembly. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 1966. URL: `http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html`.

[152] United Nations General Assembly. Convention on Registration of Objects Launched into Outer Space, 1974. URL: `https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html`.

[153] United Nations Office for Outer Space Affairs. Long-term Sustainability of Outer Space Activities. URL: `https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html`.

[154] United Nations Office for Outer Space Affairs. Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. Technical report, United Nations, Vienna, 2010.

[155] David A. Vallado. *Fundamentals of Astrodynamics and Applications*. Springer, New York, 3 edition, 2007.

[156] Petra A. Vorwig and Suzanne Malloy. Comments of SES Americom, Inc. and O3b Limite, 2019. URL: `https://www.fcc.gov/ecfs/filing/10405569822298`.

[157] Brian Weeden. Muddling Through Space Traffic Management, 9 2017. URL: `http://spacenews.com/muddling-through-space-traffic-management/`.

[158] Brian Weeden and Ian Christensen. Comments of the Secure World Foundation, 2019. URL: `https://www.fcc.gov/ecfs/filing/1040650203789`.

[159] Brian C. Weeden and Tiffany Chow. Taking a Common-pool Resources Approach to Space Sustainability: a Framework and Potential Policies. *Space Policy*, 28(3):166–172, 8 2012. `doi:10.1016/j.spacepol.2012.06.004`.

[160] Charity Weeden, Jonathan Goff, Jessica Noble, Jeremy Schiel, Dana Turse, Colin Doughan, John Carrico, and Rob Patterson. Comments of Global NewSpace Operators, 2019. URL: `https://www.fcc.gov/ecfs/filing/1040578949828`.

[161] J. R. Wertz, D. F. Everett, and J. J. Puschell. *Space Mission Engineering: The New SMAD*. Space Technology Library. Microcosm Press, 2011.

[162] William M. Wiltshire, Paul Caritj, Patricia Cooper, and David Goldman. Comments of Space Exploration Technologies Corp., 2019. URL: `https://www.fcc.gov/ecfs/filing/104050365604744`.

[163] William M. Wiltshire, Paul Caritj, Patricia Cooper, and David Goldman. Application for Modification of Authorization for the SpaceX NGSO Satellite System, 2020. URL: `https://fcc.report/IBFS/SAT-MOD-20200417-00037/2274315.pdf`.

[164] Danielle Wood. *Building Technological Capability within Satellite Programs in Developing Countries*. PhD thesis, Massachusettes Institute of Technology, 2012. URL: `http://hdl.handle.net/1721.1/79502`.

[165] Danielle Wood, John Polansky, and Mengu Cho. University Partnerships as a Model for Capability Building in Emerging Space Nations. In *Proceedings of the 66th International Astronautical Congress*, Jerusalem, Israel, 2015. International Astronautical Federation.

[166] Danielle Wood and Annalisa Weigel. A Framework for Evaluating National Space Activity. *Acta Astronautica*, 73:221–236, 4 2012. `doi:10.1016/j.actaastro.2011.11.013`.

[167] Danielle Wood and Annalisa Weigel. Charting the Evolution of Satellite Programs in Developing Countries - The Space Technology Ladder. *Space Policy*, 28(1):15–24, 2012. `doi:10.1016/j.spacepol.2011.11.001`.

[168] Danielle Wood and Annalisa Weigel. Architectures of Small Satellite Programs in Developing Countries. *Acta Astronautica*, 97(1):109–121, 2014. `doi:10.1016/j.actaastro.2013.12.015`.