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Navigating the Skies: An Exploration of Stakeholder Perspectives on Rules for Orbital Traffic Coordination using Grounded Theory and Case Study Research Methodologies

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Navigating the Skies: An Exploration of Stakeholder Perspectives on Rules for Orbital Traffic Coordination using Grounded Theory and Case Study Research Methodologies

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Dissertation Submitted to the College of Aviation in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy in Aviation

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Navigating the Skies: An Exploration of Stakeholder Perspectives on Rules for Orbital Traffic Coordination using Grounded Theory and Case Study Research Methodologies

By

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This dissertation was prepared under the direction of the candidate's Dissertation Committee Chair, Dr. Steven Hampton , and has been approved by the members of the dissertation committee. It was submitted to the College of Aviation and was accepted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Aviation.

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Abstract

Researcher: Scott Alan Haeffelin

Title: Exploring Rules for Orbital Traffic Coordination

Institution: Embry-Riddle Aeronautical University

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This dissertation explored standards, rules, or regulations ("rules") of orbital traffic coordination to reduce the risk of collisions in space between active space objects. The research questions explored topics associated with areas for potential implementation of rules include maneuvering capabilities, liability and insurance, zoning, right-of-way, and tracking of objects in space.

The researcher utilized an exploratory qualitative research method because of the developing field of study and a growing domain for potential regulation. The research design is a mixture of a case study for bounding and structuring the data collection and grounded theory for a rigorous and well-defined analysis approach. The primary data source is semi-structured interviews used to explore the perspectives of three stakeholder groups with a vested interest in space traffic management. The three groups are space industry, space insurance industry, and space law and policy experts. Amongst the three groups, 19 interviews were conducted.

The data were analyzed to summarize and compare the different perspectives of each group and across the groups. From the summarized perspectives, the intent was to recommend a set of rules, but participants offered few specific rules. Instead, the dissertation’s results present shared considerations across the six research questions to provide the current state of thinking across the community.

Results from this dissertation will provide valuable insight to policymakers beyond feedback generally received during comment periods associated with federal rule-making. National space traffic management legal frameworks need to harmonize globally to optimize space transportation operations and practices. This dissertation contributes to a larger global effort to standardize and solidify rules defining interactions between space operators by capturing the perspectives of experts primarily in and concerning the United States.

Keywords: space traffic management, space policy, orbital coordination, collision avoidance, coordination

Dedication

This dissertation is dedicated to my Grandma Haeffelin, my forever teacher and favorite person. From my earliest memories, she fostered my thirst for knowledge, seeking every opportunity to nurture my curiosity and challenge me. Her unwavering love, wisdom, and belief in my potential have shaped me as a person. She is the driving force behind my success, and I carry her lessons in my heart as I reach this milestone. Her presence has been an immeasurable blessing, and I hope to make her proud.

Acknowledgments

I am deeply grateful to those who made this dissertation possible. To Dr. Hampton, my committee chair, for your invaluable guidance. To my committee members, thank you for your insights. To my parents, husband, and friends, your unwavering support meant everything. Special thanks to my friend, Dr. Troy Techau, for giving me a push, right when I needed the encouragement. To all mentors and colleagues, thank you for shaping my academic journey.

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Chapter I: Introduction

Government and military entities initially dominated space exploration, but commercial entrepreneurs are emerging as significant stakeholders in the space industry (Meeks, 2014; Larsen, 2018). Space is becoming more accessible with the dramatic reduction in launch costs, and advancements in satellite technology, including miniaturization of spacecraft and payloads, are allowing for smaller and more numerous spacecraft (Dillow, 2015). Commercial space launch companies such as SpaceX and Blue Origin continuously work on the means to get to space affordably (Dillow, 2015). The "cost of commercial launches has dropped by a factor of 20 in the last decade" (Frandsen, 2022). Moreover, private companies, not States, conduct space operations ever-increasingly (Johnson, 2017).

The increased activity by the commercial sector, augmenting existing government investment, is expanding, and accelerating the economic and societal benefits of space (Rathberger et al., 2010). It is deepening society’s reliance on space infrastructure for civilian and military purposes, including communications, remote sensing, weather forecasting, navigation, search and rescue, television distribution, missile early warning, and situational awareness systems (Gheorghe &Yuchnovicz, 2015; Pelton, 2015). Additionally, the public utilizes space capabilities in more ways than they realize, including when doing simple everyday tasks such as purchasing gasoline (Hunter & Stephen, 2014). Therefore, a loss of space capabilities would dramatically and negatively impact modern life (Garten, 2012). Today’s dependence on space capabilities highlights the importance of assuring continued access to space and peaceful and responsible use.

The near-infinite size and lack of boundaries make space unique (Garten, 2012).

The lack of comprehensive regulations for operators and activities in outer space has drawn comparisons with the "Wild West" (Rathberger et al., 2010, p.12) by considering it an open territory to explore and exploit. Developing and implementing space policies and laws has remained challenging. State actors characterize the primary focus in current international space law (Schrogl, 2008). The focus on States is evident in the language used in international space treaties, such as the articles written around the construct of *launching states* (Schrogl, 2008). The international treaties signed during the Cold War era defining States responsibilities and liabilities have safeguarded scientific developments and squelched military and territorial conquests but increased non-governmental activities in space show a growing need for effective mechanisms to regulate these activities (Garten, 2012; Schrogl, 2008).

States have not required a complete set of space laws and regulations because of the small size of non-governmental activities relative to the government activities (Garten, 2012). Non-government entities are allowed to operate under existing laws but, under existing international law, States bear the responsibility for the actions of private entities falling under the State's jurisdiction (Contant-Jorgenson et al., 2006). Most space-faring States have some form of domestic laws and regulations on space operations which have generally been sufficient with few consequences (few collisions). With thousands of new satellites launched in the past few years and thousands more on the way, society can no longer operate "under a 'space is big' philosophy" (Maclay et al., 2021, p.152). As with every other form of traffic in the past, the volume of space traffic will reach a tipping point where existing space laws and levels of effort in coordinating space activities will become insufficient (Perek, 1982). It is as if the global space community is waiting for a major collision to occur in space to encourage the establishment of international rules of the road in space, but that is changing as a growing consensus recognizes that the space domain is reaching a tipping point (Larsen, 2018; Stilwell et al., 2020). Gaps exist in national space laws including right-of-way, liability, and zoning laws (AK et al., 2007). Conflicts will arise in the form of operations and allocation of space resources and legal disputes and lawsuits (AK et al., 2007).

The era of only simplified, State-based laws for operating in space is ending as commercial companies increase the development of technologies for easy access to space with shrunken spacecraft and in more significant numbers. The "big sky" theory of the lower probability of satellites colliding will change, particularly in low earth orbit, just as it did in the aviation industry (Hunter & Stephen, 2014; Larsen, 2018). The new era of spaceflight will call for increased responsibility to ensure objects in space do not collide and generate more debris (Maclay et al., 2021). The mean cross-sectional area flux of tracked objects in orbits like the International Space Station (ISS) has increased by a factor of 4 from 2013 through 2021. There are currently several large constellations in development with plans to launch 16,000 new spacecraft over the next decade, more than doubling the number of satellites in orbit (Frandsen, 2022; Gleason, 2020; Pardini & Anselmo, 2022). The increased scope of actions in space, a nascent space tourism industry, anti-satellite weapons, and on-orbit servicing missions further complicate the space environment (Frandsen, 2022). Complications are driving the need for effective regulatory mechanisms over private, non-governmental organizations in space and interest from more actors to be coordinated (Frandsen, 2022; Schrogl, 2008). The current approach to space operations will not be sustainable with the changes coming to the space industry, and increased government regulation is inevitable (Frandsen, 2022; Gleason, 2020).

With the paradigm shift toward extensive commercial space exploration, space policy, and legal experts have been engaged and will continue to be required to recommend future space laws and policies to lawmakers and include private sector perspectives. Future regulations will consist of the coordination of *space traffic*, with space traffic defined in 2001 as:

> [encompassing] all the phases of a space object's life, from launch to disposal. It consists of activities intended to prevent damage in the near term (such as collision avoidance and coordination of re-entry) as well as actions that must be taken to reduce the long-term potential for future damage (such as deorbiting or moving satellites into disposal orbits). (Akgun et al., 2007, p. 871)

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" (p. 20) is one definition for the more extensive space traffic coordination system or *space traffic management* (STM) (Schrogl et al., 2017; Skinner et al., 2019). The goal of STM, like air traffic control, is to use technical and legal mechanisms to decrease the probability of collisions in space (Blount, 2019).

As the definitions imply, STM is complex and spans many disciplines. A shortfall in today's world is that ideas and actors are not always connected to make actions; thus, the formation of space policy needs to be interdisciplinary (Garten, 2012). The broad scope of STM lends itself to a solution set divided into smaller components to establish a manageable yet comprehensive resolution (McKnight, 2018). Four elements define the

STM regime, "the securing of the information needs, a notification system, concrete traffic rules and mechanisms for implementation and control" (Schrogl, 2008, p.274). For safe space operations, the four elements of STM provide the foundation of orbital traffic coordination with tracking, notifying, and directing movements to avoid collision of objects in space.

Two forms of orbital threats contribute to collisions in space: debris and active space objects. Four orbital debris forms contribute to space collisions: inactive space objects, operational debris, fragmentation debris, and microparticulate matter (Nelson, 2014). Each type of threat presents unique challenges in managing the risk of collision, and this dissertation focuses on collision avoidance of whole, active space objects. In a scenario where two things consist of an actionable spacecraft and an uncontrollable piece of debris, the spacecraft is the only object that can react with the option to maneuver or not to maneuver (Kaplan, 2014). Drawing comparisons to a similar industry that people are more familiar with, the aviation industry, the proposed dissertation is not focusing on bird strike detection and mitigation but rather the aircraft-to-aircraft interaction. For instance, air traffic control cannot tell a bird to change its trajectory. Aircraft safety as it relates to the reduction in risk of bird strikes is a field of interest to the industry, but so is the avoidance of runway incursions and effective traffic patterns (Jackman & Millam, 2017).

Regarding the management of space objects, the international community has begun but has not entirely created concrete traffic rules, definitions, policies, and procedures for right-of-way rules, prioritization of maneuvers, zoning (or the creation of spaceways), and rules for geostationary orbit (GSO) and satellite constellations (Schrogl, 2008). In fact, "the actual rules of the road are under-developed from a legal perspective" (Frandsen, 2022, p.232). Although the probability of a collision in space between two spacecraft is low, with the highest risk objects being lethal non-trackable debris, there have already been near misses and impacts on orbit (Cukurtepe & Akgun, 2009). The risk of a collision is increasing, and instances will only increase as time goes on (Cukurtepe & Akgun, 2009). In 2008, the inoperable Russian Cosmos 2257 satellite collided with the active Iridium 33 spacecraft (Chen, 2011). The collision of Cosmos with Iridium was the first time in history that two intact satellites hit in low earth orbit (LEO) (Cornell, 2010). This single event is estimated to have created more than 2,000 new pieces of orbital debris (National Aeronautics and Space Administration [NASA], 2011). Significant in the Cosmos/Iridium case was that Iridium was active, had a propellant, and could have maneuvered out of the way (Ulrich, 2017). The danger of this happening frequently could be exponential growth in the population of orbital objects and the added threat for potential years to come (Ailor, 2004). As the LEO population increases, expect the frequency of close approaches to existing satellites to grow and the need to resolve the issue of accidental collisions to increase (Muelhaupt et al., 2019).

Collision avoidance is germane to discussions and implementation considerations today because of increasing space traffic and financial investments in space architectures, which could result in additional space collisions (Lyall & Larsen, 2016). Currently, over 7,000 satellites exist in orbit with speeds averaging approximately 7.5 km/s in LEO and about 3.07 km/s in geosynchronous orbit (GSO), with a growing fraction of the satellites having the capability to maneuver (18 Space Defense Squadron, 2023; Bonnal et al., 2020; Pelton et al., 2010; Union of Concerned Scientists, 2018). Unlike sea, road, or air traffic, space traffic has intrinsic issues with little equivalence to other traffic management systems, such as the inability to stop in place (Cukurtepe & Akgun, 2009).

An example scenario for managing active space objects is where the 18th and 19th Space Defense Squadron (SDS) identify a highly probable collision course between two commercial co-orbiting spacecraft (Air Force Space Command Public Affairs, 2017). The 18th and 19th SDS, working with the Combined Space Operation Center (CSpOC), is tasked with maintaining the space catalog to monitor orbital debris and to provide conjunction predictions to space operators via their website (Air Force Space Command Public Affairs, 2017; Nag et al., 2021). This information is shared via a public database accessible via space-track.org and is generally considered the gold standard for tracking data (Palanca, 2018). The first spacecraft is an advanced LEO commercial imaging satellite with a mission of taking photos of the Earth for commercial and government users. The second spacecraft was recently launched and is a small, cheap commercial spacecraft without the means to maneuver out of the way. Many active satellites, particularly in LEO, cannot perform maneuvers (Cukurtepe & Akgun, 2009). The larger spacecraft can maneuver, but in doing that, the ground operators must halt mission operations and waste valuable propellants by commanding the spacecraft to maneuver. Using time in orbit to maneuver reduces mission availability, mission product generation and potentially reduces the spacecraft's lifetime. These three factors mean that a maneuver due to a potential collision will have an economic impact on the company. The scenario described presents the conundrum a commercial company would face because of a forced maneuver to avoid crashing into another spacecraft (St. Johns, 2012). Currently, the U.S. military or other commercial space situational awareness (SSA) companies do not provide directives for spacecraft to maneuver but simply provide alerts to companies of a potential collision. Warnings will increase sharply as the catalog population grows, creating a larger workload on space operators to evaluate all collisions (Muelhaupt et al., 2019).

As a second set example of issues that will more frequently arise, Orbcomm has begun launching a constellation of satellites to support data-providing services (Faust, 2015). SpaceX, OneWeb, Spire, and Boeing have all recently announced concepts to place large constellations made up of thousands of total satellites in LEO, with some in a similar orbit as the Orbcomm constellation (Leahy, 2016). Based on filings with the Federal Communications Commission (FCC), two dozen companies have plans to launch over 20,000 satellites in the next ten years (Muelhaupt et al., 2019). One example of inter-company coordination to mitigate in-orbit collision risk was between Spire Global Inc. and Orbcomm. Spire had submitted an application seeking approval from the Federal Communications Commission (FCC) to place a constellation of satellites in orbit. Orbcomm and Spire agreed that Spire would not launch more than their initial eight SHERPA Lemur-2 satellites into an orbit that intersects the OrbComm Generation 2 (OG2) satellites, which the FCC previously authorized to fly at an altitude of 715 km (Rosenblatt & Sonnenfelt, 2016). Lastly, was a situation between the two fast growing constellations from SpaceX and OneWeb. As a OneWeb satellite ascended through the SpaceX Starlink constellation, the 18th SDS alerted the operators of a dangerously close approach that required immediate attention (Roulette, 2021).

Limited, primarily State and military uses of space drove the development of the existing international treaties, and the introduction of more commercial users emphasizes the need for a STM system. Supplementing the international treaties with an inclusive STM system with input from all users will help to protect current and future space investments and create a system to use space efficiently (A.K. et al., 2007; Schrogl et al., 2017). Westphalian, State-centric treaties to limit Cold War era space activities do not address the scenario where two privately owned satellites from the same State collide or nearly collide in space (St. John, 2012). The treaties delegate that responsibility to each State to determine. Space policy and legal experts in each State need to clarify the realities of non-governmental activity in space and make recommendations to lawmakers both at the domestic and international levels (Kayser, 2001).

Rules defining what constitutes best practice standards and negligence in space are expensive but less expensive than the alternative path of continual tort liability litigation between private space companies (Merges & Reynolds, 2010). For example, rules related to spacecraft separation, best uses of volume, right-of-way, and minimum capabilities for entering specific orbital regimes or spaceways have not been defined. At a minimum, to manage orbital traffic and minimize the risk of collision between two manufactured satellites, the community may need to create a basic rule set addressing these and similar issues. This example illustrates the need for space rules to define further the rights, responsibilities, and liabilities in space. More operators developing and launching large constellations amplify the need (Blount, 2021). This dissertation determined the considerations for recommended rules to be considered by domestic or international authorities. However, this dissertation did not discuss who would be the one to create and enforce these rules but rather sought to determine if there is a consensus on potential rules from relevant stakeholders in the community.

Statement of the Problem

STM is a comparatively new subject area, with the earliest scholarly article written by Perek in 1982. Ailor and Filho also began to publish research and academic journal articles on the topic in 2002. The International Academy of Astronautics (IAA) published the first significant summary study in 2006, the *Cosmic Study on Space Traffic Management* (Cosmic Study), with Contant-Jorgenson as rapporteur, and Lála and Schrogl as coordinators, along with several other contributors.

STM is a complex problem, and early contributors such as Perek, Collins, Williams, and Ailor have identified many issues and possible solutions. Still, progress will be slow unless "detailed and justifiable recommendations" are developed (Johnson, 2004, p. 809). As a trending topic for several years, STM has only recently started appearing in scholarly, peer-reviewed journal articles and historically were primarily conference proceedings and notes from meetings (Cukurtepe & Akgun, 2009). The early literary contributions to STM are from a small community of scholars interested in the topic. Still, there is a gap in scholarly writing where assessments from actual stakeholders are collected.

Purpose Statement

The purpose of the qualitative study was to develop a consensus-based set of acceptable rules for minimizing risks of collisions between active, manmade objects that could be used as the baseline for a future STM system. Significant investments are being proposed in space as companies and governments propose large, disaggregated satellite constellations (Taverney, 2011). Ineffective coordination of all these satellites puts billions of dollars of investments at risk. The research aimed to collect, analyze, and present expert opinions, feedback, anecdotes, and recommendations for several different perspectives from stakeholders that will either be involved, affected, or are beneficiaries of a space traffic management system. The stakeholders' assessments were from interviews of experts from three different stakeholder groups: the commercial space industry, space policy experts, and space insurance experts. The second Cosmic Study (Schrogl et al., 2017) echoes the need for conducting such research by stating that there needs to be "further research, in particular involving, in an interdisciplinary approach, relevant expert groups" (p. 120).

Significance of the Study

A review of the literature in the next chapter will show that past studies have been valuable in identifying the need for a space traffic management system. Still, several researchers recommend further interaction with STM stakeholders and more detailed answers. For example, Skinner et al. (2019) described a space safety loop made up of six phases, with phase two being "bring in the stakeholders" (p. 90).

The significance of this dissertation is three-fold. First, this dissertation highlights the critical issues associated with orbital traffic coordination and gets people interested and engaged in the topic. Few peer-reviewed publications exist on the subject. This dissertation is among the first research publications seeking expert opinions and solutions for orbital coordination rules to encourage responsible behavior in space operations. Guidelines exist, but there are no widely accepted rules of the road in outer space (Larsen, 2018). Having well-defined rules of the road will eliminate time-consuming and expensive coordination with less uncertainty and risk for space operations in a congested environment (Frandsen, 2022).

Second, space operations of the future will likely change as technology advances, space becomes even more accessible, and the movements of the large constellation of spacecraft overhead are regulated. This decade's deployment of large constellations and thousands of nanosatellites will overwhelmingly impact the LEO environment (Pardini & Anselmo, 2022). There may be a significant impact on private ventures and investment in space infrastructure due to potential new rules for spacecraft and restrictions on how and where they operate. Rules would, however, provide order in space, benefiting operators (Larsen, 2018). This dissertation offers a platform to hear from stakeholders to shape rules and ensure their interests.

Additionally, this dissertation sought to determine if there is consensus or not among stakeholders for the path forward in developing regulations related to orbital traffic coordination. Based on assessments from stakeholders, the researcher developed an initial set of considerations for rules as a means of providing informed insight for future rule development. The outcome of this dissertation could have a long-term effect on future space operations for private and public space entities.

Lastly, from a societal perspective, the use of space is vital to the everyday lives of the world's people. Destruction of the space environment would impact humans on the ground. Some predictions show that based on the current launch trends and without intervention, collisions in LEO could regularly occur beginning in 2036 (Larsen, 2018). The goal is to provide motivation and insight to encourage intervention therein protecting the space environment and the benefits of space on human life.

Research Questions

This dissertation explored the assessments of stakeholders of space traffic management constructs to determine acceptable rules for minimizing risks of collisions between orbital manmade objects. The specific questions explored in this study are:

RQ1

What do stakeholders of a future space traffic management system assess as acceptable rules regarding the maneuvering of orbital space vehicles for minimizing risks of collisions with manmade, active space objects?

RQ2

What do stakeholders of a future space traffic management system assess as acceptable rules regarding identifying tracking technologies for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?

RQ3

What do stakeholders of a future space traffic management system assess as acceptable rules regarding zoning or the creation of spaceways as a means for minimizing risks of collisions between manmade, active space objects?

RQ4

What do stakeholders of a future space traffic management system assess as acceptable rules regarding the definitions of right-of-way in space for minimizing risks of collisions with manmade, active space objects?

RQ5

What do stakeholders of a future space traffic management system assess as acceptable rules regarding insurance for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?

RQ6

What do stakeholders of a future space traffic management system assess as acceptable rules regarding liability and compensation to encourage responsible use of space for minimizing risks of collisions with other manmade, active space objects?

Delimitations

STM is a complex, multi-disciplinary subject area described by Contant-Jorgenson et al. (2006) as consisting of two dimensions and three phases. The dimensions of space traffic include scientific, technical, and regulatory aspects (Contant-Jorgenson et al., 2006). The three phases of spaceflight are the launch phase, the in-orbit phase, and the re-entry phase (Cukurtepe & Agkun, 2009). Each dimension and each phase create a different piece of the STM structure that needs to be analyzed and defined as part of a comprehensive STM system. To narrow the inquiry scope, this dissertation focuses on the in-orbit phase of space missions. The in-orbit phase is nominally where the spacecraft spends nearly all of its operating life and is the phase relevant to the orbital traffic coordination-based research questions.

The researcher selected three different types of stakeholders to provide various perspectives on acceptable rules for reducing the risk of collision between active orbital space objects. The three groups are: space industry, space insurance industry, and space law and policy experts. The three defined groups are not the only way that the groups could be stratified, but the three groups provide clear boundaries in which to perform a comparative analysis via triangulation of the three groups' responses. Satellite operators, astrodynamicists (the space industry), and space insurance providers are the groups at risk of potential effects due to collision avoidance. Space law and policy experts ultimately inform the government on recommendations of what to write into new rules.

A proposed framework by McKnight (2018) called space operations assurance (SOA) divides the problem that STM is trying to solve. The three components of this framework are space environmental effects and modeling, space situational awareness, and space traffic management (McKnight, 2018). There is an overlap between the three components (e.g., to manage interactions, knowledge of relative position and motion is required, overlapping SSA with STM), but the STM component of the SOA framework includes the management of interactions between space operators within the environment (McKnight, 2018).

This study focused on the interactions between space operators and did not focus on the space operator interactions with the environment, including orbital debris. Debris outnumbers the number of active satellites, with over 22,000 tracked debris objects by U.S. surveillance networks compared to approximately 7,000 operational tracked spacecraft (18 SDS, 2023; Bonnal et al., 2020; Pelton, 2015). Additionally, only 75% of the active objects, or 7.5% of the total objects, can maneuver (Bonnal et al., 2020). The quantity of tracked space debris does not include fragmentation debris and microparticulate matter estimated to consist of hundreds of thousands of pieces of debris larger than 1 cm (European Space Agency [ESA], 2013). Debris mitigation and avoidance is a significant problem that the space industry must contend with and a topic that most feel is the priority over spacecraft-to-spacecraft interactions (Kunstadter & McKnight, 2023). Many stakeholders consider the risk of collision with debris to be substantially higher than with another active spacecraft and that there is marginal benefit in developing a rule system to manage interactions between active objects (Havlikova, 2021). However, debris is uncontrollable, and spacecraft operators have limited options when responding to potential debris collision (maneuver or do not maneuver). Additionally, the risk of collision between two active objects remains possible, as shown by a near miss between the Aelous satellite and SpaceX's Starlink 44 satellite (Havlikova, 2021). In this scenario, both received warnings of a potential collision and engaged in some email communication, but a communication mishap meant late maneuvering without coordination (Havlikova, 2021). Clear STM rules, communications protocols, and automation could have avoided this incident.

The complexity and physics of spaceflight are very different than aviation, but the benefits and challenges related to governing traffic overlap significantly (Frandsen, 2022). Therefore, drawing comparisons to the aviation industry, hazards such as birds or other ground debris are not the primary responsibility of air traffic controllers (MacKinnon, 2018). The primary task of air traffic controllers is to coordinate the movements of aircraft during approach, landing, and taxiing and to ensure the safety of all aircraft by managing separation distances (Bureau of Labor Statistics, 2015). As part of the regulatory authority, the Federal Aviation Administration (FAA) sets the regulations and defines the concept of operations for coordinating aircraft (FAA, 2018). Within the aviation field, studies such as "Stationary Early Warning System for Bird Strike Prevention in Aviation," by Vogel et al. (2009), focusing on bird strikes exist. Still, studies also exist that focus principally on runway incursions of aircraft. An example recent study is "Data-Driven Prediction of Runway Incursions with Uncertainty Quantification," by Gurcsik et al. (2018). Analogously, the focus of this study was not on the dangers and mitigation techniques of orbital debris but on the management of active spacecraft. Note that all active space objects eventually become inactive, and this dissertation considered the impacts of the remaining space objects by exploring liability and compensation in spaceways. Still, the emphasis is not on regulations regarding end-of-life (EOL). Additionally, this study does not focus on debris generated by launch vehicles.

The purpose of this dissertation was to collect and analyze stakeholders' assessments to help inform policymakers for practical implementation solutions. This study aimed to answer the research questions by providing recommendations on rules that have a consensus amongst the stakeholders, identifying points of contention, and providing the details requested by STM authors. This study does not address the enforcement body of future rules.

Since STM is inherently a global problem, the study was not limited to U.S. participants and did accept assessments of stakeholders from the U.S. and the international community. The study's intent was not to use country of origin as a controlled variable, and there was not a defined number of people that had to be from countries outside the U.S.

Limitations and Assumptions

This study covers manmade, active orbital space objects during the in-orbit phase of a space mission. The researcher interviewed an appropriately sized sample of the population of stakeholders until data saturation, and it is reasonable to assume the results of this study are generalizable within each of the three stakeholder groups. Due to divergent requirements during each of the three phases of a space mission, the findings of this dissertation may not apply to other phases of spaceflight or inactive debris. The data collected only represent stakeholders' input at one point in time.

The goal of using grounded theory is to ensure rigor during the data analysis process and minimize researcher bias. The role of the researcher is a limitation to interviewing skills, researcher bias, and general researcher performance affecting the quality of the research. Techniques to overcome these limitations are described more in Chapters II and III. Finally, the interviewees were selected using a convenience and snowball sampling technique. The researcher assumed the participants who have worked in their respective fields for an extended duration qualify as experts. Additionally, participants complied with instructions and provided truthful and honest answers to interview questions.

Definitions of Terms

Absolute Liability	"Liability that is determined to be against the public good or negligent on behalf of a company or parties action. Any party that is assigned absolute liability may have to pay damages to affected parties" (Black's Law Dictionary, 2019).
Active Satellite	A spacecraft is currently functioning and performing its mission as intended or a modified mission in partial failures. Ground has command and control capabilities with the spacecraft.
Apogee	The point of a satellite's orbit around the Earth, which is the farthest away from the central body it is orbiting. The apogee is also the point in the orbit where the spacecraft travels at the slowest speed.

Big Sky Theory	The theory that the volume of space is so large that the probabilities of collision are so small that we do not need to worry about coordinating movements and orbits in space (Contant-Jorgenson et al., 2006).
Collision Avoidance	A purposeful action taken by operators of an active spacecraft to reduce the chance of a collision with an object in space. The object avoided is not necessarily co-orbital or active.
Comparable Traffic Regimes	Other traffic management systems can be used to draw analogies from, the best examples being air traffic management and marine traffic management.
CubeSat	A CubeSat is a small spacecraft with standardized dimensions of 10 cm X 10 cm X 10 cm being 1U. CubeSats can be built to be multiples of U in sizes such as 3U and 12 U. Capabilities of CubeSats vary. Still, they generally lack many capabilities of larger, more complex spacecraft.
Deorbit	The deliberate activity of bringing a satellite out of orbit to either burn up in the atmosphere (with potential pieces falling to the surface of the Earth) or landing the spacecraft back on the surface of the Earth. Landing can either be using a traditional runway or a capsule landing in

	the ocean or on land with the assistance of parachutes and thrusters.
Debris Avoidance	See Collision Avoidance.
Debris Environment	The condition or surroundings of space due to the presence of debris. Space debris comprises five categories: "payloads, rocket bodies, anomalous debris, mission-related debris, and breakup debris" (Chen, 2011).
Delta-V	Shorthand for delta velocity or a change in velocity. For orbital maneuvers, delta-V is used to describe the magnitude of a maneuver. Note that velocity is a vector quantity, but delta-V is often described as a scalar quantity.
Disposal Orbit	At the end of a spacecraft's usable lifetime, responsible spacecraft operators will dispose of the spacecraft to reduce the risk of collisions with other space objects. For spacecraft that have been designed and operated to have enough propellant remaining to deorbit the spacecraft, a final maneuver will be performed to enter the atmosphere, causing most of it to burn up. This type of disposal is only realistic in LEO. Spacecraft in other orbits or spacecraft that do not have enough propellant remaining to impart enough delta-V for the spacecraft to enter the atmosphere often maneuver the spacecraft into an alternative orbit

	known as a graveyard orbit. The intent is the graveyard orbit is to put the spacecraft in an orbit where it will not interfere with the operations of active spacecraft. GEO most often has this form of disposal because the propellant mass required to deorbit a spacecraft is too high. Unlike in LEO, spacecraft left in graveyard orbits near GEO experience nearly zero drag and will remain in orbit indefinitely.
Earth Orbit	The conic section-shaped path of objects revolving around the Earth.
End of Service/ End of Life	The phase of on-orbit operations when a spacecraft is no longer able or needed to perform its mission. Typically, the end of service is determined by running out of expendable items such as propellant or cryogenic fluids or due to hardware failure.
Geostationary Transfer Orbit (GTO)	The elliptical orbit that spacecraft are released into by the launch vehicle as a staging orbit to get to GSO or GEO. The apogee is typically at or slightly above GSO/GEO altitudes and a perigee in LEO.
Geostationary/ Geosynchronous Earth	

Orbit (GSO/GEO)	A specific circular orbit where the period of an orbit is equal to the Earth's rotation rate. This period is equivalent to one sidereal day, or 23 hours and 56 minutes, and occurs at an altitude of 35,786 km. GEO orbits have an inclination of zero degrees and GSO orbits have a non-zero inclination.
In-Orbit Phase	The second of the three phases of a space mission that is after the launch phase and before the deorbit or disposal phase. The in-orbit phase is typically the longest phase of a mission and is when the satellite is in orbit around the central body, performing its mission.
Insurance Experts	Professionals who work or have worked in a job related to insuring space assets.
Launch Phase	The first phase of the three phases of a space mission that is before the in-orbit phase. This is the phase where the spacecraft is lifted from the surface of the Earth through airspace into the desired orbit or transfer orbit.
Launch Vehicle	The vehicle(s) used to take a spacecraft from the surface of the Earth into an orbit around the Earth or other celestial body (heliocentric orbit). These vehicles could be traditional direct ascent rockets or rockets launched from aircraft.

Liability Convention	The Convention on International Liability for Damage Caused by Space Objects, September 1, 1972.
Low Earth Orbit (LEO)	No official boundaries delineate the different orbital regimes, but LEO is generally regarded as spacecraft orbiting below 2,000 km in altitude (Chen, 2011).
Maneuvering Capability	The ability of a spacecraft to actively change its orbit by use of propellant to impart a force on the spacecraft to create a delta-V.
Medium Earth Orbit (MEO)	Medium is a relative scale, with the low end of the scale being LEO orbits and the high end of the scale being GEO orbits. GPS spacecraft operate in MEO orbits (Gheorghe & Yuchnovicz, 2015).
Nadir	The vector from a spacecraft to the center of the celestial body it is orbiting; the point on a celestial body directly below the observer.
Nanosat	A spacecraft that is smaller than a CubeSat and typically weighs less than 10 kg (Schrogl et al., 2015).
Orbital Debris	Space objects, either manmade or naturally occurring, which are passive in space. Active satellites are not considered orbital debris while in operation.

Outer Space Treaty	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, October 10, 1967.
Perigee	The point of a satellite's orbit, which is the closest to the central body that it is orbiting. The perigee is also the point in the orbit where the spacecraft is traveling at the fastest speed.
Re-entry Phase	The phase of a space mission where the spacecraft deorbits.
Regulatory Experts	Professionals who inform on, create, or are involved in creating laws with substantial experience in making laws and related to the subject matter.
Ride-Share/ Secondary Payloads	Spacecraft that are launched on a rocket along with the primary satellite. Secondary payloads are launched to use the extra lift capacity of the rocket, share the cost of the launch vehicle, and provide a cheap ride to space for smaller spacecraft. After the primary payload is released, the secondary payloads will be released. Secondary payloads include small spacecraft and CubeSats stored and dispensed from dispensers. For example, the tiny spacecraft and dispensers can be mounted on an Evolved Expendable Launch Vehicle (EELV) Secondary Payload

	Adapter (ESPA) ring between the rocket's upper stage and the primary payload.
Satellite/Spacecraft/ Space Object	A vehicle used for travel in space. Legally, the term "space object" also includes "component parts of a space object as well as its launch vehicle and parts thereof" (Liability Convention).
Soft Law Provisions	Soft laws are not strictly binding and are the "instruments that might purport to specify standards of conduct, but do not emanate from the traditional 'sources' of public international law" (Takeuchi, 2014, p. 2). They also can be considered guidelines or non-binding laws but not wholly lacking legal significance (Hörl, 2000).
Space Surveillance	Observation and inspection of the space environment to obtain and track active and inactive space objects (including debris)—a key component of space situational awareness and space domain awareness.
Space Tourism	The industry and activity of people visiting space for pleasure.
Space Traffic	"Encompasses all the phases of a space object's life, from launch to disposal. It consists of activities intended to prevent damage in the near term (such as collision avoidance and coordination of re-entry) as well as actions

	that must be taken to reduce the long-term potential for future damage (such as deorbiting or moving satellites into disposal orbits)" (Akgun et al., 2007, p. 97).
Space Traffic Management	"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" (Contant-Jorgenson et al., p. 10).
Spaceway	A term used in this dissertation to describe the equivalent of airspace in space, or a volumetric definition of services provided, and capabilities required for particular spacecraft to fly within specified orbital regimes. As an example, class B airspace requires authorization from air traffic control (ATC) to enter, extends from the surface to 10,000 feet (sometimes in layers of differing radii), the aircraft must be equipped with a two-way radio operating at the appropriate frequencies, the aircraft must be equipped with a radar transponder, and the pilot must have at least a private pilot certificate (FAA, 2017).
Station-Keeping	The action of performing a maneuver to correct and maintain a desired orbit.

Strict Liability	"When a plaintiff makes a motion to prove harm has occurred without having to show how or why to collect damages" (Black's Law Dictionary, 2019).
Suborbital Spaceflight	Spaceflight where the spacecraft does not achieve orbital velocity and returns to the celestial body's surface without orbiting it. This differs from an air flight because the craft is not held at altitude by the flow of laminar fluids over a lifting body.
Successful Launch	A launch that places a spacecraft in an orbit that allows the spacecraft to perform its mission.
Sun-Synchronous Orbit	A type of polar orbit where the altitude and inclination are set such that the orbital plane rotates in inertial space with an angular velocity equivalent to the Earth's angular velocity around the sun. This rate is approximately 0.9856 degrees per day. The effect and utility of doing this are that the ascending node is at a fixed local time, creating a consistent angle between the sun, the spacecraft, and the Earth. SSO often creates consistent lighting conditions for Earth remote sensing applications (Curtis, 2004).
Thruster	A small rocket engine (could be mono-, bi-, liquid, or solid propellant) used to adjust a space object's orbit, dump

	momentum from onboard momentum management systems, or adjust a space object’s attitude.
Traffic Management	The process of controlling and handling the movement of transportation objects and people.
Transfer Orbit	The temporary orbit that a spacecraft is released by the launch vehicle into on the way to the spacecraft’s final orbit.
Uncontrolled Re-Entry	When a space object’s orbit naturally decays so that it descends to the surface of a celestial body, potentially burning up in the atmosphere, without thrusters to be able to control where and when the spacecraft lands.

List of Acronyms

ADR	Active Debris Removal
AIAA	American Institute of Aeronautics and Astronautics
AI&T	Assembly, Integration, and Test
ASAT	Anti-satellite Weapon/Missile
AST	FAA's Office for Commercial Space
ATC	Air Traffic Control
ATM	Air Traffic Management
COLA	Collision Avoidance
EELV	Evolved Extended Launch Vehicle
EOL	End-of-Life
EPS	Electrical Power System
ESPA	EELV Secondary Payload Adapter
FAA	Federal Aviation Administration
GEO	Geostationary Equatorial Orbit
GPS	Global Positioning System
GSO	Geosynchronous Orbit
GTO	Geostationary Transfer Orbit
HEO	Highly Elliptical Orbit
IAA	International Academy of Astronautics
I.R.	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
ISS	International Space Station

LEO	Low Earth Orbit
LPS	Liquid Propulsion System
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
OCB	Other Celestial Bodies
OST	Outer Space Treaty
R&D	Research and Development
R.F.	Radio Frequency
SBSS	Space-Based Space Surveillance
SSA	Space Situational Awareness
SSN	Space Surveillance Network
STC	Space Traffic Control
STM	Space Traffic Management
STRATCOMM	Strategic Command
TLE	Two-Line Element
U.N.	United Nations
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNOOSA	United Nations Office of Outer Space Affairs

Chapter II: Review of the Relevant Literature

The domain of STM is expansive, so the literature reviewed in this chapter will be limited to topics directly applicable to the research questions. Initially, this chapter will review the basics of space law and discuss major literary pieces and authors. The first publication covering the topic of STM was published in 1932 and provides a thorough look at the field. The article will be used as a guide to discuss the early relevant development of STM topics. The evolution of STM will then be presented in chronological order, broken into different eras.

The remaining literature in this chapter is provided to inform the reader on topics related to the research questions so that interview questions are understandable and nuances in interviewees' answers are understood. The literature review aims to provide enough information so readers can understand the reason for the inquiry and the significance of responses. The researcher grouped questions into three themes for regulations to minimize the risk of collision of active satellites: spacecraft systems, concept of operations (ConOps), and legal considerations. More details about each follow in this chapter.

Last, the researcher provides a concise summary of introductory literature on the research method. The reviewed literature will discuss why interviews are appropriate for answering the research questions.

Fundamentals of Space Law

An international framework of treaties along with a patchwork of varyingly comprehensive national laws makes up space law (Blount, 2019; Oltrogge & Christensen, 2020). The result is an ambiguous legal regime preferred by the military but one that adds risk to the commercial sector (Blount, 2019). Following is a brief discussion of space law's foundational international and U.S. national components.

International Space Law

The United Nation's treaties, agreements, and conventions (treaties), listed in Appendix A1, represent the foundation for international space law. These treaties, in effect, allow operators constrained freedoms of space exploration for peaceful purposes and strict national oversight (Akgun et al., 2007). The Outer Space Treaty (OST), the first and most inclusive of the treaties, took fundamental principles existing as international space community best practices and emerging customary space law and incorporated those practices into international space law (Rendleman, 2012). The three pillars of space law--freedom of exploration, prohibition of appropriation, and peaceful exploration--make up the treaty (Havlikova, 2021). The treaties include fundamentals related to non-appropriation of space or celestial bodies, the concept that space is for the benefit of all mankind, liability, registration, treatment of astronauts, and sharing of information (OST, 1967). The treaties have protected capabilities and assured operators in space, but since the passage of the OST in 1967, technological and economic developments related to space are quickly outdating the treaties (Rendleman, 2012). The configuration of international space law from the 1960s is mainly unchanged while technological developments are constantly advancing (Takekuchi, 2014). Technological advancement encourages new players to conduct operations in space in more significant numbers and the sub-orbital flight regime (Rendleman, 2012).

Overall, the five treaties provide a robust legal framework for space utilization but do not conceptualize a space traffic management system (Rendleman, 2012). The Cosmic

Study in 2006 and 2017 identified a list of missing features of the existing international legal framework:

- The Registration Convention does not require pre-launch notification but only requires registration following the launch. Provisions for pre-launch notifications only exist on a multilateral basis in the non-legally binding Hague Code of Conduct against Ballistic Missile Proliferation (HCOC).
- There is no prioritization of certain space activities, no *right-of-way-rules*, nor is any kind of utilization of space ruled out (as long as following the OST, meaning it must be for peaceful uses).
- There is no prioritization of maneuvers and no traffic separation (*one-way traffic*).
- There are no *zoning* rules (restricting certain activities in certain areas).
- There are no communication rules (advance notification and communication if orbits of other operators are passed).
- There is no legal distinction made between valuable active spacecraft and valueless space debris.
- There are no legally binding rules about the mitigation of space debris, the disposal of spent space objects, and the prevention of pollution of the atmosphere/troposphere.
- Space law lacks enforcement mechanisms. There is no *police* in outer space and no elaborate dispute settlement system, although the Liability Convention includes a method for the settlement of claims.

- Private space activities can, in some cases, escape (i.e., not be subject to) space law and regulations, which is still state-centered.
- The legal delimitation of air space and outer space is missing. (Contant-Jorgenson et al., 2006, p. 39-40)

Beyond establishing international laws via treaties, there are international organizations and industrial consortiums to study and formulate guidelines for all phases of space flight (Larsen, 2018). One such group is the United Nations Committee for the Peaceful Use of Outer Space (COPUOS) which has created guidelines for the long-term sustainability (LTS) of outer space activities (Larsen, 2018). The adoption of LTS guidelines is a significant step toward sustainable space operations, but they may not be sufficient because they are voluntary (Oltrogge & Christensen, 2020).

U.S. National Space Law

International space laws are not the only form of laws governing space. Article VI of the OST assigns the obligation of governing private entities to each State (Contant-Jorgenson et al., 2006). This requires each State to fill the regulatory gaps left by international space law with the expectation that States will create laws to implement the principles and requirements of international treaties. There are a few potential drawbacks to States having the right to govern their traffic, including a lack of harmonization and interoperability of laws in the international community and the possibilities of the creation of a flag of convenience (similar to the maritime industry) (Schrogl et al., 2017).

Relevant to this study is the on-orbit phase of space operations, where there is no agency with explicit authority over in-space activities and there do not exist national space laws anywhere except in an indirect fashion. For example, the FCC regulates radio transmissions in space, and the FAA issues licenses for the launch and re-entry of spacecraft (Harrington, 2015). The Commercial Space Law Amendments Act (2004) is the first legislation to specifically define human spaceflight as a commercial space activity (Meeks, 2014). The same Act also removed launch barriers by streamlining the regulatory process, balanced safety and innovation, and reallocated liability for space flight operators (Meeks, 2014). The term spaceflight participant is for people who want to travel into space aboard a commercial space provider's uncertified vehicle, with only basic training and an informed consent form required. This allows launch providers to operate without insurance on the participants (Meeks, 2014).

The U.S. has made progress on national space laws regarding various activities such as telecommunications, orbital slots in GEO, launch site operations, and the passage of the U.S. Commercial Space Launch Competitiveness Act *(*Space Act of 2015*).* The U.S. Congress passed this legislation to acknowledge the requirement for a comprehensive legal framework developed around STM and required a study of STM (Ellis, 2015). Additionally, Space Policy Directive 3 (SPD3) and the associated legislation that would implement some of SPD3, the American Space Situational Awareness and Framework for Entity Management Act, directs executive departments and agencies to pursue a national space traffic management system with the policy and guidelines included in SPD3 (Trump, 2018b). Most relevant to this dissertation is the section related to maintaining the integrity of the space environment and enabling future operations in a congested space environment (Trump, 2018b). President Trump (2018b) recommended defining a set of best practices, safety standards, and consideration factors for spacecraft operators' pre-launch. These considerations include orbit coordination, the addition of tracking aids, and minimum reliability standards (Trump, 2018b). So far, in the absence congressional action and of adequate state coordination of space traffic, industry associations are working to provide operators with the data needed to operate safely (Larsen, 2018).

An additional update to national space laws because of SPD3 was modifications to the U.S. Orbital Debris Mitigation Standard Practices (ODMSP) which began with a Notice of Public Rule Making in February 2019, followed by final rules announced and finalized in April 2020 (Dodge, 2021; Wiquist, 2020). The FCC updated its rules on satellite debris mitigation in I.B. Docket No. 18–313, FCC 20– 54, Mitigation of Orbital Debris in the New Space Age to address near and midterm debris threats (Dodge, 2021; Mitigation of Orbital Debris in the New Space Age, 2021). These new rules include statements and disclosures that state the operator conducted an assessment and the risk of collision with a large object and debris throughout the life of the satellite is less than 1 in 1,000 and 1 in 100, respectively. Additionally, the operator will disclose the accuracy with which the operator will maintain orbital parameters, trackability of the satellite, planned proximity operations, quantity of fuel reserved for deorbit, maneuverability methods and capabilities, and a list of planned or operational satellites that pose a collision risk (35 FCC Rcd 4156, 2020). The rule-making considered but passed on several additional rules, including changing the 25-year rule, disclosing and imposing an altitude variance and requirements to indemnify the U.S. government for any damage done in space (35 FCC Rcd 4156, 2020; Dodge, 2021). The committee delayed the rules because they did not have an analysis completed to justify and answer one way or another (35 FCC Rcd 4155, 2020). One of the passed rules was revisited in September 2022 when the FCC announced a new rule that any satellite at the end of its mission operating below 2,000 km must deorbit as soon as practicable but no longer than five years instead of the previous 25 years (Wilquist, 2022).

Beyond the progress described, international and national organizations that created guidelines and standards for space operators to follow voluntarily are reviewing the gaps in existing regulations for space traffic management (Hilton, 2019). Specifically, the law gap is related to "insufficient focus on SSA, algorithms, data pooling, development and mandated use of space standards, quality assurance, monitoring, completeness, timeliness, accuracy" (Oltrogge & Christensen, 2020, p.436). A STM system will require a combination of policies, regulations, standards, guidelines, and best practices (Hilton, 2019). The following section will discuss the development and maturation of the concept of space traffic management and provide further detail on relevant unanswered legal questions.

Early Literature Regarding STM

The earliest documented mention of a legal realm related to space traffic was in a 1932 publication *Das Weltraum-Recht: Ein Problem Der Raumfahrt* translated as *Outer Space Law: A problem or Astronautics* (Verspieren, 2021). The authors discussed the possibility of a complement of air law regulations to cover space activities and mentioned, for the first time, the concept of space traffic rules (Verspieren, 2021). In the 1950s and 1960s, there was a significant movement in research related to space policy, including an article published in 1957 and authored by Eugene Pepin (Verspierien, 2021). He identified five elements required to regulate space activities: (1) rockets launching through airspace, (2) re-entry, (3) collision between orbiting satellites, (4) the need for identification, and (5) radio interference (Verspieren, 2021).

International Institute of Space Law

The International Institute of Space Law (IISL) published the first distinct proposal for a set of rules for space shortly after the Moon Agreement (which the U.S. did not sign or ratify) (Perek, 1982; Verspierien, 2021). The publication, *Traffic Rules for Outer Space*, asserts that at the time of the publication in 1982, it was too early to create a complete set of traffic rules for outer space, but that there would be a time when traffic rules would be required (Perek, 1982). Emphasis was placed on proactive and preventive actions to protect the space and upper atmospheric environment. When it comes to regulations regarding similar domains such as traffic in the air, sea, on the road, and even to environmental regulations, lessons learned from many negative experiences (e.g., pollution of those domains) is driving the need to consider space traffic regulations early (Perek, 1982). Regulators must address a standard set of traffic management concepts in air, sea, and on the road for space, including collision avoidance, traffic separation, rules regarding inactive vehicles, pollution prevention, identification, and how to minimize human error. In addition to these common regulation topics, space adds a unique set of other regulatory issues, including flight under natural forces, unmanned space objects (although this is finding its way into air, sea, and ground-based traffic as well), lifetime, debris, range of space applications, and the importance of communication and cooperation (Perek, 1982). A set of principles for STM for combining the standard topics of traffic management with the unique issues of traffic management for space include:

- coordination of communications,

- collision avoidance through traffic separation,
- removal of inactive satellites,
- disposal orbits,
- reducing the amount of space debris,
- restricting human error and technical malfunctions,
- monitoring satellite movements,
- identification of space objects, and
- minimizing pollution (Perek, 1982).

The American Institude of Aeronautics and Astronautiucs (AIAA), the UN Office of Outer Space Affairs (UNOOSA), the Council of European Aerospace Societies (CEAS), and the Canadian Aeronautics and Space Institute (CASI) hosted a workshop in April 1999, with orbital congestion being one of the topics. This workshop section outlined four areas of concern and provided findings and recommendations for each area:

- orbital resource management,
- collision avoidance,
- orbital debris, and
- regulatory framework.

Appendix A2 summarizes the findings and recommendations. The phrase *orbital resource management* was coined and noted as a missing function worldwide for conflicts arising from multiple constellations wanting to launch into the same orbit (Clayton-Townsend et al., 1999).

To manage the scope of the dissertation, the principle of collision avoidance through traffic separation and the missing function of orbital resource management is relevant. It closely resembles zoning or the creation of spaceways to reduce the risk of collisions between active satellites. The potential of spaceways is recognized by discussing how regions of space have varying levels of value and that some areas of space are rarely visited, whereas others are heavily utilized (Collins & Williams, 1986; Maclay et al., 2021; Perek, 1982). Certain orbits provide space operators unique opportunities to conduct their specific mission (Hilton, 2019). Controlling authorities could reserve orbital belts or non-intersecting orbital shells assigned to different space applications and zones for particular activities (Ailor, 2002; Clayton-Townsend et al., 1999; Collins & Williams, 1986; Perek, 1982). Spaceways would use the concept of minimum requirements for operating within each different spaceway (United States Air Force [USAF], 1994). Each zone could be divided into several sub-zones so that many could operate within the larger area (Collins & Williams, 1986). Users could have specified operational rule sets in place to put satellites in orbits with slightly different inclinations to minimize the difference in velocities (Perek, 1982). Others in the shell would be held liable for any collisions created (Collins & Williams, 1986). The decay of LEO orbits is not detailed or how authorities would manage the orbits other than stating that developed schemes should allow for flexible and dynamic planning (Perek, 1982). Also, authorities would give launch vehicles clearance to pass through the zones (and the national airspace) en route to deliver new spacecraft into the designated orbits (Collins & Williams, 1986). Spaceways fulfill similar functionality for spacecraft that airways do for aircraft, such as traffic sequencing and de-confliction (USAF, 1994). Included in the concept of spaceways are the services of space route determination, route tracking and control, rerouting authority, and conflict resolution (Joyner, 2005).

Five requirements for spaceways were outlined by the USAF (1994):

- Definition of what constitutes a route – likely more complicated than aircraft (straight lines) with the spacecraft being less maneuverable, the earth rotating underneath the spacecraft, and the movements not point-to-point.
- Traffic on the route must remain on the course, and the spacecraft and controllers must have some way of verifying that.
- There needs to be a controlling agency that is responsible for assigning and monitoring routes.
- Off-route operations must be coordinated and sanctioned by the controlling authority, or the spacecraft operator must accept that they are moving with due regard.
- There must be penalties for disregarding laws with the worst-case scenario of a collision. Authorities must fix liability and levy some type of penalty, requiring a body with authority to impose these penalties.
- Spaceways are only an interim step toward a fully autonomous future for spacecraft operations. The publication also hints at rules regarding right-of-way with the goal of higher-value spacecraft having the best capabilities to avoid collisions with other space objects autonomously.

The USAF proposed developing a comprehensive space traffic control (STC) system called SPARTACS (USAF, 1994). The STC system is different from a complete

STM system in that it would provide integrated sensor information, collision avoidance information, and flight planning, including de-confliction of spacecraft movements (USAF, 1994). The proposed SPARTACS system divides space objects into three categories: debris, uncooperative or non-interactive members in the SPARTACS system, including older satellites without SPARTACS technology on board, and cooperative, SPARTACS-capable space systems (USAF, 1994). SPARTACS-capable systems include spacecraft with transponders to provide continual position updates via a network of cross-linked spacecraft (USAF, 1994). The concept would require each spacecraft to carry an internal navigation system as well as "housekeeping packages" to perform and report status on station-keeping maneuvers (USAF, 1994, p. D-6). The model would be like how aircraft operate in the national air space with transmitted aircraft position (particularly with NextGen and the requirement for ADS-B Out transponders) (USAF, 1994). The publication does not mention mandating this to be in all spacecraft but notes that the design and implementation of these systems into spacecraft are critical to the system's success and that user participation would grow as the system demonstrates its worth (USAF, 1994).

As the concept of STM evolved, the concern began to center on services for an STM system, including SSA and a service to provide government and commercial space operators with warnings of possible collisions and recommended responses. Table 1 lists the goals of the three primary stakeholders in this STM system: the operators, the government, and the service providers. SSA is not the focus of this proposal, but there are overlapping characteristics envisioned of an SSA service with an orbital coordination service. There would be a collision avoidance service for maneuver planning for as many spacecraft as possible, including tracking upcoming maneuvers and developing rules of the road to resolve interference situations. The service would be required to be reliable (Ailor, 2002). Additionally, there would need to be a regulatory body tasked with creating standards, recommended practices, and operational rules and a permanent coordinating body that monitors the progress and efficiency of the rules implemented (Filho, 2002). Operators would provide data to help regulators determine operational orbits and slots and help governments ensure they meet all their responsibilities in the international space treaties (Ailor, 2002).

Table 1

Stakeholder Goals in a Space Traffic Management/Control System

Operator	Government	Service Provider
Minimal Cost	Unimpeded access to space	Accurate and reliable predictions are provided on time
Data quality sufficient to permit a significant reduction in collision risk	Availability of space assets for commercial and nationally significant uses	Protection from consequences
Service protects the operator's assets from as many threatening objects as possible	A space operating environment that poses as few constraints as possible	Adequate and reliable information on operational characteristics (e.g., control boxes) and plans for upcoming maneuvers
Information on consequences of a mitigation action	All satellite operators abiding by the same space debris mitigation and other internationally agreed-upon rules	Unimpeded access to tracking and resident space object catalog data of resolution and frequency sufficient for reliable and accurate predictions
Sufficient warning so that the move can be planned, optimized, and verified before implementation	Information to assess compliance of operators with space debris mitigation, hardware disposal, and other requirements	Ability to request and receive additional sensor measurements should a close approach warrant
Protection of sensitive and proprietary information about the health and operational	Minimization of the rate of growth of the population of space debris	Sufficient manpower, computers, and tracking resources

Operator	Government	Service Provider
characteristics of an operator's satellites		
Rules of engagement that are fair to all parties	Protection of sensitive government data	
Improved coordination among operators		
Service provider(s) responsive to operator needs		

Note. Adapted from "Space Traffic Management: Implementations and Implications," by W.H. Ailor, 2006, *Acta Astronautica, 58*(5), 279-286 (doi:10.1016/j.actaastro.2005.12.002).

In 1982, the recommendation was to create a forecast of future space traffic, elaborate on the principles provided above, and for a design of orbital allocations to be conducted (Perek, 1982). By 1987, the goal was to have the preparatory work completed and presented to the international community for agreement creation (Perek, 1982). Perek (1982) predicted a 10-year deliberation phase with a 2-year ratification phase before going active in 2001. Creating an organized aerospace control system, such as an Outer Space Agency, was proposed to help develop and implement an international STM system (Collins & Williams, 1986; Perek, 1982). Potentially, the International Civil Aviation Organization (ICAO) would be participating in a constructive role, given its experience in managing traffic in the aviation domain (Collins & Williams, 1986; Filho, 2002). Note that the comments are that the ICAO may play a role, stopping short of recommending the ICAO create global rules, procedures, and standards for a STM system. An initial recommended step was to be taken by the UN Committee of the Peaceful Use of Outer Space (UNCOPUOS) to generate discussion about creating an international space traffic management system (Filho, 2002). Another recommendation was that an international group of insurance companies and underwriters, who have a stake in space safety, should play a constructive role in determining acceptable rules for minimizing the risk of collision in space, hence the inclusion of insurance professionals as a source of data for this inquiry (Collins & Williams, 1986; Larsen, 2018).

The USAF focused on the U.S. leading with the assumption that once the U.S. acts, others will follow in line (USAF, 1994). Historically, Congress quickly passes agreements of relatively minor interest (no national security issues), but agreements of vital national interest have trouble obtaining a consensus (USAF, 1994). A recommendation from an AIAA workshop in 1999 was that there ought to be an international authority on STM, but everyone involved had no agreement. Some feared it was too early to make those suggestions, pointing out that most countries worldwide did not support the movement for an international authority (Johnson, 2004). In 2001, the conference retracted the recommendation, and a new recommendation was that "a single monolithic space traffic control structure and organization is neither a necessary nor a practical approach" (Gibbs & Pryke, 2003, p. 60). Two important outcomes of the 2001 workshop were clarifying the two core elements of STM as preventing damage to ongoing space activities and sustainability of the space environment. Additionally, establishing a working group at the International Academy of Astronautics (IAA) focused on STM, which later produced the 2006 Cosmic Study (Verspieren, 2021).

The community perceived STM as moving slowly, with the meager progress attributed to the complexity of the issue and the perceived absence of urgency (Johnson, 2004). The thought was that development would be slow unless there were "detailed and justifiable recommendations" (Johnson 2014, p.809). Proponents of STM gave three recommendations:

- Develop a solid technical foundation on subjects related to STM to develop "specific and sharply focused" (p.809) guidelines or regulations.
- Develop a proposal for an affordable and unambiguous solution.
- Elevate the debate to decision-makers in the government for the final decisions regarding the implementation of STM (Johnson, 2004).

Cosmic Study 2006

At a second AIAA workshop in 2001, participants suggested that the International Academy of Astronautics (IAA) should conduct a study on STM. The study was published in 2006, followed by a second summary text, *The Cosmic Study*. Experts from various countries and institutions generated these two reports. Before the *Cosmic Study's* final publication, several papers were published or presented at AIAA conferences discussing the progress made by the authors who created the IAA report. Core members prepared texts related to areas of their expertise, which were later synthesized and combined with other texts to be considered a joint effort report (Lála, 2004). The approach was interdisciplinary, with technical and legal experts contributing to the report (Lála, 2004). While creating the first draft, an independent review team from various backgrounds offered input and suggestions for improving the report.

The years invested in the *Cosmic Study* created a thorough and lengthy report which included the status of space traffic, space laws, comparable traffic regimes, elements of a space traffic system for the three phases of flight, and recommendations for future research and regulations. Of relevance to this paper is the section for in-orbit operations and future recommended research and regulations. Also, the report standardized a definition for STM.

Two classes of space objects were defined where collisions and, therefore, collision avoidance are possible: active vehicles and tracked debris objects (note this study focuses on the former) (Contant-Jorgenson et al., 2006). There is currently no way to stop two pieces of debris from colliding. Still, there are changes to space law and operations that could avoid the collision of active satellites (working to eliminate the creation of even more debris) (Contant-Jorgenson et al.,2006). For operational satellites to be able to avoid one another, data needs to be available to warn operators of a potential collision. Only limited data and processing services were available for commercial space operators, but this is changing with groups such as the Space Data Association (Contant-Jorgenson et al., 2006). The executive Space Policy Directive 2 (SPD2) and the recent American Space Commerce Free Enterprise Act are also helping to direct regulators to close the gaps in STM regulations specifically related to addressing the topic of space object monitoring and a warning service for commercial providers and moving that responsibility from the Department of Defense (DOD) to the Department of Commerce (DOC) (Foust, 2018). SPD2 lays the foundation for the DOC to create a one-stop shop for commercial space regulations (Trump, 2018a).

With the information provided that a collision may occur, the most common means of collision avoidance is a maneuver. Moving a spacecraft is generally undesirable due to a service outage, expenditure of valuable propellant, and a reduction in mission lifetime because of the used propellant (Contant-Jorgenson et al., 2006). Some spacecraft, such as the Hubble Space Telescope, cannot maneuver out of the way of a potential collision. Related to maneuvering and data requirements is the length of advance notice given to operators to perform a maneuver (Contant-Jorgenson et al., 2006). Performing maneuvers earlier in advance of a collision reduce the required propellant to move the spacecraft outside the "kill box" (Contant-Jorgenson et al., 2006, p. 68).

The Cosmic Study again identified the lack of zoning of orbits or spaceways in current space operations and the idea of zoning orbits for creating restrictions of specified activities in certain orbital regions (Contant-Jorgenson et al., 2006). Some examples of restrictions include:

- Space billboards or launching the remains of deceased humans restricted to non-interfering orbits, such as extremely low orbits or escape trajectories. Note billboards in extremely low orbits will experience high amounts of drag and will not remain in orbit long.
- Environmental restrictions in heavily used orbits include banning rocket bodies from being left in intersecting orbits and mandating the use of a disposal orbit (this would indirectly create a requirement for maneuver capabilities).
- Fewer restrictions would be placed on lower orbits since the objects would naturally decay faster. Conversely, GEO may require extreme regulations for technical solutions to minimize the creation of operational debris.
- Assignment of flexible missions to alternate orbits to relieve traffic in current orbits. For example, navigation satellites can be placed in various orbits while completing their mission. Place those in obscure orbits to open space for less flexible missions (Contant-Jorgenson et al., 2006).

No entity regulates operators' choice of orbit at a national or international level (Contant-Jorgenson et al., 2006). In addition to orbit selection, no entity regulates the number of satellites in a constellation, and instead, these decisions stem from technical, political, or economic factors (Contant-Jorgenson et al., 2006). For example, Boeing (2016) proposed a constellation consisting of more than 3,000 satellites operating in LEO. Additionally, at the Space Traffic Management Conference at Embry-Riddle Aeronautical University (2016), a panelist described motions by companies such as Orbcomm to the FCC (traditionally in charge of regulating R.F. only) to block SpaceX from launching a large constellation in a similar orbital regime. The motion cites an undue burden on Orbcomm's operators for collision avoidance. In 2018, the FCC approved the SpaceX constellation if an updated deorbit plan was provided but has denied a waiver on a more manageable deployment deadline (Henry, 2018). Since then, SpaceX's constellation has been approved and is flying today.

The lack of regulations related to orbit selection and on-orbit capability is likely to change, however, as the FCC (2018) has released a notice of proposed rulemaking for streamlining the licensing procedures for small satellites. The proposed rules are only for small satellites (less than 180 kg). To be eligible for the proposed streamlined licensing process, the satellites must have a lifetime of fewer than five years, either be deployed below or be deployed from the ISS, or, if orbiting higher than that, must have a propulsion system for maneuvering. Additionally, the proposed regulations would limit the number of satellites licensed under a single small satellite license to 10 (FCC, 2018).

As regulators create laws nationally, commercial space companies could move to other countries which do not restrict the utilization of certain orbits. Going to another, more regulatory-friendly country is known as a *flag of convenience* and points to the importance of an international solution (Contant-Jorgenson et al., 2006).

Overall, findings from the Cosmic Study for in-orbit operations pointed to the growing importance and required quantity of fuel for maneuvering to avoid an in-orbit collision (Contant-Jorgenson et al., 2006). The reliability of collision probabilities relies on reliable data, which at this point, is not guaranteed. Finally, there is no systematic zoning or restriction of orbits, earlier referred to as orbital resource management (Contant-Jorgenson et al., 2006).

The relevant recommendations to this study from the 2006 *Cosmic Study* were to conduct further research on the ability and method of creating a real-time collision avoidance system and to evaluate the mission costs related to collision avoidance (Contant-Jorgenson et al., 2006). Also presented is a framework for an operational STM system. The envisioned international agreement would consist of three parts: 1) securing the information needs, 2) creating a notification system, and 3) traffic management (Contant-Jorgenson et al., 2006). Related to the in-orbit phase of traffic management, policymakers will make fundamental decisions for the creation of the envisioned international agreement consisting of 1) zoning (selection of orbits), 2) right-of-way rules, 3) specific rules for LEO satellite constellations, 4) debris mitigation mechanisms, and 5) environmental provisions (Contant-Jorgenson et al., 2006).

Lastly, the report points to a few regulatory gaps for policymakers to define in future international agreements. These gaps include the definition of a space object, clarification of fault and liability for damage caused, a framework for licensing space vehicles to include insurance provisions, and, importantly, regulations establishing an enforcement mechanism and institutional interlinks (Contant-Jorgenson et al., 2006). One last note, Haeffelin (2016) goes a step further for clarification of fault and liability regulatory gaps to include potential liability for reduction of mission lifetime due to undue burdens of excessive maneuvering for irresponsible constellation operators.

Recent STM Literature

Following the publication of the *Cosmic Study*, further research continued to be published or presented at conferences at a regular frequency. In 2007, Akgun et al. published a paper with a proposed STM system. The system they recommended consists of five services: 1) space monitoring and tracking, 2) space data management, 3) space operations, 4) space warning, and 5) space conflict management services. Three major interested parties are governments, space vehicle operators, and service providers (Akgun et al., 2007). Note how these closely align with the three stakeholders outlined in Chapter I of this dissertation. The publication reiterated the international nature of a STM service. Still, there is difficulty in getting governments interested in creating constraints on space usage and gaining consensus on what those constraints should be (Akgun et al., 2007).

Three simple STM principles are, "1) collisions in space are bad for every space user and must be avoided, 2) all objects in an orbital regime share virtually the same space, and 3) actions of a single operator have the potential to affect the operations of every other satellite sharing the orbital regime" (Orndorff et al, 2009, p. 5). The author emphasized the technological options available for pieces of the STM system with the stated purpose that there will not be a limited near-term success in a comprehensive solution without understanding available options (Orndorff et al., 2009). The technological options discussed by Orndorff et al. (2009) introduce further exciting topics related to tracking technologies, which will be addressed later in this chapter. The enabling technologies lead to a recommendation of a new paradigm for an STM system, transitioning from a ground-based sensor approach to a distributed, self-reporting architecture, like the implementation of NextGen with the requirement of ADS-B out for aircraft (Orndorff et al., 2009).

With growing momentum, Embry-Riddle Aeronautical University hosted the first annual STM conference in 2014. To date, eight conferences have assembled scholars from around the world to discuss the very problems, and many more, laid out in this dissertation. These STM conferences have generated dozens of papers on the subject, from legal to technical.

Cosmic Study 2017

The updated *Cosmic Study* is the most recent significant contribution to the STM literature. The scope of the report remains nearly the same but with the emphasis moving from summarizing the thoughts of the many to updating the progress made toward creating and implementing a STM system. The group laid out a road map similar to what Perek created in 1982, with an estimated ratification date of 2033 (Schrogl et al., 2017). Compared to the 2001 date given by Perek, one can easily observe the snail-like pace of coming to an international consensus related to STM. Early in the report, an update of research activities related to STM is given, listing books that have been written (by many of the contributors to the *Cosmic Study*), conferences that have addressed the topic, and new organizations that have begun to focus on STM. The publication admits that with progress and an ample amount of STM publications, a comprehensive approach for implementing a global-level system has not been delivered (Schrogl et al., 2017).

The 2006 *Cosmic Study* recommended a study at the end, and the updated 2017 version provides the result. The study evaluated the cost impact on operations due to debris avoidance. The study examined satellite operations at 850 km (an orbital regime of high debris density) and found an approximate impact on space operations of 10% (Schrogl et al., 2017). The increase in operations was primarily due to the need to launch a new spacecraft due to solar array damage from small untrackable debris (Schrogl et al., 2017). This emphasizes minimizing the creation of this small debris and collisions contributing to that hazard.

The group creating the *Cosmic Study* report continues to press for a top-down approach to creating a comprehensive STM system. Currently, Schrogl et al. (2017) claim that a bottoms-up approach, with many of the different facets of an STM system, is in varying levels of individual development. As part of the push for a top-down approach, the authors present the framework for an example Outer Space Convention treaty, including the recommended chapters and articles. There are no explicit details within the articles, instead a simple description of the material to include in the article. For example, Article XIII is relevant to this proposal covering space traffic coordination and rules.

Overall, the report covers the same material as the original *Cosmic Study* but provides more detailed information, particularly regarding some technical knowledge. There has always been a firm emphasis on STM's regulatory and legal aspects, and the *Cosmic Study* continues to present those topics in the report. However, regulators have made less progress in creating new space regulations.

One last note out of this most recent publication related to STM, the authors present four actions at the end of the report, the first of which presses for the need to perform the research proposed herein. "Further research, in particular involving, in an interdisciplinary approach, relevant expert groups" is recommended (Schrogl et al. 2017, p. 120).

Risk Reduction Considerations

Engineers can use specific considerations in the design and operations of spacecraft to minimize the risk of collisions in space. For example, the authorities could establish standards for the construction and operation of space objects, like how aircraft have manufacturing standards and are certified by the FAA (Larsen, 2018). As companies deploy large constellations, reliability becomes a significant consideration, with a need for high-reliability standards (Muelhaupt et al., 2019). If 10% of the satellites fail in a constellation of 2,000 satellites, the result is 200 derelict satellites in orbit (Muelhaupt et al., 2019). Multiply that over many constellations and replenishment constellations, and the issue quickly becomes obvious (Muelhaupt, 2019).

The researcher considered three aspects: spacecraft system reliability, operations considerations, and legal considerations. The following three sections and subsections, the goal is to point out parameters regulators could control to affect behavior in space and reduce the risk of collisions.

Spacecraft Systems Considerations

Spacecraft are some of the most advanced pieces of human engineering, with strict requirements to remain operational in orbit potentially for decades. The vacuum of space, extreme cold and boiling temperatures, radiation, and other atomic chemistry require state of the art materials and manufacturing. Spacecraft operate using complex onboard software and advanced ground systems. There is a paradigm shift in which technology is advancing and miniaturizing so that smaller satellites can be built and launched at far cheaper costs than traditional large and complex satellites of the past and present constellations in orbit. A shift is also happening because of a change in mission requirements and a national strategy of disaggregated space assets instead of monolithic assets (Butler, 2012).

The following sections will introduce spacecraft basics, including the classes of satellites and essential subsystems. These sections will give a complete and exhaustive description of each element and provide the reader with enough information to understand the critical aspects under consideration in the research questions for this dissertation.

Satellite Classes. Satellites are classified based on the size of the spacecraft, with only loose definitions differentiating each of the classes. The classes range from the small nanosats to the large satellites that provide the world with most of its communication, navigation, and ISR capabilities. The larger the spacecraft, the more capabilities that can be added.

Of importance to this dissertation and consideration for reducing the risk of collisions between active satellites, it is crucial to discuss CubeSats. CubeSats are measured using units of "U," where one U is defined as a 10 cm x 10 cm x 10 cm cube (United States Space Force, 2015). CubeSats can be as tiny as 1U but can be much larger, typically found in multiples of 3, 6, 9, 12, or 27 U. Greater than 27 U elevates the satellite to the small class of satellites.

CubeSats have traditionally been very simple spacecraft without the ability to maneuver or control their attitude (Schrogl et al., 2017). Operators typically launch

CubeSats as secondary payloads on rockets with one or more large spacecraft. They are, therefore, at the mercy of the launch provider and primary payload provider, although this is changing with new launch systems in development (Gheorghe & Yuchnovicz, 2015). In addition to a simple or non-existent control and propulsion system, CubeSats cannot generate large amounts of power. In LEO, the sun provides approximately 1,367 W/m2 of solar energy, with the most advanced solar panels able to convert less than 30% of that energy into usable power by the spacecraft (Larson & Wertz, 2004). Assuming a 25% efficiency solar panel on a 1U CubeSat and direct lighting conditions, the maximum expected power generated would be 3 or 4 watts. This power is stored in small batteries to allow the spacecraft to operate through the once-per-revolution eclipse characteristic of LEO orbits. The spacecraft uses this power to run the onboard computer, payload, and R.F. energy for the communications system.

Related to tracking, CubeSats are a size that allows for ground-based tracking infrastructure to find and track them (Garber, 2012). The lower limit for tracking on a large scale is currently approximately equal to the size of a 1U CubeSat (Rendleman, 2012). There are concerns that the future volume of CubeSats in orbit will provide challenges for tracking networks unless the capacity and capabilities of these networks are improved (United States Space Force, 2015).

Satellite Systems. Several satellite systems are brought together through systems engineering processes to create a functional spacecraft that can adequately perform its mission. Subsystems that apply to dissertation research topics: the attitude determination and control system, the propulsion system, and the command and data handling system. These three systems are related to the maneuvering and tracking requirements discussed in the research questions.

Attitude Determination and Control System. Spacecraft attitude refers to the angular orientation of a spacecraft with respect to an external coordinate system (Griffin & French, 2004). In short, attitude describes in which direction the spacecraft is pointed. The onboard hardware and software that determine and control the orientation are known as the attitude determination and control system (ADCS). ADCS is one of the significant vehicle subsystems on a spacecraft and drives many of the overall spacecraft requirements (Griffin & French, 2004). Reliable units of the ADCS subsystem tend to be massive, require significant power, and demand considerable onboard processing (Griffin & French, 2004).

There are two ways to control a spacecraft's attitude: actively and passively. An example of each is momentum wheels for an active system and a boom for a passive system (using gravity gradient stabilization) (Griffin & French, 2004). For sensing the spacecraft's orientation, sensors are onboard the spacecraft to provide measurements of external references. Typical spacecraft attitude determination sensors include a star tracker, sun sensors, and Earth-horizon scanners (Griffin & French, 2004).

Propulsion System. Broadly, space propulsion systems do three things: put objects into orbit (or sub-orbit), change orbits, or are used by the ADCS subsystem (Larson & Wertz, 2004). For the scope of this study, the researcher only discusses the latter two. For orbital changes, this is most relevant to moving satellites for debris avoidance or maneuvering spacecraft into disposal orbits. Most spacecraft utilize a monopropellant, bipropellant chemical propulsion system, or one of the several available electric propellant systems (Larson & Wertz, 2004). The propellant for electric power systems is exceptionally light, and the technical performance parameters, such as specific impulse, are superior to chemical thrusters (Larson &Wertz, 2004). However, electric thrusters have a much lower thrust than chemical thrusters, requiring more time to move a spacecraft (Larson & Wertz, 2004). The steady increase in low-thrust electric propulsion systems is creating problems for existing tracking and collision avoidance processes (Muelhaupt et al., 2019).

Command and Data Handling. The command and data handling (C&DH) subsystem allows for instructions and other data to be sent to and from the spacecraft in orbit from the ground (Griffin & French, 2004). At a high level, this subsystem consists of antennas, receivers, processors, and onboard data storage (Griffin & French, 2004). Hardware for the C&DH subsystem has extreme power, mass, and volume limitations which was the original push for the low-power and miniaturized technology that has led to consumer electronics (Griffin & French, 2004). A key term related to the C&DH (or communications) subsystem is the associated *link budget* for the mission. The link budget is essential for designing the communications subsystem, comprising many performance and geometric parameters. The purpose of a link budget is to evaluate the communication link between the ground and the spacecraft and helps to size the amount of required transmitted power and antenna aperture (Larson and Wertz, 2004).

Maneuvering Requirement. Several of the authors in the published STM literature mentioned the concept of zoning in space or restricting access to valuable orbits by placing conditions on spacecraft capabilities. One of those possible required capabilities is the ability to maneuver to avoid a collision in space. As discussed, most CubeSats lack the capability for maneuvering. Therefore, the requirement of maneuverability could be very limiting. As an example, recall current methods for the launch of CubeSats. They are typically launched as secondary payloads and end up in the orbit determined by the launch provider and primary spacecraft provider, potentially in a valuable orbit. Requiring maneuver capability in the valuable orbit could eliminate or reduce the supply of these shared rides of CubeSats as secondary payloads on rockets. Reduced supply could increase the launch cost of CubeSats and perhaps stifle innovation in that market.

Tracking Technology. Before regulators can manage space traffic, users of the system need to be able to determine where others in the system are. Knowing where everything is in space has been discussed by previous authors as the topic of SSA. Access to more accurate SSA data is the most cost-effective safety improvement in the framework of today (Muelhaupt et al., 2019). Orndorff et al. (2009) suggest learning from the air domain and creating an architecture in which active space objects have onboard and ground-based capabilities to help with tracking and collision avoidance. This requires six capabilities: the aircraft must 1) know where it is at, 2) broadcast this data, 3) get data from other spacecraft, 4) have the capability to sense objects in the very near vicinity, 5) process data to determine any future conjunctions, and 6) communicate any planned maneuvers with other users of the STM system (Orndorff et al., 2009). Possible technologies to fit into a system that makes tracking operational spacecraft easier include automatic dependent surveillance-broadcast (ADS-B) for space, RFID technologies for proximity operations, or even future technologies such as photonic telemetry (Orndorff et al., 2009). Requirements that require spacecraft to broadcast their position place several burdens on spacecraft, including complex sensors, processors, and software to determine the spacecraft's position in space and a powerful enough transmitter for the data to reach the ground. As with a requirement to maneuver, a requirement for an active tracking system may add additional cost and complexity to push out smaller satellites from operating in restricted orbital regimes. Engineers could develop other passive technologies to enable ground-based assets to track small space objects more easily to defeat this drawback.

Concept of Operations Considerations

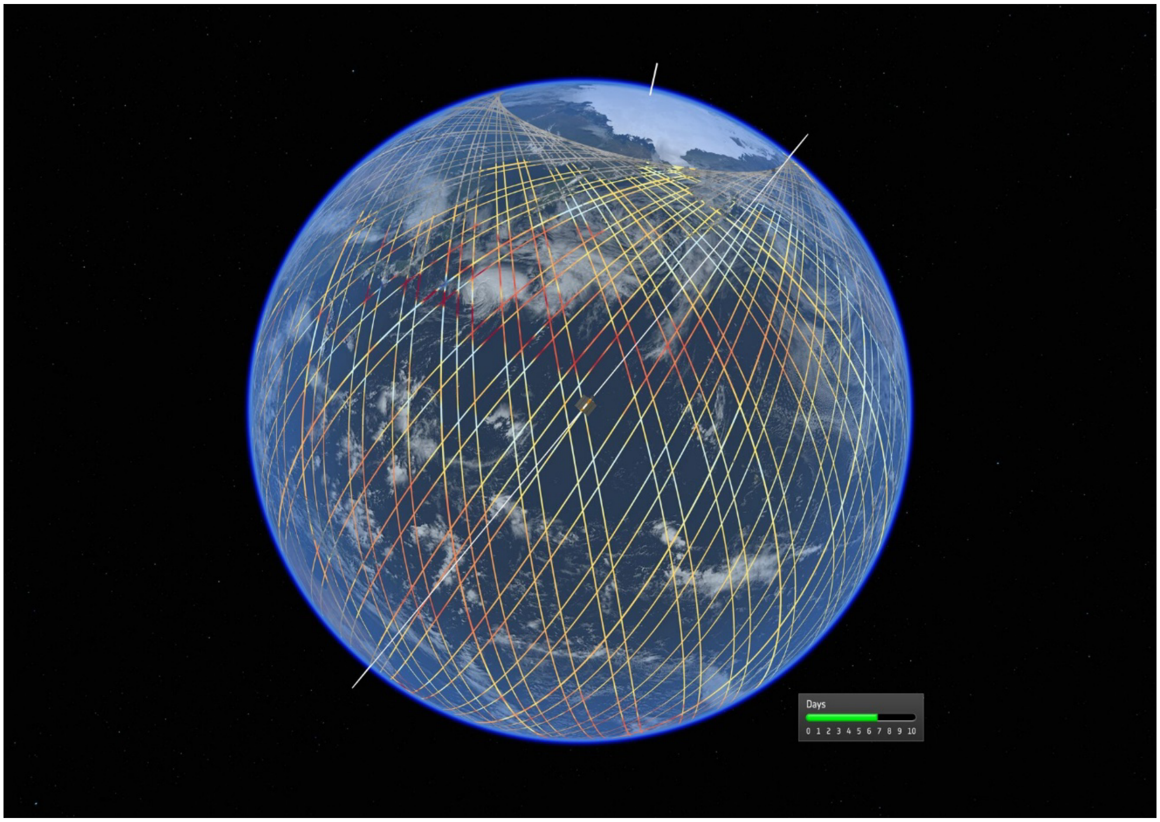
Considerations related to ConOps are ways in which spacecraft are allowed to operate in space. A primary example is the orbits that spacecraft are allowed to operate in and the rules of the road within those orbits to deconflict traffic. The following sections will discuss those considerations through the lens of risk reduction for collisions in space.

Zoning/Spaceways. Pelton and Jakhu (2010) presented a common usage to describe spaceways as serving "the purpose of routing traffic transitioning to and from space" (p. 112). Spaceways would be part of a larger STM and NAS deconfliction system used in conjunction with space transition corridors (STC) to allow spacecraft to traverse through the NAS. STCs are dynamic volumes of airspace that would be closed to aircraft as spacecraft cut their way through the NAS on their way to orbital or sub-orbital space (Pelton & Jakhu, 2010). Other authors published this definition of spaceways in a variety of other literature, but Pelton and Jakhu (2010) also describe spaceways as "similar to today's airways and jet routes" (p.112). This definition is comparable to most of the literature presented. Recall that the USAF (1994) described spaceways as "like today's airways and jet routes" (p. D-16) but with the concept being traffic deconfliction and sequencing in orbit. One can think of spaceways as strategic placement of spacecraft in pre-defined and deconflicted orbits to reduce the number of collision avoidance maneuvers and therefore reduce the risk of collision (Watson, 2012). The researcher evaluated an example architecture specifically for sun-synchronous orbits and designed a *slot architecture* to mitigate conjunctions between participating active satellites without burdening each spacecraft (Watson, 2012).

Space is unique from other traffic regimes because solar system gravitational forces are the primary force controlling space routes (Elder & Hughes, 2005). Physics makes defining spaceways more complicated than describing different airspace classes (Haeffelin, 2016). GEO orbiting objects can maintain positioning in a tightly defined volume of space, but other orbits outside of GEO cannot do that with current technology (Finch, 1986). Orbits create halos around the central body and create volumes similar to toroids or hollow spheres, as shown in Figure 1. Six fundamental parameters define orbits: inclination, right ascension of the ascending node, the argument of perigee, eccentricity, mean motion, and mean anomaly (Kaiser, 2015). The six orbital elements define the exact orbit but do not provide parameters for an ideal solution for bounding spaceways (Haeffelin, 2016).

Figure 1

Example Space Used by a Spacecraft Over Several Days

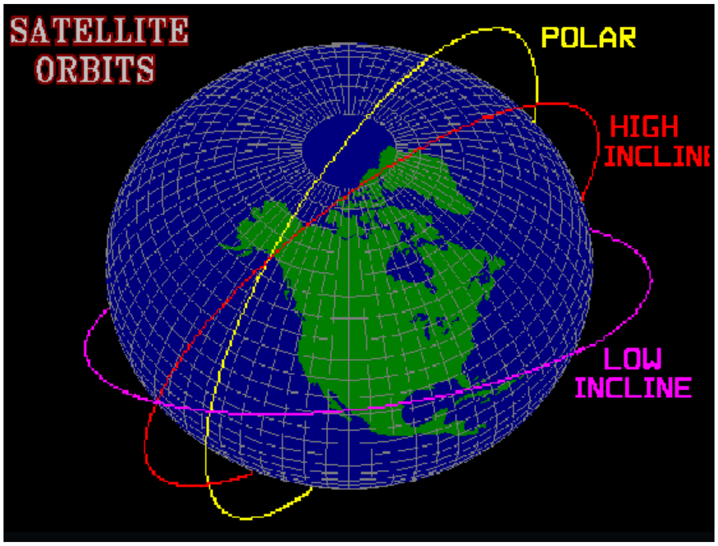


Note. From *Copernicus Sentinel-6 orbital tracks*, by the European Space Agency, 2020, (https://www.esa.int/ESA_Multimedia/Images/2020/11/Copernicus_Sentinel-6_orbital_tracks). In the public domain.

Orbits with different orbital elements may face the danger of conjunctions. For example, two spacecraft in orbits of different inclinations but operating at the same altitude could have a conjunction at two different points, as shown in Figure 2.

Figure 2

Conjunction for Satellites of Different Inclinations



Note. From *The Astronomy Cafe* by Sten Odenwald (http://www.astronomycafe.net/qadir/orbits.gif). In the public domain.

In comparison to the aviation industry, regulators created airspace and the associated requirements for operating within each airspace to protect and maintain high levels of safety in volumes of variable use (Haeffelin, 2016; Muelhaupt et al., 2019). Regulators could use a similar concept of requirements for operations in specific volumes in space by defining the highest-density orbits or orbits with the most applications (Rathgeber et al., 2011). Operators often use GSOs for telecommunications, and LEOs from approximately 400-1,000 km, including polar orbits and sun-synchronous orbits, are typically utilized for Earth observation satellites (Rathgeber et al., 2011). A proposed architecture for synchronous sun orbits was designed and analyzed by Watson (2012).

Right-Of-Way. Regulations define how one spacecraft can gain certain rights-of-way over another to determine which spacecraft is required to maneuver in the event of a potential collision (Schrogl et al., 2017). For most people, the concept of right-of-way is associated with driving, for example, coming to a four-way stop with another driver approaching a stop sign from a different direction. Regulators have created laws to say who goes first so both cars do not lurch into the intersection simultaneously, causing a collision. In navigating at sea, there are defined laws for right-of-way, and vessels are either described as a burdened vessels or privileged vessels (Schrogl et al., 2017). Neither vessel has an absolute right-of-way (Schrogl et al., 2017). A power-driven vessel tends to give way to an unpowered vessel, but with two power-driven vessels headed toward a collision, both are required to give way to the other vessel. Similar rules in space do not exist.

Other traffic rules related to right-of-way are regulations regarding the direction of movement (one-way movements in the sea example), separation standards between vessels, zoning, and corridor rules (Schrogl et al., 2017; Frandsen, 2022). Again, regulators have not defined these traffic laws for space, but regulators could define laws for safer operations and a reduction in collisions.

Legal Considerations

One of the fundamental roles of laws in society is to minimize risk by increasing predictability with standardized interactions between actors (Blount, 2019). The first two considerations discussed are using regulatory authority, but they do not involve regulations alone. This next section quickly mentions two forms of legal considerations to alter operators' behaviors in space.

Liability and insurance. This dissertation already addressed the topic of liability in the discussion of the five international outer space treaties. There is clear guidance on liability in the space between signatory States of the Liability Convention. The State that causes damage to another State's space asset is liable for damages (if one can prove it, of course) (von der Dunk, 2011). However, liability between private parties is not explicitly defined. This consideration for reducing the risk of collision in space focuses on the definition of accountability between private parties to encourage people to act responsibly in space and to place responsible constellations into orbit.

Space losses stem from two primary factors: a reduction in operational lifetime and a reduction of the satellite's overall capability (Fabre, 2002). Fabre (2002) defines three distinct risk categories for losses in space: 1) total loss, 2) constructive total loss, and 3) partial loss. Total loss is simple: the satellite is destroyed and unable to perform its mission. Constructive loss is either a reduction in spacecraft lifetime or function capacity by some threshold amount that the operator could be compensated for (say by having to maneuver frequently due to the placement of a third-party constellation) (Fabre, 2002). Partial loss fits somewhere in the middle. Earlier considerations and literature related to maneuvering in space discussed that maneuvering requires using the valuable propellant on board a spacecraft and, in doing so, reduces the spacecraft's lifetime. When, if ever, do satellites operating without the ability to maneuver or in an irresponsible way, causing others to maneuver, become liable for those actions?

Insurance companies have substantial power in a future STM system, particularly in debris mitigation (Harrington, 2015). The most crucial factor in managing the on-orbit population of objects is compliance with debris mitigation standards (Muelhaupt et al., 2019). Insurance companies could employ technical experts for analysis to provide input to adjust premiums based on debris mitigation measures (Harrington, 2015). Spacecraft with superior space debris mitigation mechanisms reduce the future risk of spacecraft and promote responsible space usage. If governments cannot come to an enforceable consensus regarding debris mitigation requirements, they could, in effect, be implemented by insurance companies (Harrington, 2015). Insurance companies could also provide recommendations on whether and when a spacecraft should maneuver, including creating standards for maximum collision probability to require a maneuver (Harrington, 2015).

An additional option for insurance companies would be to provide incentives such as premium reductions or a requirement for spacecraft to have physical protection against debris impacts (Cox, 2007). The consideration for this requirement is that added physical protection adds mass to the vehicle, increasing launch costs and spacecraft fuel consumption (Cox, 2007).

As with other considerations, additional requirements could add burdensome costs or restrictions to some users, effectively blocking some stakeholders from using a resource defined in international treaties as open for the use of all mankind.

STM Academic Literature

Many publications related to STM have been conference proceedings, literature reviews, or a collaboration of texts from a collection of interested scholars. There is value in the literature generated in these formats, but academic writing such as a dissertation is severely lacking for STM. At the time of this writing, a search for the term "Space Traffic Management" associated with thesis and dissertations resulted in less than 20 relevant academic writings. There are many technical and legal publications related to topics involving the interdisciplinary subject of STM but not directly identifying STM as their area of focus.

Several common trends appear in academic papers written about STM. First and foremost, all but one of the authors use qualitative methods to address their research questions. Half are review papers. Two papers utilize qualitative research techniques, including a case study and a descriptive study with surveys as the data source. Due to the nascent nature of STM, qualitative research methods make the most sense as researchers use them to explore subjects versus test hypotheses (Bowen, 2005).

There are five primary qualitative research traditions: biography, case study, ethnography, grounded theory, and phenomenology (Creswell, 2014). This current research uses interviews as a form of grounded theory and case study to explore the topic of STM.

Ground Theory and Case Studies

Grounded Theory

Grounded theory is an inductive research method used to extract meaning from qualitative data sources and is the first methodological systematic approach for qualitative data analysis (Autry, 2013; Boettcher, 2014; Gardner et al., 2012). The term grounded theory comes from discovering new theories grounded in data created by Anselm Strauss and Barney Glaser (Boettcher, 2014; Gardner et al., 2012). The discovery is made possible by systematically obtaining and meticulously analyzing the social research data (Boettcher, 2014; Saldaña, 2016). Being a combination of exploratory research and a system to develop rigorous conclusions has earned many supporters of the research method (Garner et al., 2012).

The grounded theory approach creates rigor through the detailed procedures used for analysis (Boettcher, 2014). The detailed methods include the development of categories of information, interconnection of the categories, and building a story that associates the categories to enable the researcher to create theoretical propositions (Strauss & Corbin, 1990). The rigorous nature of grounded theory does not guarantee good data or a correct theory because the data collected, and the theory created is dependent on the quality of the questions asked and the quality of the input from interviewees (Boettcher, 2014).

Contrary to empirical theory-testing research, the emergence of categories and themes is made as data is collected (Mumm, 2014). This flexible nature of grounded theory allows for continual adjustments to explore a phenomenon in depth and does not skew the results, but rather it augments the results (Mumm, 2014). In grounded theory, the researcher gathers enough data once theories emerge (Mumm, 2014). In particular, grounded theory helps analyze narrative data, such as interviews, to establish categories and reveal structure (Autry, 2013). As related to the dissertation, grounded theory can mean a systematic analysis of interview transcripts with the ability to go back and forth between the data collection and the data analysis to form a theory (Gardner et al., 2012).

Glaser and Strauss' original publication on grounded theory was published in 1967 with an emphasis on using qualitative data for theory development (Corbin & Strauss, 2015). The grounded theory method provides a systematic but flexible framework for collecting and analyzing qualitative data to construct theories (Charmaz, 2014). An iterative, inductive process alternating between the data and analysis is invoked along with analytical strategies such as constant comparisons (Charmaz, 2014). Using the constant comparison technique, the researcher analyzes the data by breaking it down into smaller, manageable pieces, which the researcher compares for similarities and differences (Corbin & Strauss, 2015). The systematic approach of constant comparisons of data allows thematic concepts to develop, which the researcher groups to form categories or themes (Corbin & Strauss, 2015; Sheikh, 2014).

Furthermore, linkages between the categories or themes must be defined, and a higher-level, abstract concept is defined and called the *core category* or *concept* (Corbin & Strauss, 2015). The core category represents what the researcher deems as the main theme of the research and should be broad enough to be representative of the entire population studied (Corbin & Strauss, 2015). The concepts form the theoretical explanation to address the research questions, and the constructed theory is said to be grounded in and developed inductively from the data analysis (Sheikh, 2014). The developed theories provide a strong foundation for future studies using other quantitative methods (Corbin & Strauss, 2015).

For many forms of research, including qualitative research, theoretical frameworks are appropriate to define but are discouraged when performing grounded theory studies (Corbin & Strauss, 2015). The whole point of grounded theory is to create a theoretical explanatory framework, so it makes no sense for the researcher to define it at the onset (Corbin & Strauss, 2015). The theory is created via well-developed categories and explanations of their respective linkages and relationships to form the theoretical framework and to explain the phenomenon (Corbin & Strauss, 2015).

Since 1967, Glaser and Straus have continued to develop the concept of grounded theory, but they have diverged slightly in their approach (Sheikh, 2014). The two approaches are the Glaserian and Straussian approaches to grounded theory (Halaweh, 2012). “Glaser’s treatment of theory contains strong positivist leanings,” and today is called objectivist grounded theory (Charmaz, 2014, p.235). Straus was joined in later publications by Juliet Corbin, with their early work defined by numerous scholars as post-positivist or somewhere between objectivist and constructivist (Charmaz, 2014). Later publications by Straus and Corbin place their more current view, particularly Corbin, with the constructivist position (Charmaz, 2014). They join Charmaz on the constructivist side of grounded theory, where she describes the constructivist approach as a subset of interpretative tradition (Charmaz, 2014). “A constructivist approach theorizes the interpretive work that research participants do, but also acknowledges that the resulting theory is an interpretation. The theory depends on the researcher’s view; it does not and cannot stand outside of it” (Charmaz, 2014, p. 239). This dissertation aligns primarily with constructivist grounded theory.

One difference between the two approaches is that Glaser has remained true to the original approach and the remaining familiar dictum of grounded theory of avoiding doing a literature review before commencing the study (Charmaz, 2014; Halaweh, 2012). Avoiding doing a thorough research review before beginning the study is to avoid constructing assumptions and beliefs that could bias the researcher (Halaweh, 2012). Researchers build grounded theories from concepts from the collected data through the defined research process and do not choose them before the research commences (Corbin & Strauss, 2015).

Corbin and Straus' modified approach acknowledges that there should be a literature survey before collecting data so that the researcher has some knowledge of the phenomenon being studied (Halaweh, 2012). The modified approach also assists the researcher in formulating appropriate and intelligent questions for initial interviews, particularly for semi-structured interviews (Corbin & Strauss, 2015). After the first several interviews, Corbin and Strauss (2015) recommend adjusting questions based on concepts derived from initial data analysis. As mentioned, the initial data analysis should result in concepts that become the basis for further data collection (Corbin & Strauss, 2015).

Case Study

Case studies are appropriate for contemporary research where the questions are framed by how or why (Shiekh, 2014). In contemporary and historical research, the researcher engages directly by making observations or conducting interviews (Sheikh, 2014). Early publications took a narrow view of case studies to be participant-observations or fieldwork as a data collection process and never elaborated on the definition of case study research (Yin, 2018). Yin (1994) defines case studies in one sentence as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (p.3).

For a case study, a case may be a project or a system with the focus being individuals, groups, or organizations (Halaweh, 2012). In other words, a case study may have an individual, group, or organization as the unit of analysis (Halaweh, 2012). There are three types of case studies: exploratory, descriptive, and explanatory, and case studies can either be positivist or interpretative (Halaweh, 2012; Shiekh, 2014). Positivist case studies are like the Glaserian approach in grounded theory, where researchers use controlled observations and deduction to create generalizable results. Interpretive case studies are like Straussian grounded theory, where the researcher is not concerned about repeatability but "focus[es] on the principles of the interpretive paradigm concepts and interpretations of the informant" (Halaweh, 2012, p. 34). Interpretative case studies align well with grounded theory because the concern of an interpretive case study is for theory creation, not theory testing (Halaweh, 2012).

The Combination

Case studies are not a research methodology choice but a choice of the object to be studied (Stake, 1994). By not being the method, the focus of inquiry is the evaluated phenomenon within multiple contexts rather than the focus being on adherence to tenets of methodology (Sheikh, 2014). The method provides researchers with intellectual flexibility to evaluate numerous perspectives of the issue under consideration (Sheikh, 2014). Researchers who attempt to perform a case study without a clear focus are quickly overwhelmed by the bevy of data to analyze (Eisenhardt, 1989). Therefore, the researcher must clearly understand the purpose of the research questions and the study’s limitations (Sheikh, 2014). Therein lies the dominant characteristic of case study research: creating boundaries, including the scope of cases and unit of analysis. From a grounded theory standpoint, this boundary can be seen as a negative aspect of case studies because emerging issues may not be able to be captured within the defined boundaries (Halaweh, 2012). For the purpose of this dissertation, this boundary is chosen on purpose to focus the inquiry.

Case studies have four fundamental strategies to assist the researcher in the analysis and coding process. Grounded theory is one of the four strategies, and the dissertation will use the grounded theory strategy as the approach for analysis (Halaweh, 2012; Yin, 2018). The pairing of grounded theory and case studies is because each method shares similarities but has different goals (Fischer, 2011). Case studies aim to describe contemporary situations in a real-life context. In contrast, the objective of grounded theory is the development of theories that "describe or explain particular situations and accurately perceive and present another's world" (Savage, 2005, p. 1). A combination of case study research and the grounded theory method of analysis offers the potential to researchers studying socio-technical systems (Fernandez & Lehmann, 2011). The grounded case study approach allows for flexibility and fine-grained research data inherent to grounded theory while bounding the research with the structure of case studies (Halaweh, 2012; Laws & McLeod, 2004).

One of the major criticisms of a case study is the lack of a standard analysis approach (Halaweh, 2012). Case studies, in combination with grounded theory, provide the systematic procedures for analyzing collected data necessary to ease the criticism of case studies (Halaweh, 2012). A weakness of grounded theory is related to the evaluation of research carried out purely using a grounded theory approach and concerns about the quality of the research (Halaweh, 2012). As a case study, the research will be evaluated with criteria suitable for interpretive research, "which makes the evaluation of the proposed methodology more rigorous" (Halaweh, 2012, p.38). The marriage of the two methods improves the weakness of each technique to create a rigorous and structured form of research (Halaweh, 2012).

Summary

This chapter gave an overview of existing STM literature starting from an original publication in 1982, which provided a thorough overview of the need for a STM system and identified a comprehensive list of requirements of such a system. Affirmations, developments, and a broader set of publications were explicitly discussed related to the concept of orbital coordination, and topics related to three thematic considerations (space systems, ConOps, and legal) were covered. Finally, the chapter finished with a review of the literature related to the research methodology described in the next chapter.

Chapter III: Methodology

The content of Chapter II covered the benefits of using a blended approach of case studies for bounding and structuring the data collection and grounded theory for a rigorous and well-defined analysis approach. This chapter discusses the details of the grounded case studies methodology for this dissertation research.

Research Method Selection

The research method is a qualitative study with interviews as the data source. Interviews are the most common and essential forms of qualitative data collection and were chosen as the qualitative source because interviews provide richer, deeper, targeted, and more insightful content than surveys (Charmaz, 2014; Rowley, 2012; Yin, 2016). Prospective selected participants are more likely to be responsive to interviewing opportunities versus filling out questionnaires, and interviews reduce the potential risk of a low survey response rate (Rowley, 2012). The researcher did not select surveys due to the complexity of the issue and the requirement for more detailed insights (Rowley, 2012). Lastly, the researcher formulated the research questions in Chapter I for interviews as the data collection method, and thus interviews are the most effective way of obtaining the desired data (Charmaz, 2014).

The interviews were semi-structured to explore the constructs related to policy to minimize the risks of collisions between active space objects (McMullen, 2015). The interviews consisted of structured, open-ended questions with opportunities for the interviewer to ask probing questions in between the structured queries and resembled a guided conversation (Yin, 2018). Semi-structured interviews provided the structure and consistency (standardization) of structured interviews but allowed further probing to ensure that the topic was covered in detail (Harrell & Bradley, 2009). It is important to note that it is common when conducting qualitative research with interviews as the data collection method for the interview protocol to change. There are several reasons for the interview protocol (or even changes to the research design) to evolve through the data collection process. The case study methodology is adaptive and modifiable by new information, discovery during data collection, or because of suggestions from the interviewee (Yin, 2018).

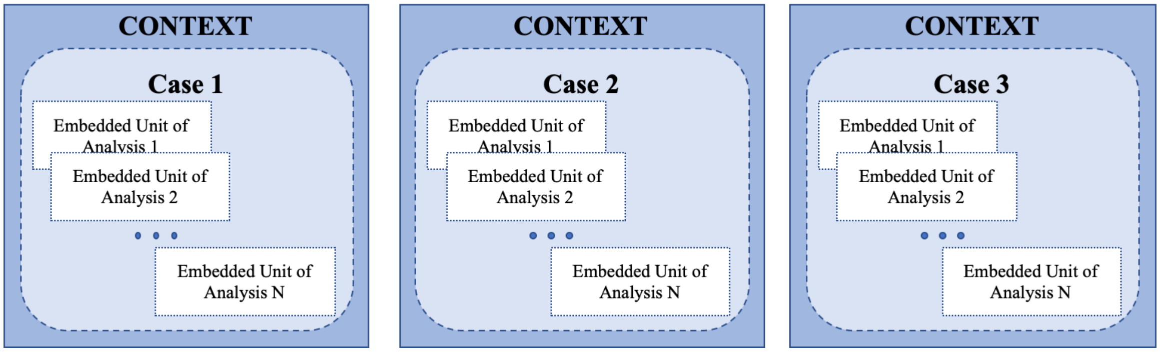
Further revelations are critical and can lead to altering or modifying the original research design (Yin, 2018). When interviewing, the researcher will nearly always conclude with a need to add or change questions (Gardner et al., 2012). As discussed in Chapter II, the goal of grounded theory data collection is saturation. Modifying the interview protocol allows the researcher to explore the topic more deeply to understand and represent the participants' perspectives.

Research Design

The research design for this dissertation was a comparative or multiple case study design using the grounded theory methodology developed by Strauss and Glaser for analysis (Halaweh, 2012; Sheikh, 2014). Working with case-based data grounded in theory provides the researchers with slices of data to analyze, and a multiple case study design is considered more compelling and robust (Fernandez & Lehmann, 2011; Yin, 2018). Figure 3 gives a graphic representation of the research design. For this dissertation, the three cases are the three groups: space industry professionals, space insurance professionals, and space law and policy experts. Within each case, the embedded unit of analysis is the participants within each group. For multiple case study designs, there are two different methods for designating the groups and assigning various participants to each group. The first is literal replication, where individual cases are selected to predict similar results (Yin, 2018). The second is theoretical replication, where individual cases are assigned to predict contrasting results for anticipatable reasons (Yin, 2018). This dissertation utilized the latter method.

Figure 3

Multiple Case Study Design



Note. Adapted from *Case Study Research and Applications: Design and Methods* (p. 48), by R.K. Yin, 2018), Sage (https://study.sagepub.com/yin6e).

Overlapping recommendations in the relevant literature chose the three groups. One source recommends governments, space vehicle operators, and service providers as the three interested parties in STM (Cukurtepe & Akgun, 2009). Space insurance companies should have a constructive role in developing the rules that minimize the risk of collisions in space (Collins & Williams, 1986). The addition of space insurance companies aligns with the second source, which notes the interconnectedness between space insurance, STM, and regulations (Harrington, 2015).

Population/Sampling

Population and Sampling Frame

This section describes the three groups, a definition of who qualifies to be a participant, and the distinguishing characteristics of participants within the three groups (Yin, 2018). Table 3 describes the three groups, the features of the three groups, and some example organizations.

The researcher did not limit professional qualification to the years a professional had worked within one of the three groups due to the nascent nature of space travel (McMullen, 2015). The second consideration was position within their organization. The intent was to ensure the inclusion of the perspectives from many of the new space companies. For example, Jeff Bezos at Amazon does not have a background in space travel, nor has he been working in the space industry for a long time, but he owns one of the emerging launch companies, Blue Origin.

Beyond qualifications, the researcher sought participants that maximized the researcher's ability to evaluate similarities and differences between and within concepts (Corbin & Strauss, 2015). Participants may not be well informed on the broad subject of STM. Still, the interview protocol design is such that participants need not be STM experts but can share their assessments based on their experience in their respective fields of expertise.

Table 2

Group Selection Criteria

Group Name	**Characteristics**	**Example Organizations**
Space Industry	• Professionals from manufacturers of spacecraft • Operators of spacecraft, including constellations of many satellites • Astrodynamicists • Academic professionals with interests in future space capabilities	• Intelsat • SpaceX • The Boeing Company • Lockheed Martin • Maxar • National Aeronautics and Space Administration • Universities • US Military
Space Insurance	• Professionals who work for companies or researchers interested in underwriting or brokering for spacecraft and launch vehicles	• Marsh • AXA • XL Catlin • Universities
Space Policy and Law	• Academic professionals with research interests in space law and policy • Professionals from organizations with interests in space law and policy • Employees from regulatory agencies • Law and legislative professionals in the corporate world	• Universities • United Nation's Committee on the Peaceful Uses of Outer Space • Department of Commerce • Federal Communications Commission

Note. Adapted from *Exploring the Competitive Advantage of the U.S. Commercial Space Transportation Industry: A Qualitative Case Study* [Doctoral dissertation, Northcentral University] (p. 123) by S.A.H. McMullen, 2015, ProQuest Theses and Dissertations (https://www.proquest.com/openview/8f7b01e7f205f0c3aa5885eb07b685bb/1.pdf?cbl=18750&pq-origsite=gscholar).

Sample size

Traditional approaches to sampling, particularly in quantitative research methods, require a predefined and structured volume of data to be collected (Corbin & Strauss, 2015). Grounded theory sets the population (STM stakeholders), but the sample size is undefined, which means no definite number of participants or types of participants (Corbin & Strauss, 2014). Proposing a dissertation with so little definition regarding data volumes is unacceptable, so the researcher added structure by defining a minimum number of participants. There were several differing recommendations from well-respected experts on the subject of qualitative research to help guide the total number of participants that the dissertation required:

- Creswell (2014) recommends 20-30 participants when doing a grounded theory research design.
- Strauss and Corbin advise that at least ten interviews with detailed coding are necessary to build a grounded theory (Saldaña, 2016).
- Smith, Flowers, and Larkin (2009) view a Ph.D. dissertation as equal to approximately three typical Masters-level research projects. For each typical Masters-level research project, they recommended no fewer than three participants, up to six participants. That means that for a Ph.D. dissertation, they recommend 9-18 participants.
- Other experts on this methodology have recommended 20, 30, or 40 participants (Saldaña, 2016). A grounded study by Saldaña (2016) utilized interview data from

> 15 participants. The resulting data was variable enough to create a core category and describe it entirely regarding properties and dimensions.

Therefore, to assure data saturation and rigor, six subject experts from each group of stakeholders (space industry, the insurance industry, and space law and policy experts) were targeted to be interviewed for a minimum sample size of 18 total interviewees (Smith et al., 2009). The maximum sample size was left undefined due to the idea of saturation from grounded theory, which dictates that the researcher should stop collecting data when categories or themes are saturated. Said another way, researchers stop collecting data when gathering new data no longer sparks new insights or reveals new properties and dimensions (Creswell, 2014).

Sampling Strategy

Interpretive research and constructing theory demands that ideas be explored entirely and considered from many different angles or perspectives (Corbin & Strauss, 2015). Case studies often contain perspectives from various disciplines and seek to integrate as closely as possible to the subject of interest (Laws & McLeod, 2014). Interview participants were purposively selected to ensure a diverse representation of key stakeholders in the space and insurance industries and space policy and legal experts (Creswell, 2014). Purposefully selected participants helped the researcher understand the problem and answer the research questions. Purposeful selection does not necessarily suggest random selection (Creswell, 2014). The researcher used a combination of convenience and a snowball sample to find participants to create an initial list of prospective interviewees from each of the three groups based on literature reviews in the field, introductions at conferences, and outreach to leaders from the commercial space industry. Later, recommendations from past interviewees, further literature review, online networking websites such as LinkedIn, and identifying members of the government who are actively working STM related topics identified more participants. Participant selection emphasized individuals with first-hand experience related to the research topic (Charmaz, 2014).

Research Processes and Procedures

Dissertation Process

Figure 4 depicts a high-level dissertation process. Following approval to conduct the research (including institutional review board approval), the researcher conducted a pilot study before the full-scale research and data analysis. Details of the pilot study, full-scale study, and analysis will be detailed later in this chapter.

Figure 4

Dissertation Process

Interview Protocol Development Process

Using an interview protocol helped the researcher conduct the interviews and assured discussion consistency (Charmaz, 2014). Semi-structured interviews vary in form with no consistent number of questions, but six to twelve well-chosen and well-phrased questions are generally recommended (Rowley, 2012). Asking broad, open-ended, and non-judgmental questions to encourage participants to make unanticipated statements allows rich and vibrant stories to emerge (Charmaz, 2014). Approximately a one-hour conversation with the participants drove the design of the interview protocol (the interview protocol is in Appendix B).

The researcher developed the interview protocol in several iterative steps by outlining the entire protocol. The outline consisted of an overview of the research, a discussion of the procedures, expectations for the interview, and the questions related to the research topic (Yin, 2016).

For the protocol, the literature review of books, journal articles, reports, and conference proceedings used as the foundation for the previous chapter created the basis for the interview questions. Chapter II introduced three constructs--spacecraft systems, concept of operations, and legal--and divided the protocol into those three themes. Under each theme, the researcher wrote high-level, broad questions to answer questions identified through the literature review process. Some participants were naturally more verbose in their responses, and the interviews were by no means capped to a one-hour time limit. Other participants were terser, and so on the next iteration, between two and four stimulating sub-questions or prompts were noted for each interview question on the protocol to help encourage the participant to speak freely and at length (Rowley, 2012). A third iteration reviewed each question to ensure it would invoke lengthy, detailed responses (e.g., it is not a yes or no question). With the initial set of questions defined, the researcher aligned each query with the research questions to ensure that data from the interview provided sufficient scope and freedom to explore the topic (Corbin & Strauss, 2015). The last iteration came after feedback from proposal reviewers with some minor modifications to questions.

Interview Procedure

The researcher delivered most questions in the same order for each interview but had some flexibility regarding the order of questions or the extent of probing (Rowley, 2012). Having planned questions resulted in smoother, even toned, and less confrontational questioning, which is typically the goal of intensive interviewing (Charmaz, 2014). Designed, intensive interviewing allows one to explore the subject thoroughly but with a balance, so it does not feel like an interrogation (Charmaz, 2014). Intensive interviews meant gently guiding the participant through a one-sided conversation to fully explore their perspectives and experience with the research topic (Charmaz, 2014).

For qualitative research using interviews, the researcher was as much a part of the research process as the participants (Corbin & Strauss, 2015). The researcher aimed to connect with the participants and see the world from their perspectives to develop a sense of complex relationships (Corbin & Strauss, 2015). It was important for the researcher to listen to each of the participants and to gain an understanding based on what the participants shared (Creswell, 2014). Therefore, the interviews began with an introduction of the researcher, the research, the purpose of the study, and a discussion of the rules and procedures for the interview. The rules and procedures explained the IRB requirements of confidentiality, including how data was processed, stored, analyzed, and reported, with the participant’s privacy of utmost concern. The participant signed the informed consent form before the interview commenced. Initial interview questions inquired about the participant's demographic information, experience, and familiarity with topics related to STM. Background questions did not count toward the minimum six to twelve interview questions. When possible, the researcher conducted interviews using video conferencing software, but most interviews were via telephone.

Interviews were audio recorded and transcribed using voice-to-text software and manual transcription by the researcher. Each data collection session (interview) was followed by a memo-writing session so that the researcher could record his thoughts, perspectives, questions, and impressions related to the interview. Memos provided data beyond just the interview transcripts and provided context to the data (Corbin & Strauss, 2015). "Context not only grounds concepts but also minimizes the chances of distorting meaning or misrepresenting intent" (Corbin & Strauss, 2015, p. 70). Analysts emphasize concepts rather than raw data because concepts allow analysts to group similar data, making the amount of data the researcher is working with more manageable (Corbin & Strauss, 2015). In addition, concepts are the building blocks that lead to theory formation (Corbin & Strauss, 2015).

For interviews conducted with teleconferencing software, the researcher used an Apple iPhone with the built-in Voice Memos application to capture audio of the entire conversation. The researcher used a secondary recorder as often as possible to ensure data capture and that the audio was clear. One interview had unusable audio and no backup source of audio recording. The researcher did not record the video for consistency in analysis and to reduce file sizes.

The second method for capturing voice data for transcription was for interviews conducted over the phone. During the interview, the researcher avoided using a recording device and speakerphone for voice clarity. Instead, he used the TapeACall Pro application to record the phone conversation. This app creates a three-way phone call with the participant, the interviewer, and a third line that records the conversation. This recorded conversation is then available through the application as a .mp3 file. The application is on the researcher's iPhone and protected with facial recognition biometric security. The researcher uploaded discussions to a limited-access cloud storage folder.

The audio was converted to text transcription using a two-step process for these methods. First, the software did most of the transcription. Temi software converted each audio file into text. Following the initial automated transcription, the researcher manually listened to each audio file while reading along with the software-generated transcript to fix errors and assure accuracy in the transcript.

Each participant was assigned a unique identification number, and all files associated with the participant were named to include the identification number. A master spreadsheet was the decoder to tie the participant's data to the collected descriptive data. The spreadsheet is password protected and stored securely and separately from the interview audio and textual data. The dissertation does not identify participants by name; they are only be referred to by their anonymous unique identification numbers.

Pilot Study

The researcher conducted two preliminary interviews with participants willing to provide a higher level of support to the research project. The intent of the pilot case study was not for it to be a pre-test or dress rehearsal but to help refine data collection plans for the content of the data and the analysis procedures and codebook for the full-scale study. The pilot case study was informative to assist in developing relevant questions and to provide conceptual clarification for the research design (Yin, 2018). All that said, the pilot study also provided practice interviews to help the researcher avoid mistakes during subsequent interviews (Corbin & Strauss, 2015).

In addition to the standard interview time required by all participants, the preliminary participants for the pilot study agreed to review the interview protocol after the interview. They provided feedback on recommended changes to the protocol. Additionally, the researcher performed an initial coding analysis and summarized their understanding of the participant's perspectives on the research questions. The participants reviewed the analysis and summary of perspectives and evaluated them for accuracy, clarity, and completeness. The aim of qualitative research was for sensitivity rather than objectivity, and this process helped tune the researcher's ability to listen carefully and to respect the participant and data (Corbin & Strauss, 2015). The researcher identified alternative codes, themes, and perspectives and modified the interview protocol and codebook. The results and Appendix summarize the analysis, changes, and new interview protocols.

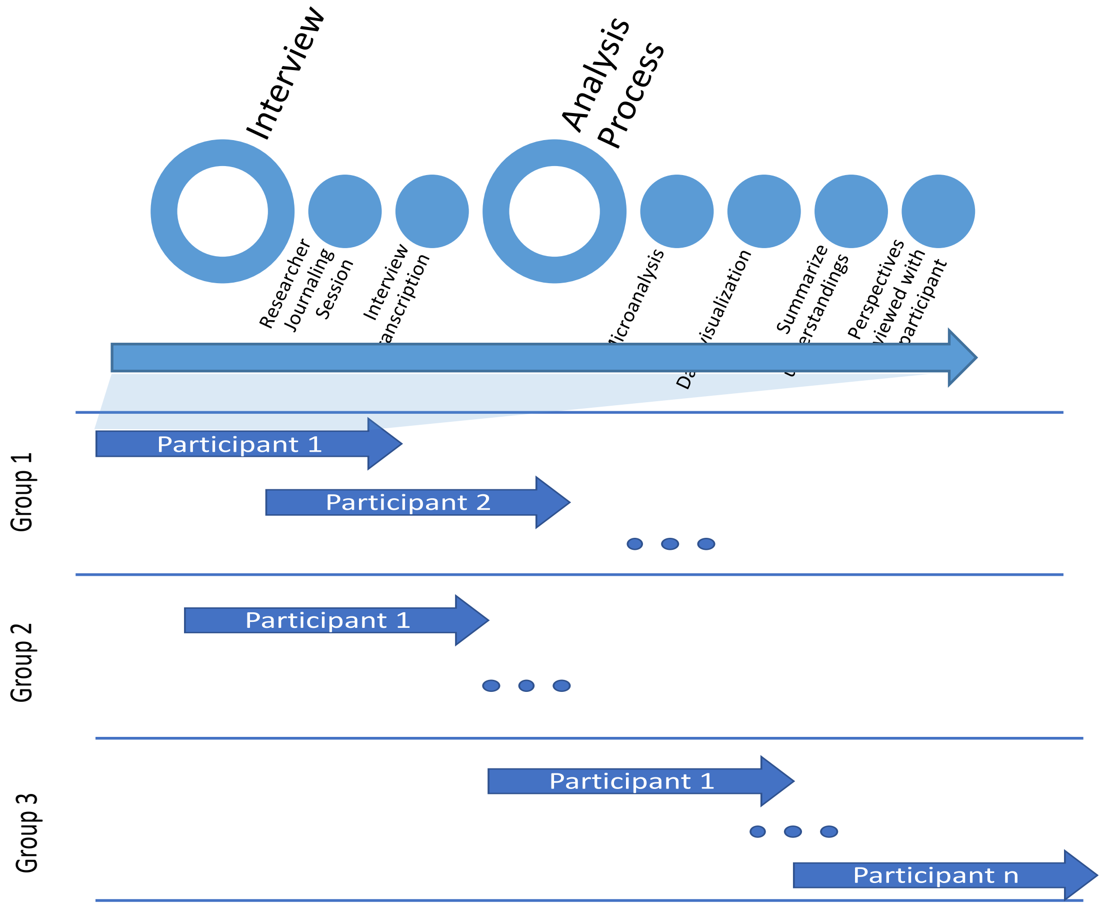
Full-Scale Study

The procedures described in this section aimed to enable the researcher to examine the research topic from many different angles and use the collected perspectives to comprehensively explain the research questions (Corbin & Strauss, 2015). The researcher needed to begin keeping a research journal with the intent of recording activities, thoughts, and plans (Charmaz, 2014). The journal assisted in the research process by allowing the researcher to become more self-aware of their bias and assumptions, track the progress of the data collection and analysis, track changes made during the research process, and collect rationale for making changes throughout the research (Charmaz, 2014). Continual review of the research journal held the researcher accountable and ensured nothing was missed or forgotten (Charmaz, 2014). The appendices does not include the journal.

Figure 5 summarizes the data collection process with two processes: the process for each participant and the management of the participants concurrently.

Figure 5

Data Collection Process



The top of the graphic shows each participant's process in two parts: the interview and the analysis process to follow. A previous section of this chapter detailed the interview process, and the analysis is described in a later chapter.

The bottom half of the graphic shows a high-level overview of a hypothetical timeline of how participant data is collected. Each arrow includes the steps of the larger arrow at the top with the process for each participant. In the lower half of the graphic, the first interviewed participant was from Group 1. After that, the researcher completed the interview and memo-writing, but before conducting the analysis, he interviewed another participant from Group 2. The method does not mean the discussions occurred at the same time or even on the same day. It means both participants were in the process simultaneously but at different stages. Herein highlights the importance of the research journal mentioned at the beginning of this section: to keep track of notes, progress, and thoughts and to remain organized as the research data collection and analysis process progresses.

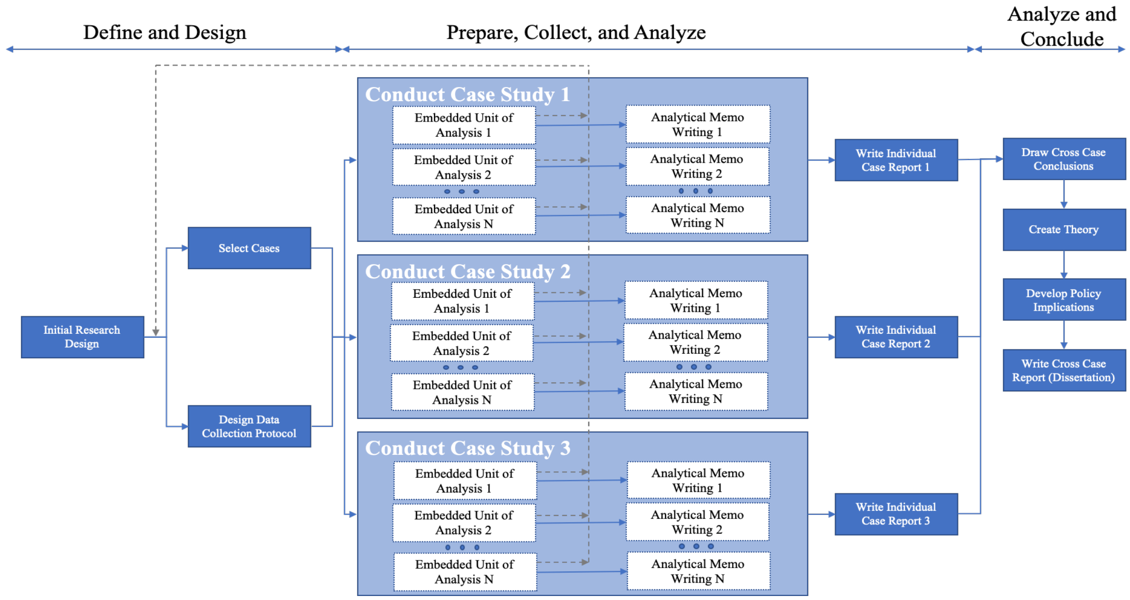
The final step of the participant process is important; the researcher performed an initial analysis and provided a summary of their understanding of the participant's perspectives. Each participant then had the opportunity to clarify or correct the researcher's understanding. The participant reviewed and evaluated the perspectives for accuracy, clarity, and completeness. The review and evaluation were similar but different from the participant review during the pilot study. The participants did not review the interview protocol and codes but only the findings of the initial analysis of their interview performed by the researcher.

Additional participants continued to go through the procedures in Figure 3 until the data saturated. Data saturation happened for the three case study groups at different times. Once a group reached data saturation, the researcher wrote an individual case report summarizing the data analysis outcomes for that group, as shown in Figure 6. Each interview was analyzed and compared against other interviews within the same group.

Once the researcher had written all three individual case reports, he also wrote a cross-case report that compared the three individual case reports. Concepts developed by each group were aggregated and compared among the other groups. The comparison among the group is known as triangulation (Corbin & Strauss, 2015; McMullen, 2015). The results section of this dissertation discusses in detail the concepts identified, the linkages between ideas, and the similarities and differences among individuals and groups in the cross-case report. The dissertation includes all four accounts in the results chapter.

Figure 6

Detailed Research Design Flowchart



Note. Adapted from *Case Study Research and Applications: Design and Methods* (p. 58), by R.K. Yin, 2018, Sage (https://study.sagepub.com/yin6e).

Ethical Considerations

Interview research inherently uses human subjects, and ethical considerations ensure no harm to participants. For the topic of this dissertation, it was doubtful that interviews would harm participants. Additionally, the IRB reviewed and approved the initial communications templates and an informed consent form. The researcher emailed the consent form to participants in advance of the interviews. The informed consent made it clear that participants were not obligated to participate in the interview, the interview was entirely voluntary, and they may stop it at any time for any reason. Additionally, the informed consent clarified processes and procedures to assure participant anonymity.

Data Analysis and Approach

Participant Demographics

Early in the interview protocol are questions to collect demographic information and a self-assessment of suitability in discussing topics related to STM. The researcher did not use descriptive statistics to analyze the collected qualitative data. He used descriptive statistics to characterize the research participants and provide the reader with a sense of the credibility of the participants. Statistics provided included years of related experience, level of education, and duration of the interviews.

Credibility, Transferability, Dependability, and Confirmability (Reliability and Validity)

Regardless of the research method, quantitative or qualitative, data collection instruments and research designs must be verifiably valid and reliable for quality research (Dikko, 2016). Statistical techniques are the standard methods used when determining the validity and reliability of quantitative techniques (Noble & Smith, 2015). Unfortunately, for qualitative research, statistical methods are not possible. Criteria for judging the quality of a study, such as construct validity, internal validity, external validity (generalizability), and reliability, do not mean the same thing for qualitative research as it does with quantitative analysis (Creswell, 2014; Yin, 2018). “Reliability and validity are conceptualized as trustworthiness, rigor, and quality in qualitative paradigm” (Golafshani, 2003, p. 604).

Qualitative research emphasizes methodological strategies to ensure trustworthiness (Noble & Smith, 2015). The four factors that provide the trustworthiness of conclusions from qualitative research are credibility, transferability, dependability, and confirmability (Bowen, 2005; Creswell, 2014).

Credibility can be considered internal validity and is related to establishing the trustworthiness of the researcher's findings (Yin, 2018). Qualitative validity means the researcher utilizes specific procedures to check for the accuracy of the results (Creswell, 2014). In practice, the strategies summarized below improve the credibility of this qualitative study:

- Acknowledged and accounted for one's personal bias throughout the data collection and analysis process with ongoing critical reflection.
- Meticulous record-keeping and memo writing to show a clear path to interpretations, including a description of thought processes.
- Utilized rich and robust descriptions from interview transcripts to support findings.
- Data triangulation to establish comparisons across interviews to ensure the results represent all the different perspectives.
- Engaged with participants and other researchers to review derived concepts and themes and to point out personal biases.
- Peer debriefing (pilot study).
- Prolonged engagement.
- Auditing and negative case analysis (Bowen, 2005; Creswell, 2014; Laws & McLeod, 2014; Noble & Smith, 2015).

Lastly, the credibility of this research method is naturally high because of data collection in its natural setting, with respondents sharing their life experiences (Laws & McLeod, 2014). Respondents could lie, omit information, or make false claims to degrade the credibility of this dissertation, but chances of that are unlikely (Laws & McLeod, 2014).

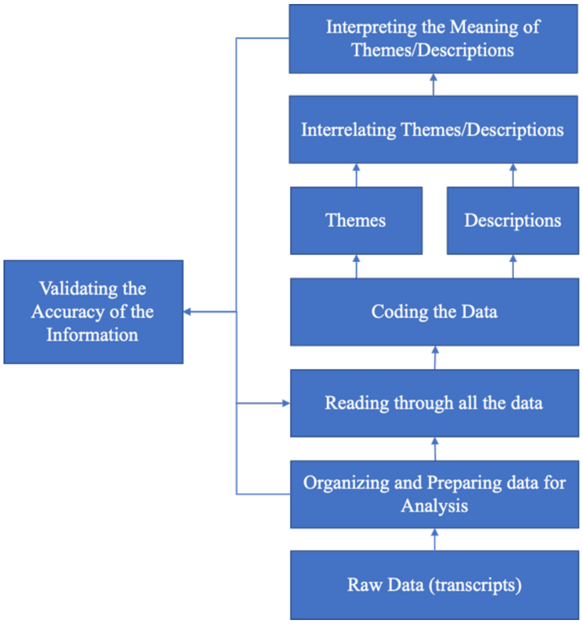
Transferability is conceptually like external validity, showing whether a case study's findings can be generalized. Generalization is limited for qualitative research since this form of research intends not to generalize results to subjects external to the study (Creswell, 2014). In case study research, the goal is to expand analytic generalization, not to infer statistical inferences (Yin, 2018). "Case studies are generalizable to theoretical propositions, not populations or universes" (Yin, 2018, p. 20).

Dependability is related to the levels of rigor required in qualitative research. Yin (2018) suggests that qualitative researchers need to document the procedures of their case studies and as many of the steps of the procedures as possible (Creswell, 2014). The intent is to show that another researcher can repeat the study with similar results (Yin, 2018). Qualitative reliability can also mean that the researcher's approach employs techniques consistent with other researchers and other projects (Creswell, 2014). For this dissertation, the researcher modeled the design after other researchers and documented and showed a well-defined and systematic process throughout the data collection and analysis process (Halaweh, 2012).

Conformability shows that the themes, concepts, categories, and theories emerged from the data rather than from bias and preconceptions by the researcher (Halaweh, 2012). The methodological techniques employed to help confirmability are bracketing to actively identify personal biases and put those assumptions aside (Chan et al., 2013). Identifying one's biases was accomplished through a reflexive process during the data collection and interpretation process. The researcher reflected on his background and experiences and how they may affect his interpretations of collected interview data (Charmaz, 2014; Creswell, 2014). Reflexivity enables the researcher to scrutinize their values, beliefs, and interests and how those may affect the research results (Chan et al., 2013). The memo-writing process included the personal reflection by the researcher.

Figure 7

Data Analysis Process



Note. Adapted from *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (p. 197), John Creswell, 2014, Sage (https://study.sagepub.com/creswellrd4e).

Data Analysis Process

Case study data analysis is one of the least developed facets of case study research (Yin, 2018). Unlike statistical analysis for quantitative research, there are few fixed formulas or recipes to use as a guide (Yin, 2018). There are no qualitative algorithms to perform operations on the words to calculate a median, mean, or standard deviation (Saldaña, 2016). There are, however, methods for synthesizing the whole of the terms to arrive at a consolidated meaning (Saldaña, 2016). Figure 7 depicts an overview of the data analysis process, where the first steps in the analysis process were to organize, read, and digest the entire raw transcript and "play" with the data (Creswell, 2014; Yin, 2018). The analysis process involved the researcher interacting with data with the help of the computer-assisted qualitative data analysis software (CAQDAS) Atlas.ti for the researcher to explore the data (Charmaz, 2014). Initial analysis was open and stimulating, similar to brainstorming and included the helpful practice of memo writing from grounded theory (Charmaz, 2014; Yin, 2018).

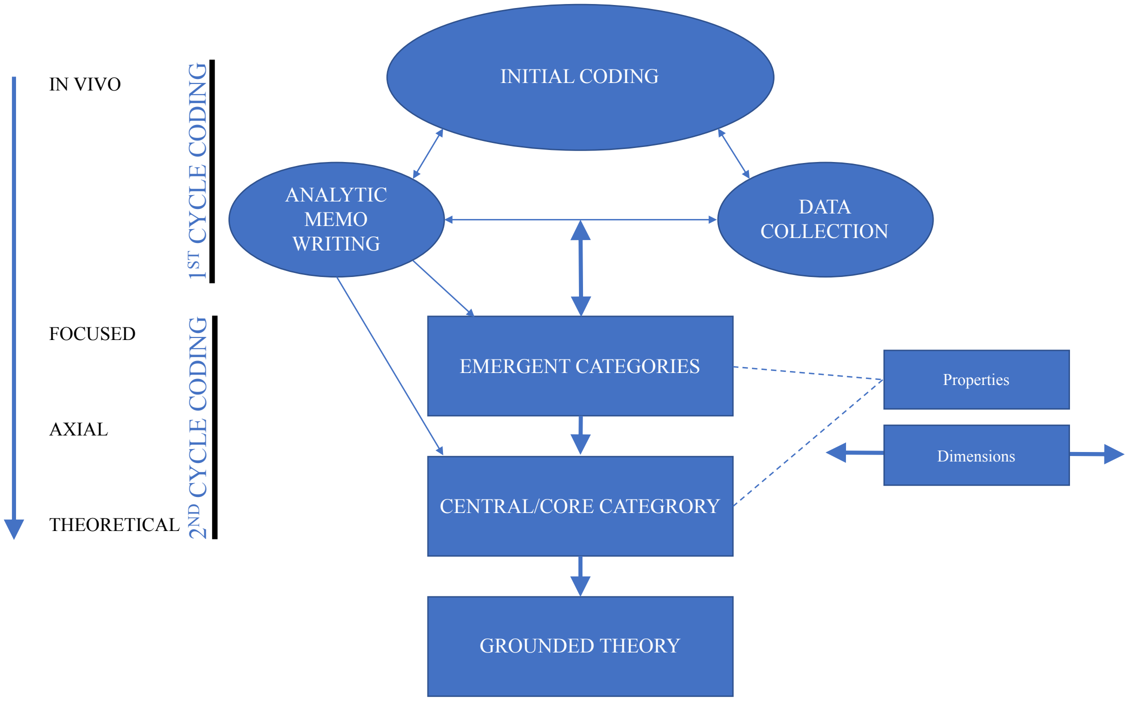
The next stage of the data analysis process was coding the data through a cyclical process that permitted data to be divided, grouped, reorganized, and linked to consolidate meaning and develop explanations (Saldaña, 2016). Coding is "the search for patterns in data and for ideas that help explain why those patterns are there in the first place" (Saldaña, 2016, p. 9). Since the number of codes can accumulate quickly and change as the analysis progresses, a codebook stores a record of the evolving codes (Saldaña, 2016).

It is rare for the first cycle of coding data to be perfect, and the analysis plan for this research used more than one coding method (Saldaña, 2016). To develop a new theory, such as the classic grounded theory method used for this research, in vivo/initial, focused, axial, and theoretical coding was utilized, as shown in Figure 8. In vivo and initial coding are first-cycle methods used by formalizing the "playing with data" For interview transcripts, this method attunes oneself to participant perspectives (Saldaña, 2016). The methods used words as codes and did what grounded theory calls open coding or breaking data into discrete parts to perform microanalysis.

Microanalysis is open, detailed, and meant to explore the data to get a sense of the meaning and to identify concepts representative of the meaning (Corbin & Strauss, 2015). It focuses on smaller data pieces and deeply explores meanings to develop concepts and relationships (Corbin & Strauss, 2015). As a coding strategy, microanalysis generates several possible meanings for data which can be compared against other data (Corbin & Strauss, 2015). The researcher discarded irrelevant words, phrases, and definitions, and revisions to interpretations of the data were made (Corbin & Strauss, 2015). The researcher invested time considering all possible implications by fully exploring and analyzing words, phrases, and sentences (Corbin & Strauss, 2015). The researcher asked questions about the data, and at the beginning of the analysis, the questions did not need to be clever or earth-shattering (Corbin & Strauss, 2015). The questions intended to get the researcher consciously thinking about the data and to explore the different meanings of the data (Corbin & Strauss, 2015). Reflecting on possible variations in meanings helped the researcher identify words and phrases of potential significance and avoid premature extrapolations of meaning and concepts (Corbin & Strauss, 2015). The questions helped the researcher better understand the problem and possible solutions from the participants' perspective, think about what the participant was trying to communicate, and develop themes from the data (Corbin & Strauss, 2015; Creswell, 2014). Good questions should also be foresighted to consider what future potential participants may believe (Corbin & Strauss, 2015). The researcher identified properties and relationships between concepts. This step was a crucial period during the research process where the researcher continued the extensive memo-writing process for self-reflection to become more aware of his assumptions and how these assumptions may be skewing the interpretation of the data (Charmaz, 2014).

Figure 8

Coding Methods

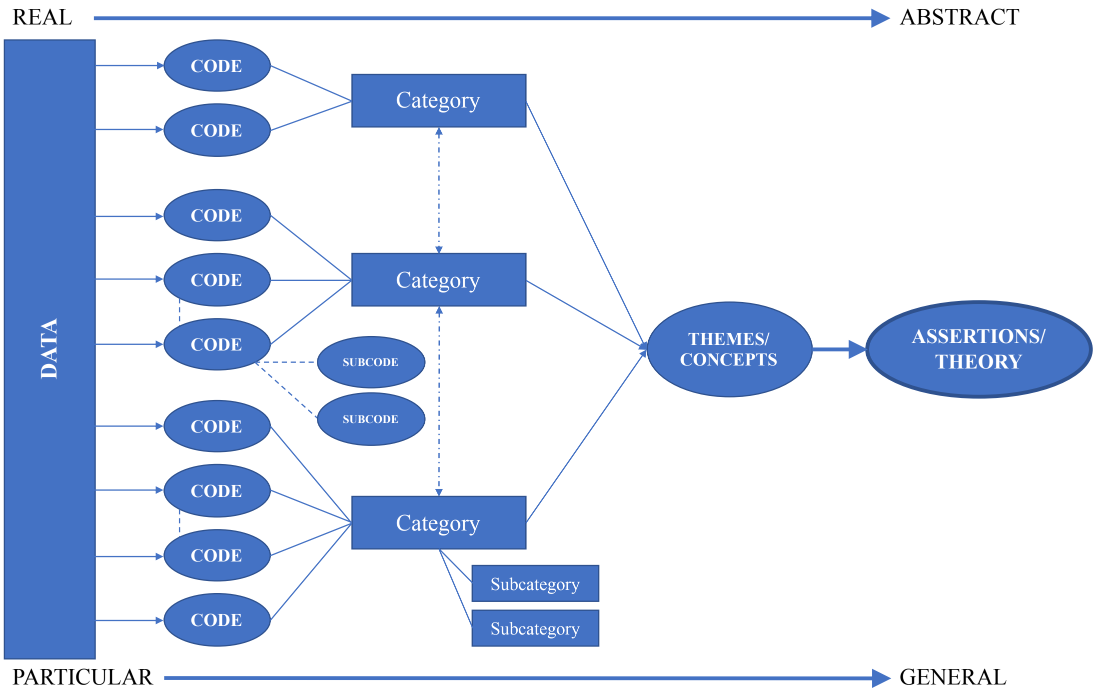


Note. Adapted from *The Coding Manual for Qualitative Researchers* (p. 56), Johnny Saldaña, 2016, Sage (https://study.sagepub.com/saldanacoding3e).

In the later stages of developing grounded theory, the second cycle coding methods of focused, axial, and theoretical were used (Saldaña, 2016). Figures 8 and 9 show the second iteration of coding, which logically categorized the initial codes by linking unrelated facts (Saldaña, 2016). The focused coding method grouped codes based on thematic or conceptual similarities to create categories (Saldaña, 2016). The axial coding strategy explored each category's properties and dimensions and how categories and subcategories relate (Saldaña, 2016). Finally, the theoretical coding method themed the data to discover the central or core category. The core category identified the primary theme of the research, and as the product of all the data analysis, there were condensed few words that best explained what the study was about (Saldaña, 2016).

Figure 9

Coding Process



Note. Adapted from *The Coding Manual for Qualitative Researchers* (p. 14), Johnny Saldaña, 2016, Sage (https://study.sagepub.com/saldanacoding3e).

Summary

This research utilized an exploratory qualitative research method, with the qualitative data from interviews with individuals placed into three groups. Draft questions originated from books, journal articles, and conference proceedings. The research design is a hybrid of a case study for bounding and structuring the data collection and grounded theory for a rigorous and well-defined analysis approach. Grounded theory focuses its sampling population around data saturation, which leaves too much flexibility for this research. For a doctoral-level thesis, sources recommend a minimum of 18 interviews to show sufficient levels of rigor (McMullen, 2015). The researcher did not require additional interviews to reach a data saturation point and for concepts, linkages, and relationships to emerge. Qualitative research validity is established with a well-documented and rigorous explanation of the research process and establishing the author's credibility. Memo writing is part of the well-defined analysis approach of grounded theory, and the researcher used memo writing throughout the data collection and analysis process. A combination of in vivo, initial, focused, axial, and theoretical coding methods were used.

Chapter IV: Results

Ineffective coordination amongst satellites and operators puts billions of dollars of investments and the space environment at risk. The purpose of the qualitative study was to explore the assessments of stakeholders of a space traffic management system for acceptable rules for minimizing risks of collisions between active satellites and to provide a consensus-based set of recommended rules. The assessments of stakeholders were from a collection of interviews with experts from three different stakeholder groups: the commercial space industry (Group 1), space insurance experts (Group 2), and space policy experts (Group 3). This chapter describes the interviewed participants and the results.

Participants

Expert qualifications were not limited to the number of years of relevant experience but also considered positions within their organization and the organization itself. The intent was to ensure the inclusion of the perspectives from many new space companies in the study. Interview participants were purposively selected and used a combination of convenience and snowball samples. An initial list of prospective interviewees originated from a literature review, conference introductions, and seeking leaders from the commercial space industry. To assure data saturation and rigor, six subject experts from each group of stakeholders were targeted to be interviewed for a minimum sample size of 18 total interviewees. Groups 1 and 3 exceeded the six experts target, but Group 2 only had three participants. Group 2 missing the target was due primarily to rapid data saturation in the stakeholder group, with additional interviews adding little to the understanding of that group's perspectives. The second reason for the smaller group size was the lack of availability and willingness to participate in the study. Group 2 is the smallest stakeholder group and had a disproportionally sizeable non-response rate to queries for interviews. The space industry experts (Group 1) had 8 participants, and the space policy experts (Group 3) had 7 participants bringing the total number to 18. The researcher did not include the data of one additional space policy expert participant for two reasons. First, the expert could not commit to a full interview and requested responding to the interview protocol directly via email, followed up by a quick follow-up phone call. That phone call was approximately a half hour long and could have counted as an interview, but the audio recording was silent. Therefore, the participant's perspectives are not captured in the results section but may be included later in Chapter V. One other participant had access to the interview protocol before completing the interview because their place of employment required a review to ensure no conflict-of-interest concerns. That participant did not respond to the interview in written form and completed a full, approximately one-hour interview.

Once successfully contacted, participants were willing to contribute to the study. The most significant barrier to finding study participants was finding contact information (i.e., email addresses) for the prospective participants. Many people did not respond to a request for interviews, and several agreed to participate but would stop responding when it came time to schedule dates and times for the interview.

Despite some challenges in recruitment, the participants in this study have extensive relevant experience, ranging from 10 to 46 years, with a mean of 30 years and a standard deviation of 11 years. Six participants have a Ph.D., three have a Juris Doctorate

(J.D.), and 10 have a master's degree. Four of the participants are retired Air Force officers.

Space Industry Experts (Group 1) Summary of Participants

Group 1 participants' years of relevant experience ranged from 10 to 35 years, with a mean of 24 years, making it the group with the lowest average experience. In this group, one person has a Ph.D., six have a master's degree, and two are former Air Force officers. Seven of the participants are males, and one is female. All are at high levels in their respective organizations with job titles of chief executive officer, vice president, senior director, director, colonel, senior engineer, and SSA lead. Organizations represented by this group include Blue Origin, Boeing, LeoLabs, Iridium, and three other new space companies. Prior experience of participants in this group includes experience at the FAA, White House Office of Science and Technology Policy, NASA, a.i. solutions, Mapbox, and several venture capital organizations.

Space Insurance Experts (Group 2) Summary of Participants

Group 2 participants' years of relevant experience ranged from 38 to 40 years, with a mean of 39 years, making it the group with the highest average experience. In this group, one person has a J.D., and two have a master's degree. All the participants are males. All are at high levels in their respective organizations with senior vice president, division lead, and senior director job titles. Organizations for this group include Marsh and Axa. Participants' prior experience in this group includes experience at aerospace law firms, Lockheed-Martin, Boeing, Thales, and Raytheon.

Space Policy Experts (Group 3) Summary of Participants

Group 3 participants' years of relevant experience ranged from 16 to 46 years with a mean of 32 years, making it the group with the second-highest average experience. In this group, five people have a Ph.D., two have a J.D., and two are former Air Force officers. Four of the participants are males, and three are female. All are at high levels in their respective organizations with job titles of senior researcher, senior technical fellow, director, executive director, professor, and vice president. Organizations for this group include Aerospace Corporation, Blue Origin, Relativity Space, and three small aerospace policy consulting companies. Prior experience of participants in this group includes experience at COMSPOC Corporation, NASA, Lockheed Martin, FAA air traffic controller, deputy council for an aerospace company, and experience in the legislative branch of the federal government. One has been on the National Space Council.

Table 3

Participant Experience Summary

Group 1	Experience (Years)	Group 2	Experience (Years)	Group 3	Experience (Years))
SPI-1	10	SII-1	39	SPE-1	32
SPI-2	30	SII-2	40	SPE-2	46
SPI-3	24	SII-3	38	SPE-3	16
SPI-4	21			SPE-4	41
SPI-5	29			SPE-5	37
SPI-6	35			SPE-6	46
SPI-7	33			SPE-7	20
SPI-8	11			SPE-8	18
Mean	24		39		32
Std Dev	10		1		13
			GRAND	Mean	30
			TOTAL	Std Dev	11

Pilot Study Group

There were two participants in the pilot study, one from the space insurance experts (Group 2) and one from the space policy experts (Group 3). The pilot study group participant's years of relevant experience ranged from 32 to 39 years, with a mean of 36 years. In this group, one person has a Ph.D., and one has a master's degree. One of the participants is male, and one is female. Both are at high levels, with executive director and division lead job titles in their respective organizations.

Interview Data

All interviews were conducted virtually, with all but one via telephone. One participant joined the interview using Zoom. An Apple iOS application called TapeAcall Pro recorded the telephone-based interviews. Additionally, most interviews used the iPhone Voice Memo application to record the conversation as a backup to the primary audio recording source. The iPhone Voice Memo application recorded the Zoom interview. The researcher did not capture the Zoom interview video. A summary of the interview durations by participant and group is in Table 4.

Table 4

Interview Duration Summary

Group 1	Duration (h:mm:ss)	Group 2	Duration (h:mm:ss)	Group 3	Duration (h:mm:ss)
SPI-1	1:01:08	SII-1	0:50:38	SPE-1	0:52:02
SPI-2	1:01:08	SII-2	1:01:43	SPE-2	0:59:18
SPI-3	1:09:23	SII-3	0:55:10	SPE-3	0:59:46
SPI-4	1:11:23			SPE-4	0:53:23
SPI-5	1:15:14			SPE-5	
SPI-6	0:53:37			SPE-6	1:01:25
SPI-7	0:31:58			SPE-7	0:59:03
SPI-8	1:06:10			SPE-8	1:00:59
Total	8:10:01		2:47:31		6:45:56
Average	1:01:15		0:55:50		0:57:59
				GRAND TOTAL	17:43:28

Note. Adapted from *Exploring the Competitive Advantage of the U.S. Commercial Space Transportation Industry: A Qualitative Case Study* [Doctoral dissertation, Northcentral University] (p. 127) by S.A.H. McMullen, 2015, ProQuest Theses and Dissertations (https://www.proquest.com/openview/8f7b01e7f205f0c3aa5885eb07b685bb/1.pdf?cbl=18750&pq-origsite=gscholar).

The two audio recordings during the pilot study used TapeAcall's automated transcription service to create an initial transcript for each interview. The researcher then listened to the audio recording while modifying the transcript generated by the automated service to verify the transcription's accuracy. Listening to the audio and changing the text in disjointed applications was cumbersome and time-consuming, so Temi made the remaining transcripts. Temi is a cloud-based service that uses TLS 1.2 encryption for transferring and storing the data to ensure the privacy and security of the interview data. The researcher uploaded each audio recording to his password-protected Temi account, and Temi generated an initial transcription for each audio recording. The advantage of using Temi was viewing transcripts, and the associated audio played within one application, making modifying and validating the transcripts less cumbersome and time-consuming. Clean transcripts were exported as Microsoft Word files and stored in the researcher's password-protected iCloud drive for use later during the coding process. At the end of the transcription process, there were 337 pages of interview transcription data.

Each interview transcript was reviewed again with the support of the audio recordings while the researcher wrote memos summarizing the critical details of each interview. To ensure credibility and qualitative validity, the researcher utilized specific procedures to check for the accuracy of the findings (Creswell, 2014). In practice, this was done by engaging participants to review derived concepts and themes. The researcher sent summary memos to each participant to verify the researcher's understanding and key takeaways from their interviews. All but two of the participants responded in agreement with the summary or with minor feedback or corrections. Eight of the participants provided feedback or changes to the summaries. The summary memos were later used during the coding process, along with the interview transcripts, to develop and understand the themes.

Results

The results in this section are the byproduct of the data analysis process described in Chapter III and began with coding the data through a cyclical process that permitted data to be divided, grouped, reorganized, and linked to consolidate meaning and to develop explanation (Saldaña, 2016). The first cycle through the data was an in vivo or open coding process with the assistance of Atlas.ti qualitative analysis software. By the end of this first coding cycle, there were 262 unique codes and 683 quotations. The second cycle followed the initial coding process, which grouped codes based on thematic or conceptual similarities to create categories explored to understand how categories and subcategories related (Saldaña, 2016). Finally, the researcher developed different themes by condensing codes and categories into a few words that best explained the research (Saldaña, 2016). As the volume of data condensed, the researcher stopped using Atlas.ti for the 2nd stage of coding and instead used pen and paper and Excel for a more manual coding method.

To present the results logically, the codes were categorized by research question and then mapped to themes related to that research question. Each research question shows the mapping of codes to the relevant theme, and then a section will describe the results for each group, followed by a cross-case summary of the results. Relevant quotations for each question are in Appendix D.

It became quickly evident during the data analysis process that many of the research questions had large, overlapping scopes and overlapping codes. The researcher examined spaceways regulations in research question three, while research question four focuses on rules regarding right-of-way. Both topics involve extensive discussions of maneuvering. As for research question one, it has already delved into rules concerning maneuvering. The following definitions guided the results to avoid repetitive, complex, and nuanced results with overlapping scope across the research questions:

- Research question one will focus on the general rules related to maneuvering capability on the spacecraft. Not how the maneuvering capability is employed. Should spacecraft have a maneuver capability or not?

- Research question three will focus on support or opposition for defining spaceways, and defining the minimum capabilities spacecraft would need to operate in specific regions or orbits. Maneuvering is one of several capabilities associated with this research question. Should we limit where spacecraft can be, based on capabilities?
- Research question four will focus on how spacecraft could employ a maneuvering capability to define right-of-way rules if that capability exists. When should the spacecraft maneuver, if possible?

Additionally, research question five explores rules regarding liability, and research question six explores rules regarding insurance. There was no distinction between the two in the data, and liability is an insurance category, so the researcher combined the results for questions five and six.

Pilot Study

The researcher conducted two preliminary interviews with two participants willing to commit more time than the standard interview. After completion of the interview, the pilot study participants agreed to review the interview protocol and the resultant categories of initial coding and provided feedback on recommended changes. This was in addition to reviewing and providing feedback on the interview summary memos provided to all participants.

The initial categories from the pilot study were Aviation and Maritime Comparisons, Decision Points, Insurance, Legal, Level of Control, Mission, Possible

Issues, RAAs, Solutions, Space Environment, SSA, STM System Architecture, and Users. Feedback from the pilot study did not result in changing codes or categories in the code book. However, conducting further interviews during the full-scale study added codes and categories to this initial set reviewed by the pilot study group. Participants provided feedback regarding the interview protocol, and the researcher created a second version (see Appendix B2) to conduct the remaining interviews.

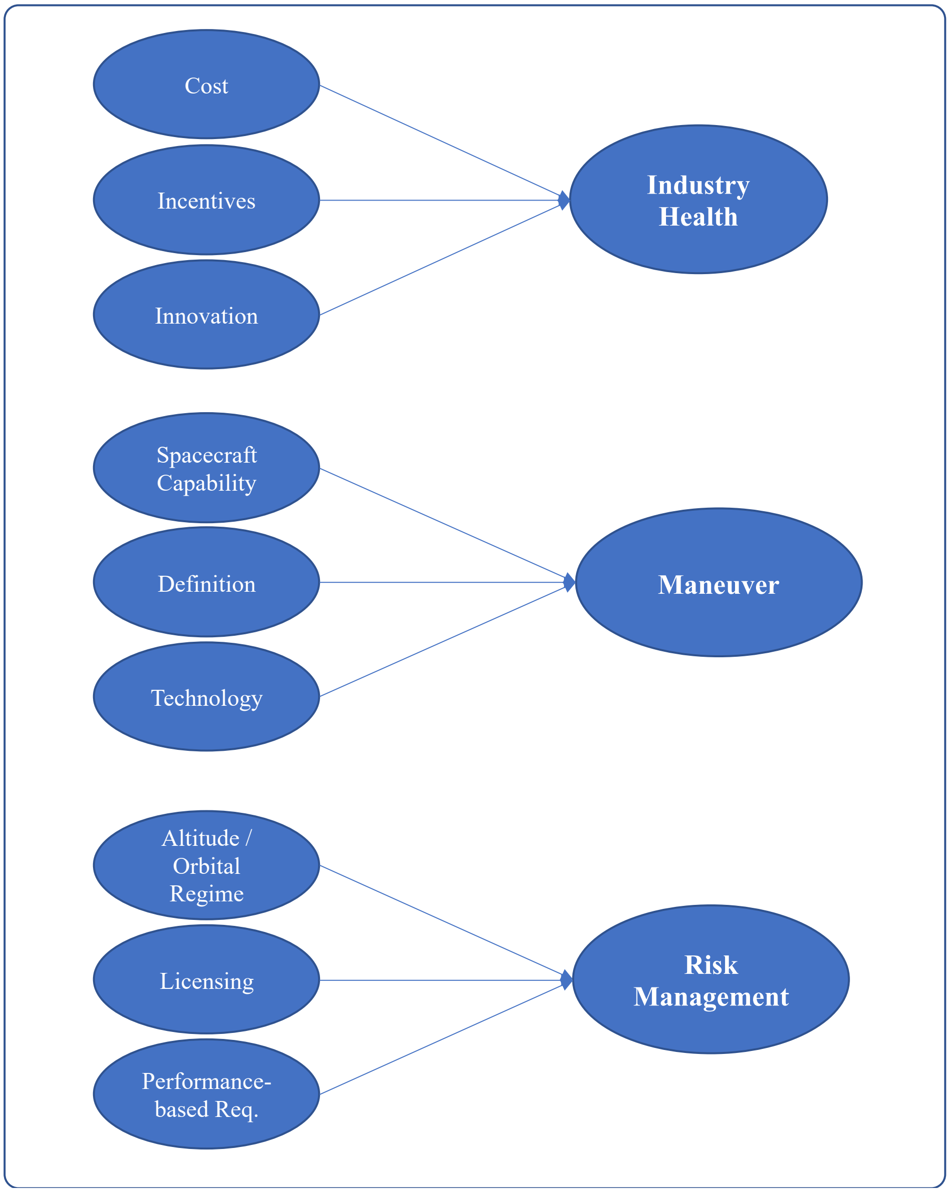
The results of each of the questions were not determined for just the pilot study participants. The following sections are the results from all the participants, including the pilot study participants.

Research Question 1

What do stakeholders of a future space traffic management system assess as acceptable rules regarding the maneuvering of orbital space vehicles for minimizing risks of collisions with manmade, active space objects? Reviewing participant perspectives across the groups for Research Question 1 resulted in three themes: Industry Health, Maneuver, and Risk Management, as depicted in Figure 10. The maneuver theme is a consolidation of the definition of a maneuver, satellite capabilities, including technology, that can effect a change in the satellite's orbit. The risk management theme concerns maneuverability rules that allow users and the community to control risk. The considerations include orbit altitude, licensing, and performance-based requirements. Lastly, the industry health theme stemmed from comments meant to ensure a growing and innovative field that is unhindered by burdensome regulations too early in the development phase. The following sections describe each group's perspectives on the three themes, followed by a cross-case finding. The cross-case findings section includes a theme matrix to identify which groups contributed perspectives for each theme.

Figure 10

Codes and Themes Related to Rules Regarding Maneuver



Space Industry Professionals (Group 1). The experts in this group had a majority perspective that a requirement to have the ability to maneuver is justified in some cases. Two participants questioned the need or disagreed with having mandated maneuvering capability because of the prescriptive nature of a requirement. Instead, the desire was that operators would have an obligation to ensure they did not interfere with the operations of other operators and there was no impact on orbit viability (Participant SPI-2).

For the remaining participants who support some form of a maneuverability mandate, they gave two qualifiers. First, a definition for a maneuver needs to be clarified because a maneuver does not necessarily mean that the satellites must have a propulsion system. Participant SPI-6 mentioned that satellites have additional maneuver methods that do not require a propulsion system.

A second qualifier the group shared is related to managing risk and conforming with existing debris-mitigating standards of behavior. The qualifier was an orbit altitude at which a maneuverability mandate would be justifiable, meaning that there would be “some altitude ranges where you require a capability to maneuver” (Participant SPI-3). In addition to a unanimous agreement for a maneuvering capability standard in GEO, three participants repeated the LEO value of approximately 400 km as the maximum altitude for non-maneuvering spacecraft. The value of 400 km is associated with minimizing risk for manned space and the altitude of the ISS. A second value (600 km) was associated with the 25-year deorbiting timeline requirement. The 25-year rule is a long-standing standard of behavior that states that objects should be removed from orbit, intentionally or naturally, within 25 years. The implication in these discussions was that if a spacecraft is in orbit above approximately 600 km, then operators “must have a plan to deorbit [the] satellite within 25 years” in an intentional way (Participant SPI-8).

Participant SPI-5 took a firmer stance on the requirement for a maneuvering capability precisely because of the term space traffic management. To manage space traffic, there must be a way to control objects in space to manage risk and limit the burden on other operators. Maneuverability is the key to managing collision risk and traffic in space; therefore, everyone should be able to maneuver.

A final point discussed was the importance of small operators (i.e., universities, CubeSat companies) and the need to ensure continued access to space (Participant SPI-8). Protections for small operators would allow these operators to continue to operate, innovate and prevent banning a subset of operators.

Space Insurance Industry (Group 2). Experts in Group 2 shared two of the three primary themes. The themes that emerged from this group were Industry Health and Risk Management.

From an industry health perspective, Participant SII-2 stated support for a maneuverability requirement only if it was economically feasible and not a significant burden (cost) on operators. Participant SII-1 sees the economics from a different perspective and thinks that requiring maneuverability above 400 km makes more economic sense because “the economic incentive is for us not to create more debris,” and having a maneuvering capability minimizes the risk of generating more debris.

In addition to the reluctance due to economic considerations, Participant SII-3 hesitated about whether the government should step in and impose a maneuvering requirement. The alternative was a performance-based requirement requiring that operators “ensure that satellites are deorbited at X time and then let the owner-operators figure out how they’re going to do that.” Similarly, Participant SII-2 mainly saw the requirement for maneuver being associated with a need to deorbit, not for collision avoidance.

The final point discussed by this group was related to reliability and a concern for the inability of spacecraft to deorbit due to failures in the propulsion systems. No specific point was made other than reliability should be considered and that creating a mandate for maneuver does not assure the spacecraft will be able to maneuver.

Space Policy Experts (Group 3). The experts in this group had a majority perspective that a requirement to have the ability to maneuver is justified in some cases. The conversations related to maneuvering oscillated between maneuver as a means of deorbit and maneuver as a means of collision avoidance.

Before two participants discussed a maneuvering requirement, they debated the foundational question of defining a maneuver and what would satisfy it. Added to that definition, compared to Group 1, was the notion of how timing may drive the definition. Can the spacecraft maneuver a certain distance within a quantitative period of warning time (Participant SPE-6)? Collision avoidance is assumed to be the reason for the maneuvering capability for this definition. To do that, there is a minimum distance that the satellite must be able to change at some specific time in the future to avoid an object. The timing consideration also points to non-prescriptive performance-based requirements that consider timing and physical location to allow technology advances and innovation (Participant SPE-3).

When asked about making a maneuvering capability mandatory, one participant, Participant SPE-1, was the only participant in this group who did not support the requirement with a concern for the CubeSat and nanosat industry. Unlike other participants, Participant SPE-1 did not add qualifiers for potential operators with maneuver capability, simply that the requirement is unrealistic.

Other participants supported a maneuver requirement, but the requirement could be a function of altitude and congestion levels. New deorbiting technology and missions in very low earth orbit (VLEO) might not require maneuverability, but higher up or as the environment gets congested, the case for maneuverability grows (Participant SPE-8). As with Group 1, participants gave altitudes of 400-600 km as the limits for where a maneuver capability should be a requirement with the value associated with the natural demise of the spacecraft in a short period or altitudes below the ISS (Participant SPE -6, -7). Rules would force CubeSats with no maneuverability to operate in VLEO (Participant SPE-7).

Several participants brought up concerns related to putting the environment at increased risk. Participant SPE-1 noted a potential perverse incentive to design a less maneuverable satellite, at least in the short term, which would increase the environmental risk. From the perspective of Participant SPE-2, the only way to manage traffic is with the ability to manage risk, which directly correlates to the ability to maneuver. They advocated putting collision avoidance capabilities on every satellite to protect the environment. Lastly, Participant SPE-1 noted that maneuverable spacecraft would add cost and complexity. With added complexity, there is an increased risk in debris-generating failure modes, potentially increasing environmental risk.

The last topic discussed was related to the timing of regulations. First, participants noted the need to be careful about phasing regulations in rapidly innovating industries with a risk of early standardization and regulation limiting the ability to take advantage of operational enhancements (Participant SPE-1). Second, good technical analysis is required to justify new rules and ensure sound decisions. For example, the FCC declined to set a new proposed maneuver mandate rule in their recent orbital debris mitigation guidelines because there was insufficient technical analysis to support or not support a mandate. More time is needed to complete that analysis.

Cross Case Findings. The clear outlier group of the three is the space insurance expert group. Comments from this group were hesitant to support a maneuverability mandate with or without qualifiers (e.g., altitude thresholds). Instead, this group focused on economic impact with contention between two participants on the most significant financial consideration, either impact to the satellite owner or the economic impact of a debris-filled environment. One area that the space insurance experts group (Group 2) aligned with the space policy experts group (Group 3) was by including a discussion on failure modes and reliability. Group 3 identified the potential increase in debris generation due to more complex spacecraft. Still, Group 2 took the concept further and discussed the possibility of reliability requirements for satellites operating at higher altitudes.

Table 5

Research Question 1 Theme Matrix

Category	Theme	Group 1	Group 2	Group 3
Cost	Industry Health		X	X
Efficiency	Industry Health	X	X	
Fairness	Industry Health	X		
Incentives	Industry Health	X		X
Innovations	Industry Health			X
Spacecraft Capability	Maneuver	X		
Definition	Maneuver			X
Technology	Maneuver	X		
Altitude/Orbital Regime	Risk Management			X
Licensing/Enforcement	Risk Management	X		X
Maneuver Strategy	Risk Management	X		
Standards	Risk Management	X		
Performance-based Req	Risk Management		X	

The space industry experts group (Group 1) and the space policy experts group (Group 3) aligned better overall than either did with Group 2. The alignment is partly due to both groups reaching a majority consensus that maneuverability is required or will be in some future congested state. Participants made a distinction for the motivation to maneuver, which was to maneuver for collision avoidance or to maneuver to deorbit at the end of life. Group 1 had three participants mention or define altitude thresholds where a maneuverability requirement would be needed, with two participants justifying a maneuver requirement to comply with the 25-year rule. The 25-year rule lends itself to the topic raised by one participant, which was using performance-based requirements to drive desired behavior. A Group 3 participant also raised a similar point.

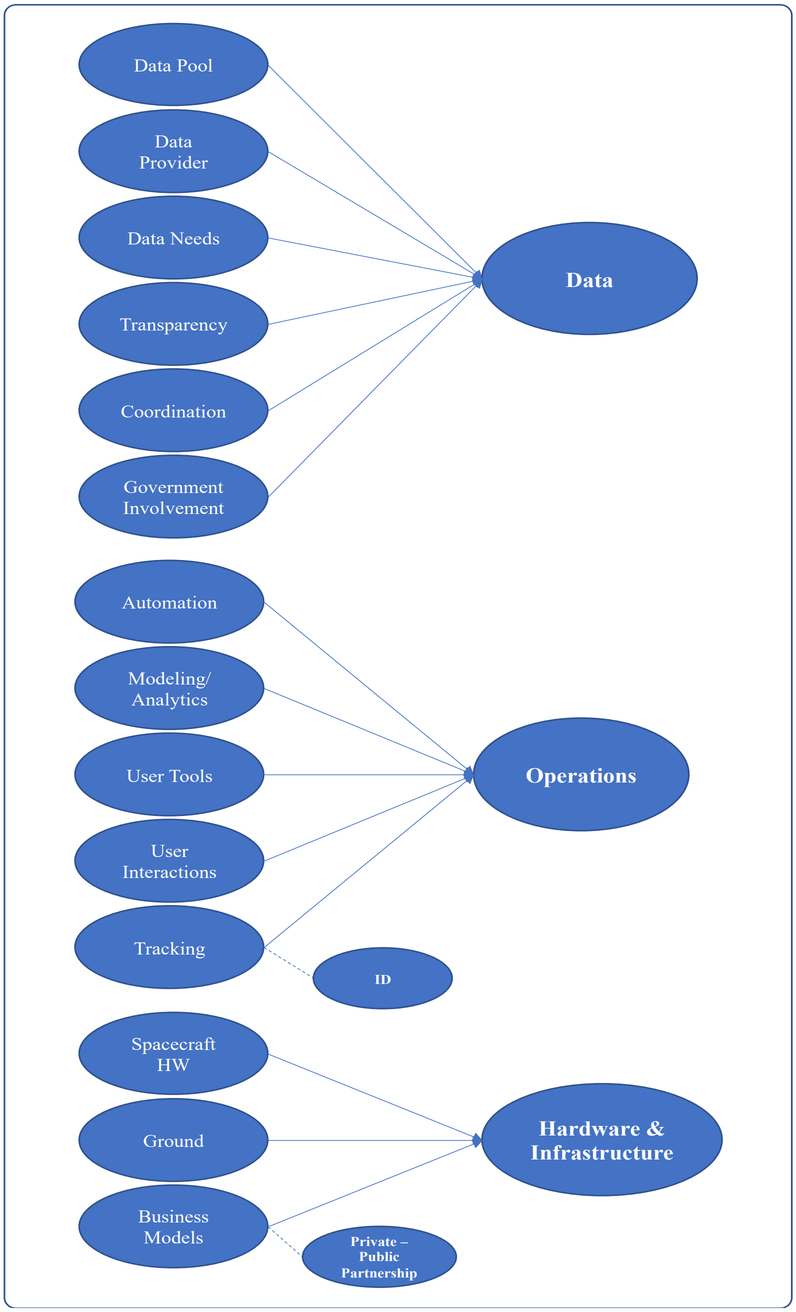
Group 3 was the most outwardly in favor of a maneuver requirement, with five participants supporting a maneuvering capability with some sort of qualifier, such as an altitude threshold. Groups 1 and 3 raised the point that maneuver must be defined. The definition must include some performance-based requirements related to the time required to execute a maneuver of a specified size.

Lastly, a participant in Group 1 was emphatic about the need for a maneuver capability to manage the risk of operating in a congested environment. Without the ability to act, the community cannot manage risk and increase the likelihood of further debris generation. One participant in Group 3 also commented on the environment, stating that at some point, operators will have to think beyond the consequences of their system but will have to consider environmental implications.

Research Question 2. *What do stakeholders of a future space traffic management system assess as acceptable rules regarding identifying tracking technologies for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?* Reviewing participant perspectives across the groups for Research Question 2 resulted in three themes: Data, Operations, and Hardware and Infrastructure, as depicted in Figure 11. Regarding tracking and tracking technologies to minimize the risk of collisions, participants discussed in detail access to quality data and coordination among operators. Codes associated with this theme were aligned with understanding data needs, assuring transparency, and sharing data to optimize operations and simplify coordination. Data enables operators to make informed decisions to execute collision avoidance strategies smartly. Leveraging the data to perform collision avoidance requires scrutinizing operations and potential improvements for the operational phase of a mission. To support quality data, space, and ground infrastructure considerations were the last central theme for Research Question 2. The following sections describe each group's perspectives on the three themes, followed by a cross-case finding. The cross-case findings section includes a theme matrix to identify which groups contributed perspectives for each theme.

Figure 11

Codes and Themes Related to Rules Regarding Tracking



Space Industry Professionals (Group 1). Tracking and the related space domain awareness aspect of STM were popular topics during the interviews. For rules regarding tracking technologies, both the space and ground segments of the system were discussed. Specifically for the space segment, the topic of either an active or passive beacon on future spacecraft was covered with two different categories of usage defined by the space industry experts in Group 1. Conversations related to the ground segment revolved around sensors, data, data availability, data quality, modeling of future positions, and coordinating amongst users.

First, for the space segment, the first use of a beacon would be used to help improve the tracking ability of the spacecraft. The support for a beacon on the spacecraft to enhance trackability, particularly if a requirement, vacillated among the participants in this group. Some concerns were the size and cost of a beacon and that a beacon may only help in certain circumstances and, therefore, may not provide much value. The was also a bifurcation made between small satellites and large satellites. In particular, beacons for smaller satellites had the most support but for identification, not tracking. The need for identification was more than just for space traffic management but also to help operators locate and communicate with their satellites. To accomplish the identification, the beacons must have a unique identifier (Participant SPI-8). Most participants thought a beacon would not help large satellites since they are easily seen and often launched alone or with only a few satellites simultaneously. In contrast, CubeSats can be launched hundreds at a time.

Detecting, tracking, and identifying the space objects is only the first challenge. An additional challenge is maintaining the tracks and providing relevant and actionable data to operators (Participant SPI-5). The ground segment and data exchanges on the ground could facilitate this. Historically speaking, the government has been the leading or only provider of tracking data. Still, in recent years, the commercial sector has begun to deploy its sensors to complement the government's collection methods. Participant SPI-6 commented that the government is upgrading by adding space fence data to the space surveillance network data but also noted that the government "should integrate commercial data sources because that's just much more persistence." This trend is already seen where "some commercial actors like LeoLabs and ExoAnalytics are now providing tracking services both to government clients and the commercial industry" (Participant SPI-5). Participant SPI-4 expressed a desire for more data, but they pointed out one unique issue with the existing network of sensors "is that most sensors are in the northern hemisphere" (Participant SPI-4). Another benefit to the addition of commercial data sources is sensors explicitly designed to track spacecraft since the space surveillance network utilizes radars initially designed and still used for missile warning. An area of potential future growth for commercial data providers is the addition of space-based tracking (Participant SPI-6).

A third data source discussed was operator-provided data that could be self-reported, emphasizing the need for data transparency across the industry. One key benefit to self-reporting data is alleviating some of the burdens on the tracking systems to allow more tracking of the more significant threats of debris (Participant SPI-4). Another benefit is that "in general, operators are likely to know where their assets are more accurately than trying to track them remotely" (Participant SPI-5).

For self-reported data, two participants brought up two concerns or challenges of integrating self-reported data into the larger pool of data, including biases in each operator's data and a desire to avoid a one-size-fits-all approach to reporting (Participant SPI-2, -5). Participant SPI-3 countered that concern by supporting a standardized reporting system with recommended required machine-to-machine connections from operators to a central repository. The industry is coalescing around data pools to house all SSA data, with the government, commercial companies, and other international governments running potentially multiple data pools (Participant SPI-4).

The view of the need for a data pool was not shared across all participants, particularly by SPI-1. Their rationale was that we do not have such a repository in other traffic regimes, such as maritime, so why would it be required for space when the density of spacecraft is far smaller than the density of ships on the water?

Regardless of the usage of a data pool, participants also noted that the quality and accuracy of the data that operators use to make decisions are essential. The whole STM problem is about predicting, knowing where an asset is, and knowing what its predicted trajectory is going to be (Participant SPI-5). Participants discussed two main topics to improve the quality and accuracy of data: better sensors and better modeling. For sensors, participants emphasized an improvement in tracking persistence and the accuracy of the sensors. Participant SPI-5 claimed that improving accuracy instead of seeing more objects would have a more considerable positive impact on the community. For modeling, participants recommended that information shared across operators and with data pools should also include physical information about spacecraft to improve the modeling of drag and the ballistic coefficient. Sensor operators should share the errors and uncertainty sources in the sensors with other operators to gauge the quality of data (Participant SPI-8).

A final topic discussed by this group was coordination between the different users. The two main perspectives shared by the participants were that the current means of coordination is sufficient going forward, so no other technology is needed, or that the current system of emailing or calling an operator to coordinate is not adequate and that some system to help coordinate and encourage communication is warranted.

Space Insurance Industry (Group 2). Participants in this group touched on topics related to two of the three themes for Research Question 2, hardware and infrastructure and data, although not to the level of detail of Group 1.

Participant SII-1 shared a contrary opinion when asked about the sufficiency of the existing system, commenting that the current system cannot protect against all collisions. An idealized goal of space tracking systems was "a system where you track the path of everything in space, on a constant basis" (Participant SII-2). For the community to achieve that goal, participants discussed the role of self-reporting. Participant SII-1 stated that a self-reporting requirement could be achievable nationally. Still, that requirement may disadvantage U.S. companies competing in the space economy. They also mentioned that some operators might not want to share data without a requirement, and there would be data gaps. Participant SII-2 remained open to a self-reporting requirement, but they emphasized following the path of highest efficiency when deciding whether to prioritize sensors or self-reported data.

For spacecraft hardware, the concept of beacons was discussed, with Participant SII-1 being a strong advocate for beacons stating that if "everyone had a beacon, then we would be a lot smarter" and "we think every object that is launched should have a beacon." They do note that not everyone is supportive of the concept.

Participant SII-3 differentiated the beacon type as active or passive and was more apprehensive about an active beacon because of reliability concerns. Passive beacons mitigate the reliability concern, but Participant SII-3 did not necessarily support requiring more hardware onboard.

A final comment that this group touched on was where to store the data and the concept of data pools. Participant SII-1 mentioned the Space Data Association as a place where "the space data association *was* [emphasis added] a very useful forum for that not everyone has bought into."

Space Policy Experts (Group 3). All three themes of Data, Operations, and Hardware and Infrastructure are present in the data from group 3. Multiple participants highlighted the importance of tracking and SSA with statements that SSA is STM's foundation and number one priority. Participants stated that the current construct and policy are appropriate, but that community attitude needs to change to commit more strongly to safety by being more transparent and improving processes (Participant SPE-1). Technology is not seen as the limiting factor as sensors evolve to provide higher fidelity data (Participant SPE-4).

One issue that plagues the industry related to data fidelity is the number of false positive conjunction alerts and the cost that adds to the sector (Participant SPE-1). To reduce this cost on the industry, there is a stated need to have higher fidelity information and better-quality data to reduce conjunction alerts (Participant SPE-1, -7). The path to higher fidelity data will require government and commercial systems emphasizing new technology and more flexible commercial systems that integrate new sensors more easily (Participant SPE-2).

Participants also discussed the quality of sensors with mixed opinions. Participant SPE-2 does not see the need for commercial companies as driven by the quality of the sensors but by the difficulty in changing the legacy systems run by the military. While not the driving force behind the integration of commercial, Participant SPE-4 did state that commercial companies have much better data but at a cost. A structure similar to the launch industry could work with the government as the customer providing adequate commercial incentives for the industry to continue to build SSA sensors (Participant SPE-1).

A second means of getting higher fidelity data to the users is by operators self-reporting their orbital information for use by all others and contributing to a common operating picture (Participant SPE-1). Some operators are not willing to share their data out of concern for others knowing where their satellites are, but participants in this group did sympathize with those operators.

A participant described an effort underway in the United States called the Open Architecture Data Repository (OADR) as a data repository with all kinds of information, including space weather information, environmental information, total electron count measurements, and the space object catalog. The OADR is an effort driven by the United States for domestic use. Still, there have been other efforts at the international level to create a similar data repository that the United States' government has not supported, particularly the United States Department of Defense (Participant SPE-8).

Inherent in sharing data is coordination, which most participants emphasized. Currently, “it’s a manual system,” which is not difficult, but one concern is that there is “no standardized way” to coordinate among users (Participant SPE-1). The current system was described as “ad-hoc” by both Participant SPE-4 and Participant SPE-7, with a recommendation “that the notifications and the discussion should be more automated and not manual” (Participant SPE-4). “Sharing of data, the coordination part,” is what the “Department of Commerce is starting to take on in a larger sense” (Participant SPE-8).

Group 3 discussed ways to improve space situational awareness, first through modeling on the ground. Prediction capabilities are directly related to the community’s ability to model the environment and the frequency of measurements. For the most effective modeling, there will need to be a balance between data fidelity and tracking regularity (Participant SPE-7).

The second means of improving SSA is technology and hardware that could be incorporated into the satellite, primarily associated with beacons. The participants saw the use case of beacons for identification and ease of tracking. Specifically, participants thought about using a passive beacon for identification, a beacon to make smaller satellites more visible, and having one in case of a satellite failure so that trackers could still monitor the spacecraft. Participant SPE-6 gave an example of why identifying CubeSats can be difficult. A recent launch released 143 satellites, almost all of them CubeSats, and days later, the space tracking community was still working to identify and track all the objects.

Participant SPE-4 supported beacons on all objects in case of satellite failure showing mixed support for beacons. Other participants supported beacons primarily for smaller satellites due to the perceived ease of tracking large spacecraft (Participant SPE-2). Participant SPE-6 challenged the difficulty in tracking large spacecraft and noted the common misconception that people assume large objects are easy to track. Large objects are easy to detect, but tracking is more than being able to detect an object one time but knowing where it will always be. Recall the modeling discussion. Large satellites are likely to be performing a mission and have the ability to maneuver. Maneuvering frequently to remain within one's desired orbital parameters makes large satellites the most challenging targets to track (Participant SPE-6).

To finish Group 3's perspective, Participant SPE-3 sums up the two main points, "better tracking and better communication of the data across users," with a vision of the future, of automating interactions and taking the humans out of the loop (Participant SPE-3).

Cross Case Findings. Across all three groups, there is a consensus that today's system needs improvements to accommodate a future of congested space operations. The space industry experts group (Group 1) and the space policy experts group (Group 3) provided ideas in the areas of spacecraft hardware and ground infrastructure, data, and operations to improve tracking and, therefore to improve safety. Group 3 noted that SSA is the foundation to space traffic management because, to operate, operators need to know what is going on around them. With today's traffic volumes, there is already a burden on the industry due to false positive collision conjunctions. Improving tracking and the associated conjunction analysis would remove some of that burden.

Table 6

Research Question 2 Theme Matrix

Category	Theme	Group 1	Group 2	Group 3
Data Pool	Data	X	X	X
Data Provider	Data	X		X
Data Needs	Data	X		X
Transparency	Data	X		X
Coordination	Data			X
Government Involvement	Data	X		X
Automation	Operations	X		
Modeling/Analytics	Operations	X		X
User Tools	Operations	X		
User Interactions	Operations	X		
Tracking	Operations	X		X
-ID	Operations	X		X
Spacecraft HW	HW & Infrastructure	X	X	
Ground	HW & Infrastructure	X		
Business Models	HW & Infrastructure		X	X
-Private-Public Partnership	HW & Infrastructure			X

The first way discussed to improve tracking was the addition of beacons on the spacecraft. The space insurance experts group (Group 2) had mixed opinions on beacons. One participant was concerned that doing so at the U.S. level would disadvantage U.S. operators compared to other international operators. Groups 1 and 3 were both mostly in support of beacons with varying degrees and rationale. Beacons used for identifying small satellites typically launched in large numbers were the most supported use case for beacons. The beacons would also make the smaller spacecraft easier to see. There was a consensus that large spacecraft are not hard to see, so the advantages of a beacon may not be present. One participant in Groups 1 and 3 did not agree with the consensus, mainly because they envision beacons providing valuable data in the event of a satellite failure.

There was no specific recommendation on whether the beacon should be active or passive, just that it should not burden the operators and be reliable. One active method is having a GPS sensor instead of a beacon. For a GPS sensor to work as a beacon, that data would need to be shared by the operator with the community. Sharing data was an important topic discussed by Groups 1 and 3, emphasizing the need for transparency. Group 1 discussed specifics of data-solvable concerns, such as biases in different data sets. In contrast, Group 3 discussed the limitations in legacy systems for adding more data sources and the need to use commercial data pools to combine data. Groups 1 and 3 had majority support for using data pools, but some participants questioned the need for data pools, particularly in Group 1.

A final topic agreed upon by all groups was the importance and need for direct coordination between operators. The current state was described as ad hoc by participants in Group 1 and Group 3, with some participants satisfied with the coordination methods. Others see a future where coordination is less manual, less ad hoc, and facilitated through a system with the potential for adding automation and machine-to-machine interactions. The majority perspective leaned towards the former of less government interaction but the expectation of communication and coordination.

Research Question 3. *What do stakeholders of a future space traffic management system assess as acceptable rules regarding zoning or the creation of spaceways as a means for minimizing risks of collisions between manmade, active space objects?* Reviewing participant perspectives across the groups for Research Question 3 resulted in three themes: Minimum Capabilities, Users, and Rulemaking, as depicted in Figure 12 and Figure 13. When it came to zoning or the creation of spaceways to minimize the risk of collisions, conversations revolved around potential satellite capabilities that could be recommended or required by operators with specific characteristics. Those characteristics could help define rules to drive a safer system. The safer system will have positive and negative impacts on users. Participants in all groups shared their perspectives on issues to weigh before deciding on the path forward for the community. The following sections describe each group’s perspectives on the three themes, followed by a cross-case finding. The cross-case findings section includes a theme matrix to identify which groups contributed perspectives for each theme.

Figure 12

Codes and Themes Related to Rules Regarding Spaceways

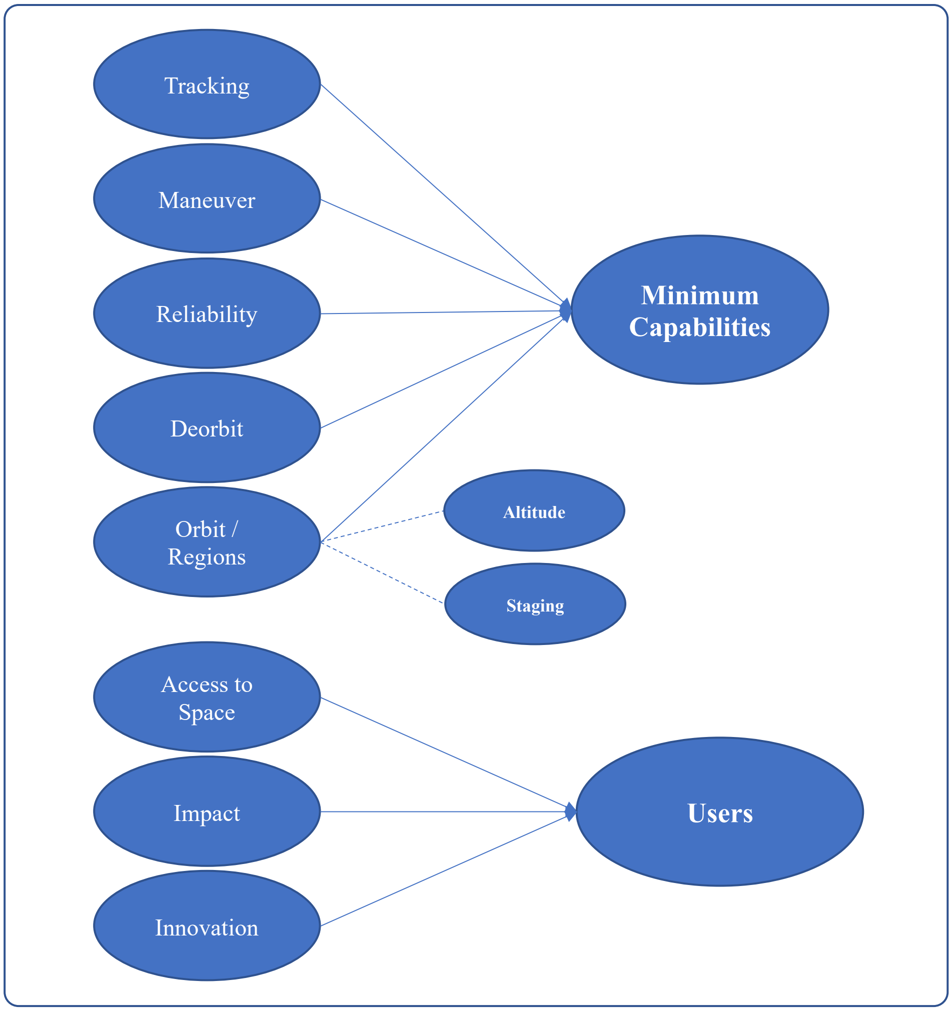


Figure 13

Codes and Themes Related to Rules Regarding Spaceways continued

Space Industry Professionals (Group 1). The discussion with Group 1 related to zoning and spaceways consisted of two parts. First, the definition or conceptualization of what a spaceway could be, and second, the idea of orbit allocation.

Participants described spaceways as layers or shells in space for controllers to manage, like how air traffic control manages airspace in the aviation industry (Participant SPI-3). Regulators could make different rules or constraints to manage each shell, such as rules or restrictions related to reliability, maneuverability, and deorbit timelines (Participant SPI-4, -5, -6, -7). Participants provided examples of potential spaceways as subsets of LEO, MEO, GEO, and highly eccentric orbits (Participant SPI-3). Higher altitudes could be for high-tech and science payloads within LEO, and lower LEO altitudes for large constellations (Participant SPI-3). At very high LEO or MEO orbits, the volume of space gets to be so large, and the number of satellites operating becomes so tiny that the risk of collision decreases dramatically so that this area may be managed differently (Participant SPI-5). In GEO, since the orbit is so valuable, operators would need to "be able to put [themselves] in a disposal orbit" at the end of the mission life (Participant SPI-3). Lastly, spacecraft in highly eccentric orbits will traverse through many different orbital regimes, so a special license could be required to operate in those orbits (Participant SPI-3).

Orbital management or orbital allocation manages where future satellites and constellations can orbit. The benefit of an active orbit management approach is that orbits can be more densely populated safely while also increasing the capacity of LEO and not inflicting excess burden on operators (Participant SPI-4). A participant used orbit allocation in GEO as justification for orbit allocation in LEO (Participant SPI-5). Further rationale for orbit allocation was a discussion on the magnitude of the increase in operator burden with large constellations in similar orbits (Participant SPI-4). The ITU, an international organization, manages GEO, and participants were pessimistic that agreement across all the nations of the international community to institute a similar organization for LEO would happen in the short-term (Participant SPI-4). In the long term, participants shared support and understanding of the need for orbital allocation.

Related to orbital management was a discussion with Participant SPI-4 and the use of frozen orbits. Frozen orbits are “an effective mechanism of minimizing the amount of volume” that satellites orbit through, which minimizes the probability of a conjunction. If regulators allocate orbits, operators will need to be able to maintain their orbital slot. In the spirit of performance-based requirements, Participant SPI-4 noted that the “requirement should be that the possibility of a conjunction shouldn’t exist,” which would force the industry towards active orbital management while not stifling innovation with prescribed solutions. “People need to get on board, and we have to sustain space operations. They just need to get over it and innovate around that” (Participant SPI-6). For participants who are not supportive of mandates, this approach aligns with their vision of operators having the “obligation to ensure that what you are doing is not interfering with either anybody else’s freedom of operation or, in general, the viability of an orbit” (Participant SPI-2).

One concern brought up from experience in GEO, and its current system of orbit allocation that could affect a new orbit allocation system in LEO was adherence to the rules and the inability to hold bad actors accountable (Participant SPI-6).

Space Insurance Industry (Group 2). Participants in this group had codes related to all three themes, although not inclusive of all the codes, with the little feedback they provided on this question.

There was an understanding that certain orbits are more valuable or useful, but there was no clear consensus that different orbits should have different requirements or constraints. One capability Participant SII-1 mentioned in Research Question 1 was a maneuver capability requirement for satellites orbiting above 400 km, which would mean two spaceways, one below 400 km and one above 400 km, with a minimum capability of maneuverability.

Group 2 did not discuss an active orbit management system with the allocation of orbits to users. Still, Participant SII-1 brought up the concern of a de facto orbit management system with satellites launched into orbits where they want to claim squatter's rights. Operators would not legally own an orbit but putting satellites in an orbit would deter others from launching satellites in the same orbit, effectively allowing the squatter to own the orbit (Participant SII-1). This behavior is dangerous and not supported (Participant SII-1).

Participant SII-3 had strong words to say against a top-down government approach to managing orbits but agreed on a need for orbit management. They think industrial associations or something similar could manage orbits instead of the government.

Space Policy Experts (Group 3). In discussing the concept of spaceways, Group 3 used analogies to other traffic domains to clarify the idea. For aviation, Participant SPE-1 compared aviation airspace classes to the concept of spaceways. "Airspace classes require minimum equipage levels to participate in that airspace class" (Participant SPE-1). For orbital systems, minimum equipage could be a maneuvering capability.

In addition to aviation, Participant SPE-7 compared the ground domain and roadway restrictions. The comparison presented forbidding a satellite with limited capabilities from operating in congested orbits. This would be like "bicycles not being allowed on the freeway," raising the risk for participants in that traffic domain. (Participant SPE-7).

They support minimum requirements for valuable orbits aligning with the responses in Question 1 of this dissertation. Meaning maneuverability requirement in certain orbits such as GEO or higher LEO altitudes and for purposes of deorbit.

Spacecraft reliability, resiliency, and standards during the design phase were other areas commonly discussed regarding minimum standards for accessing orbits. The design standard is to reduce the amount and risk of untrackable debris (Participant SPE-2). Designers could do this by protecting tanks or other sensitive items on board to ensure that if debris strikes, there are no explosions and there is redundancy to ensure the spacecraft can be communicated with and controlled through the end of life (Participant SPE-2). Regulators could use additional factors in determining access to valuable orbits, such as the operators' behavior in space and the ability of the operators to show a history of responsible space operations (Participant SPE-7).

Participants raised concerns about having minimum capabilities in certain orbits due to such requirements' impacts on low-end users (Participant SPE-1). Additionally, with resiliency standards becoming a burgeoning topic, Participant SPE-2 only supports the standards voluntarily to allow for innovation and flexibility. Two participants disagreed, saying that licensing should be contingent on reliability standards and the government should decide whether operators get to go to certain orbits based on spacecraft capabilities and meeting standards (Participant SPE-7). A requirement to dispose of spacecraft promptly would focus operators on paying more attention to the reliability and post-mission disposal while not forcing resiliency requirements specifically on operators (Participant SPE-4).

Participant SPE-7 provided one final example of orbit management with operators testing specific capabilities before operating in certain orbits. In this example, Participant SPE-7 described the concept of operations for SpaceX’s Starlink constellation and how they act responsibly by launching into a lower orbit, verifying each spacecraft is operating correctly, and then raising their orbits to an operational altitude. The dead satellites will quickly deorbit while the operational orbit is then not littered with dead satellites (Participant SPE-7).

Cross Case Findings. A typical comment across all three groups was about maneuverability rules and where maneuverability may be a recommendation or requirement. There is overlap among the groups in other areas, but the focus of each group was distinct.

Table 7

Research Question 3 Theme Matrix

Category	Theme	Group 1	Group 2	Group 3
Tracking	Minimum Capabilities	X		
Maneuver	Minimum Capabilities	X	X	
Reliability	Minimum Capabilities	X		X
Deorbit	Minimum Capabilities	X		
Orbit/Regions	Minimum Capabilities	X		X
-Altitude	Minimum Capabilities			X
-Staging	Minimum Capabilities			X
Access to Space	Users	X		X
Impact	Users		X	X
Innovation	Users	X		
Licensing	Rule Making	X		X
Orbit Allocation	Rule Making		X	
Prioritization	Rule Making	X		
Mission	Rule Making	X		
Timing/Phasing	Rule Making	X		
Squatters	Rule Making		X	
Management Entity	Rule Making		X	
Norms	Rule Making			X
-Insurance Role	Rule Making			X

Space industry expert group (Group 1) defined spaceways' different domains or classes in more detail than the policy expert group (Group 3). Group 2 did not discuss the other domains besides an altitude limit for non-maneuverable spacecraft. The domains defined by Group 1 were very low LEO, LEO, GEO, and then a region above LEO and below GEO that is not contested and has a vast volume area where the risk of collision is extremely low. Group 1 also discussed a possible prioritization scheme in orbits with mixed capabilities. Group 3 mentioned only LEO and the same altitude delineation as the insurance expert group (Group 2).

Group 1 was also the only group to mention the timeline of implementing such a system, noting that a system of spaceways with defined minimum capabilities is likely in the distant future but coming. Group 1 highlighted an orbital allocation management system. A view shared by several participants was that satellite placement should be intentional and planned, and the volume of space that a satellite can fly through should be controlled and minimized. In particular, altitude separation of large constellations should be the default. Altitude separation would prevent conjunction between active satellites and allow operators to focus on debris avoidance. Group 3 discussed orbit management by recommending that a licensing function could review constellation plans before launch. It should also scrutinize satellites to ensure they are built to a standard to minimize the risk of failure in congested and controlled orbits. Statements were that someone should verify that operators can safely get to space, operate in space and make good decisions while in operations and at the end of life. Group 1 also mentioned reliability standards.

The groups differed in the authority of who would manage an orbit management paradigm. A participant in Group 2 wants an industrial association with real-world experience to handle that. Group 1 and Group 3 relied on the government to fulfill those roles. A participant in both Group 1 and Group 3 brought up concerns over squatters claiming orbits on a first come, first served basis.

At least one participant from every group was not supportive of a tightly controlled orbital environment; instead, they thought that norms of behavior, expectations, and self-interested incentives would be enough to maintain and safe and useable space environment. One participant in Group 3 also stated concern for low-end users who could have fewer opportunities to launch or require expensive additional equipment.

Research Question 4. *What do stakeholders of a future space traffic management system assess as acceptable rules regarding the definitions of right-of-way in space for minimizing risks of collisions with manmade, active space objects?* Participants across the three groups did not have many concrete rules regarding right-of-way in space. Still, they did provide large amounts of discussions of factors to consider while developing rules on right-of-way. Three major themes emerged from those discussions: factors contributing to operators' decisions when evaluating right-of-way, considerations for holding operators accountable to guidelines or rules, and factors that could drive rules. The following sections describe each group's perspectives on the three themes, followed by a cross-case finding. The cross-case findings section includes a theme matrix to identify which groups contributed perspectives for each theme.

Figure 14

Codes and Themes Related to Rules Regarding Right-of-way

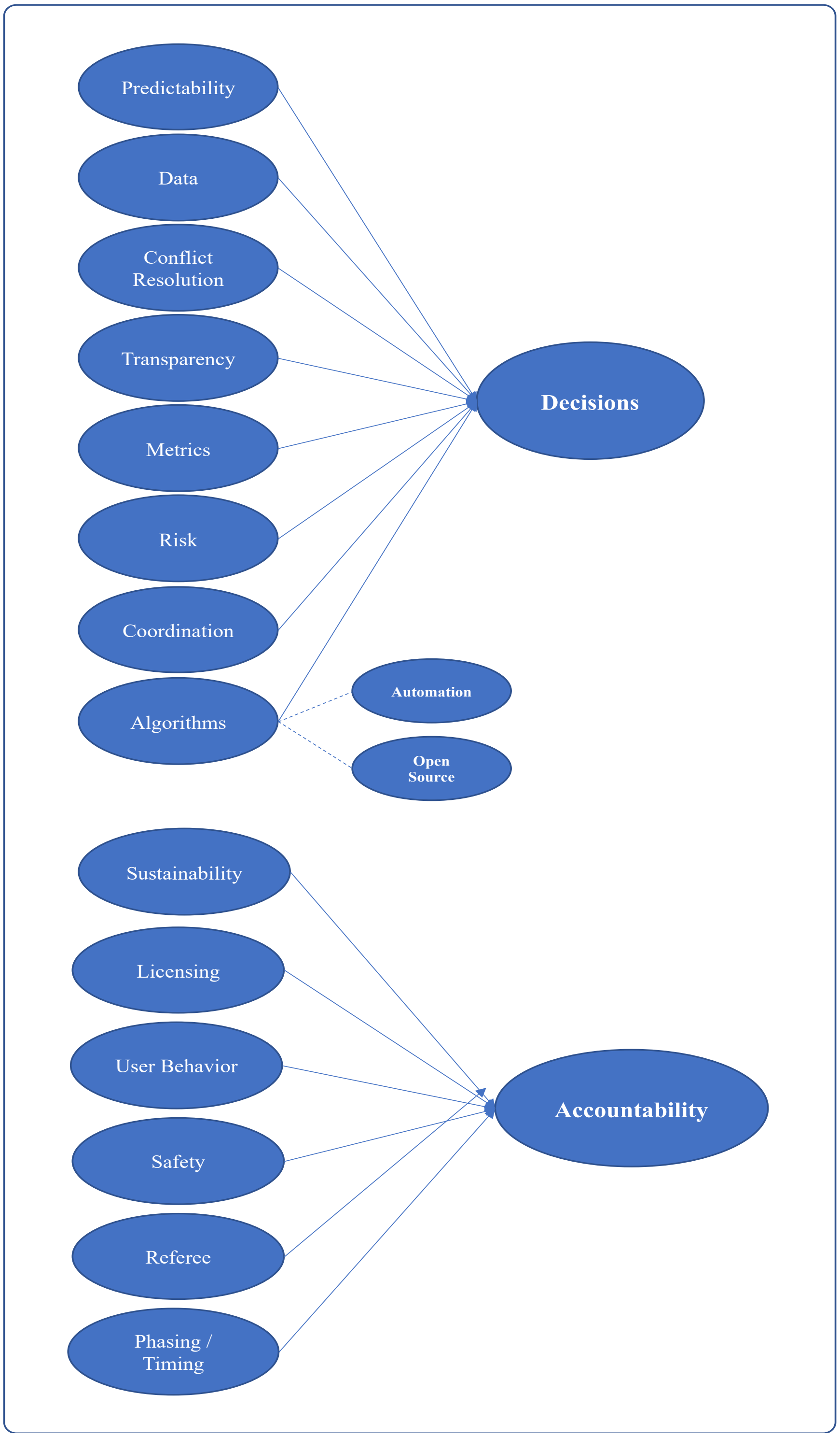
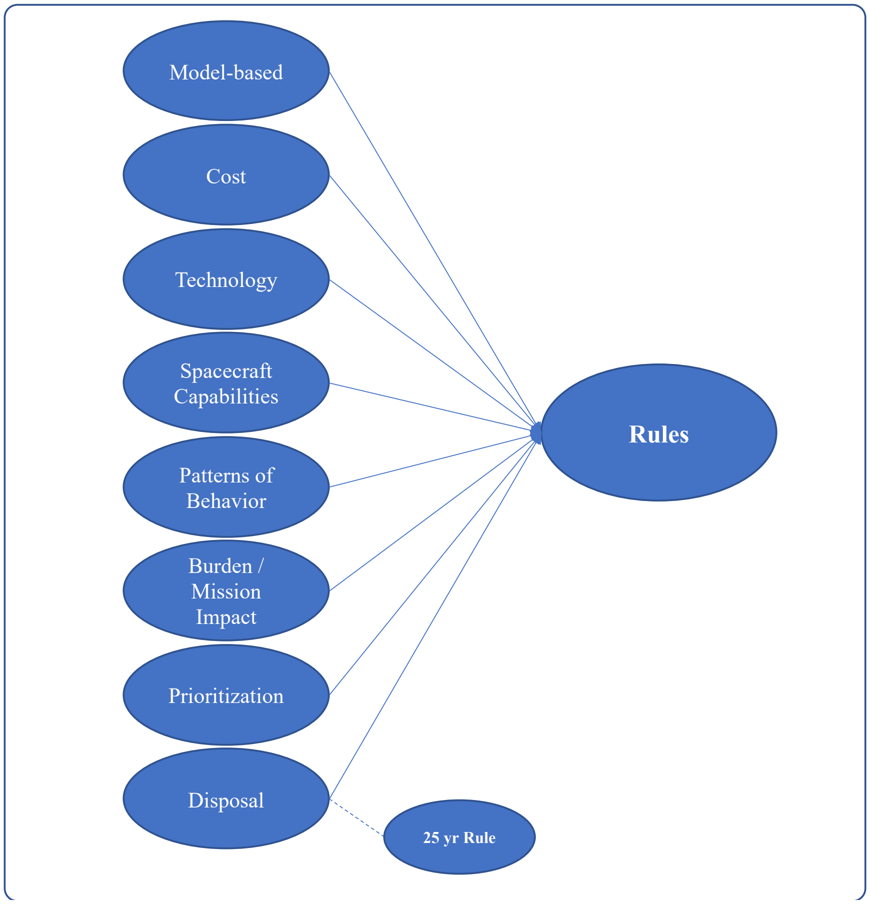


Figure 15

Codes and Themes Related to Rules Regarding Right-of-Way continued



Space Industry Professionals (Group 1). The conversations focused on transparency, communication, and coordination during discussions regarding right-of-way for space traffic. Across the participants, most thought that operators should work things out independently and that government intervention is not necessary, at least in the short-term (Participant SPI-5). No participant could present a concrete set of recommended rules of the road in the traditional sense, but some participants discussed who could have the burden of moving. Determining who should maneuver could be based on who is in a transit orbit and who is in a mission orbit, who has more or less fuel left, and who has more or less mission life left (Participant SPI-4, -7).

Additionally, participants included the 25-year rule for disposal in the discussion of right-of-way rules to simplify concerns and increase safe operations in space. For right-of-way, the general rule would be the junk does not get the right-of-way, so be a responsible actor and dispose of hardware quickly (Participant SPI-5). Quickly is a relative term, but there was strong support from this group for reducing the 25-year rule (really just a standard) to something more reasonable, such as five years, and holding operators accountable for meeting that target (Participant SPI-1, -4).

Participant SPI-8 noted that while they have no recommended rules of the road other than some obvious rules, communication is crucial. The importance of communication, sharing data, and coordination was obvious by widespread agreement among the participants. For data sharing, participants described data pools such as one hosted by the Space Data Association as a place where operators can voluntarily send information about their satellites for others to access to encourage data sharing and safe operations in space (Participant SPI-4). As discussed in previous questions, this group noted that the industry is slowly coalescing on data pools (Participant SPI-4).

Beyond data sharing, coordination was emphasized, particularly in right-of-way, conjunctions, and maneuvers. Participants described today’s current method of coordination between operators as ad hoc, with operators using a centralized email list to coordinate. Some participants felt the current mode of operation was sufficient, for now, even if the method is not exceptional or elegant. Others find the ad hoc nature and often missed or ignored emails as an insufficient means of coordinating, particularly when technology could provide fantastic solutions. Companies are working on other ideas to make coordination more effortless and faster and provide safer operations (Participant SPI-6). Participants in the group widely supported the concept of harnessing automation to help coordinate space operations with a caveat that automation should not exclude coordination between operators (Participant SPI-5). Without operator-to-operator coordination, operators must make massive assumptions and significantly trust their automation. The non-automated operator must trust the data, how the automation calculates collision probabilities and covariances, the reliability of the spacecraft and its algorithms, and even that the spacecraft is active in the constellation and not a defunct asset (Participant SPI-4, -5, -8). Lastly, automation without coordination means only one operator gets to automate because if both operators have uncoordinated independent and unilateral automated decision processes, they both move and potentially not in a constructive way (Participant SPI-5).

Regardless of how coordination happens, part of the information exchanged with data sharing and through coordination should not only include spacecraft location information but also include operators' intentions (Participant SPI-2). Operators should retain the ability to maneuver last minute and autonomously, but the maneuver should be reported to the community promptly (Participant SPI-2). Reporting maneuvers quickly after the fact could also be supplemented by operators sharing the criteria their algorithms use to decide when to maneuver so others can predict when satellites will move (Participant SPI-8). Participant SPI-3 described a vision of the future, which heavily favors automation and normalized practices at ground stations with electronic machine-to-machine connections between some sort of centralized tracking system.

When asked which metric is best to use for determining when someone should move out of the way of another spacecraft, Participant SPI-8 said that it comes down to operator preference. They do it differently, but the generally preferred metric is the collision probability followed by the Mahalahobis distance. Improvements in modeling will be necessary as the environment gets more congested because operators will have to calculate maneuver metrics and spend more time assessing conjunctions and reacting to them (Participant SPI-5).

Regardless of the data quality, metrics, and assumptions used, Participant SPI-8 had concerns about the lack of accountability in today's paradigm, partly due to a lack of visibility of when a close call happens. An operator can choose not to maneuver even with a high collision probability conjunction, placing the environment at an elevated risk without penalty or anyone aware of the situation. Another possible scenario is two operators are both aware of a possible conjunction, but neither wants to move, and there is currently no one to resolve that conflict. This will not be an issue in the near term, but a forum for conflict resolution may be required (Participant SPI-5).

Space Insurance Industry (Group 2). Group 2 acknowledged the difficulty in creating rules of the road and did not provide specific recommendations other than reducing the 25-year rule to create a safer operational environment. Participant SII-1 gave an example of the difficulty in setting the rules of the road by contrasting US automobile interactions with spacecraft interactions. For automobiles, the person gives way on the right. What is the right in space? In general, Participant SII-1 thought that instead of setting those hard-set rules for giving way, operators could simply work out the interaction between themselves. To "just work it out," they mentioned an effort by the

Space Data Association as a repository of data for operators to use to decide on collision avoidance. They also supported all spacecraft above 400 km, having a propulsion system so collision avoidance maneuvers could be negotiated and executed (Participant SII-1).

Participant SII-3 thought the most significant issue was related to satellites that are no longer operational and are slow to deorbit. They also noted that they are not concerned with the large constellations because operators plan, manage, and receive a license as a group before the constellation launches. They also think that the government can block irresponsible operators in space through the licensing process, “what you could do if somebody’s a bad actor you could not give them a launch license” (Participant SII-3).

In the spirit of Participant SII-1’s comment about coordination among operators without extra burden with extra maneuvers, Participant SII-3 described how operators could better time already planned maneuvers to eliminate future possible conjunctions. Participant SII-3 also does not want a top-down approach to setting right-of-way rules and would prefer the industry to be involved. For rules created with input from the industry, or perhaps even through an industry association, Participant SII-3 would like the rules not to be prescriptive but performance-based requirements instead. An example is by changing the 25-year rule, which they note a possibility of reducing the guideline timeline to disposal from 25 years to something on the orders of weeks or months.

Space Policy Experts (Group 3). To begin the discussion of right-of-way rules through the perspective of Group 3, a ground-based analogy was given by Participant SPE-8 describing the somewhat chaotic world of ground traffic (participants such as cars, bikes, and people, potholes, debris in the streets, etc.) and how it somehow all works out fine. The rationale was that it worked out because everyone had a solid understanding and anticipation of what they will do. That understanding and anticipatory aspect of ground traffic do not exist in space. Participant SPE-8 sees that the lack of rules of the road and a lack of clear understanding of what behavior to expect will hinder the space economy from growing to its maximum potential. Operators must have a way to anticipate what others will do, have means to communicate between operators, and have rules of the road for coordinating. Predicting what other operators will do in the space environment relates to collaboration, transparency, and data sharing.

Some in the community remain in an era where they think their orbit and maneuver plans should be protected from an intellectual property perspective, hindering overall industry transparency (Participant SPE-6). Patience for people of that mindset were thin among this group with a desire for operators to realize that it is “more important to share where your satellite is to protect the environment or protect your satellites than it is to protect some competitive advantage” (Participant SPE-6).

Some data sharing and coordination happens today, but participants described the coordination as ad hoc (Participant SPE-7). There is a solid incentive to coordinate because operators do not want to lose a satellite in a collision with another satellite (Participant SPE-8). Coordinating directly between operators also allows for creative solutions and negotiations directly between the operators (Participant SPE-4). Support for data sharing is broad, and support is increasing with advocacy coming from companies and associations (Participant SPE-7).

Ad hoc coordination has worked in the past, but as the number of satellites has increased, there is a need to speed up coordination between operators (Participant SPE-8).

To get everyone to share their data, there needs to be a forcing function where people are not just coordinating amongst themselves; coordination happens through a central entity (Participant SPE-2). One long-term solution to reach the shared transparency and communication goals is to have a globally integrated system that spans all users (Participant SPE-3). This will be very difficult to achieve. Not everyone shares this view, including the US Department of Defense, which has been unwilling to negotiate changes to existing international treaties to create such a system (Participant SPE-8).

Conversations with Group 3 also wandered into taking a holistic view of STM and the phasing of STM development. Participant SPE-8 described STM as encompassing many tasks, including monitoring, consultation, and coordination on one end of the spectrum, while space traffic control is on the other. Society has operated primarily in the monitoring regime for much of the space age. We are now moving into the consultation and coordination phases of STM but are not to the point of moving all the way to space traffic control (Participant SPE-8). That may change over time. Participant SPE-2 agreed, "we're a long way away from compelling people to take actions the way people think of air traffic control." Participant SPE-2 went so far as to say that they did not think we would ever get to a point where we would need space traffic control. For this participant, STM is only space environmental monitoring (SSA) and operators making their own decisions.

While Participant SPE-8 and Participant SPE-2 do not see space traffic control coming soon, Participant SPE-7 had a different perspective. Even though space is a very different environment than the other regimes we operate in, we are likely to see analogs in space regarding rules of the road that we see in other domains (Participant SPE-7).

They see space following a similar path as other traffic domains because managing traffic in all those domains makes sense; it will likely also make sense for space in the future. As with the additional traffic domains controlled by the government, Participant SPE-7 thinks the default idea of the government making the call on some set of principles and rules of the roads is likely to occur with input from industry.

The next topic discussed by several participants was the risk and risk acceptance. The researcher asked participants if they had a metric and threshold they thought appropriate for operators to maneuver. Risk came up as a topic about making decisions for right-of-way maneuvering because each operator has different algorithms, metrics, and, therefore, different cutoff rates for acceptable risks. A risk assessment by operators may vary based on several other factors, including the phase of the mission. Later in the mission, when fuel reserves are low, and it has been successful for more than the vehicle's design life, operators may feel less compelled to protect their assets than an operator with a brand-new satellite in orbit. Another consideration that may affect the level of risk that operators are willing to accept will be how many satellites they have in orbit and how losing one satellite will affect their operations (Participant SPE-6). Losing one satellite in a constellation of one will significantly impact the business compared to losing one satellite in a constellation of thousands.

Some companies are beginning to take humans out of the loop and have satellites perform autonomous maneuvers. Support for autonomy was high, and the future is autonomy, but there were some concerns with today's automation. A participant compared self-driving cars and how someday they will be safe and integrate with regular traffic, but they still have human oversight right now. Space should follow the same line of thinking by keeping humans in the loop. Long-term, the vision is autonomy to enhance safety with machine-to-machine communication and coordination where you have autonomous maneuvers that are optimized based on a future conjunction (Participant SPE-4)

Also related to automation concerns, Participant SPE-8 wants companies who are automating operations to share the algorithms so that other operators can anticipate when the systems will maneuver and plan their operations accordingly.

Pivoting to the next topic of sustainability, Participant SPE-1 has a background in air traffic control. They provided a perspective of why space sustainability is so important, different compared to aviation, and why understanding and managing risk is essential. In aviation, rules were built over many years with thousands of accidents to learn from, and when a plane crashes, it is no longer in the operational environment (Participant SPE-1). Space does not have that luxury of rules based on reactions to an accident (Participant SPE-1). A collision between two objects in space creates an exponential hazard for the future of space sustainability. The consequences of an accident are long-term for the operating environment (Participant SPE-1).

For long-term sustainability, changing behavior guidelines to reduce the likelihood of debris generation and operators will need to be held accountable to those guidelines (Participant SPE-7). Four participants brought up the 25-year rule, and there is broad support for updating this rule due in part to the fact the rule was for already exceeded volumes of space traffic and primarily for GEO (Participant SPE-7). Some ideas were to change the rule to 1 year, which coincides with about 400 km orbit, or makes the disposal timeline a factor of the primary mission length (Participant SPE-4, -

8). Another note was that the 25-year rule had not kept up with technology, and the development of electric propulsion systems means shorter disposal timelines (Participant SPE-4).

A related concern is that the 25-year rule no one enforces it, and that leads to bad behavior by space operators. Participant SPE-4 provided an example where an operator used all of their fuel to make extra revenue. Still, they could not perform their post-mission disposal maneuver without repercussions to that company. The company claims they will remove the satellite within 25 years by an external means, but have yet to.

For the final topic of the group, participants discussed actual right-of-way rules. As mentioned at the beginning of this section, there were not many concrete recommendations for the rules of the road. First, spacecraft in their operational orbit should get priority. Second, whoever can decrease the collision probability with the smallest maneuver should have to maneuver. Lastly, and the most obvious, if only one of the two can, they must maneuver (Participant SPE-4). A participant noted the requirement for data sharing, coordination, and communication for these ideas (Participant SPE-4). Participant SPE-6 brought up an interesting system that would operate similarly to a carbon credit system, but in the case of space, it would be a maneuver credit system. Some sort of exchange could exist where an operator could avoid maneuvering by paying for credits that would fund someone else to maneuver (Participant SPE-6).

Cross Case Findings. A clear consensus across all three groups was that coordination, cooperation, communication, and transparency are the most critical aspects of any space traffic management system. There was not a consensus on the need for rules of the road, at least in the near term, and there were very few discussions on specific rules of the road. Most agree that the question of the rules of the road is a complex and challenging issue. All three groups mentioned using data pools to help with coordination and provide operators with information to make data-based decisions. Another area of agreement was in updating the 25-year rule. Group 2 also mentioned that licensing authorities (e.g., the FCC) could limit space access for space operators not following orbital mitigation guidelines.

Table 8

Research Question 4 Theme Matrix

Category	Theme	Group 1	Group 2	Group 3
Predictability	Decisions			X
Data	Decisions			X
Conflict Resolution	Decisions			X
Transparency	Decisions	X		X
Metrics	Decisions	X		
Risk	Decisions	X		
Coordination	Decisions	X		X
Algorithms	Decisions			X
-Automation	Decisions			X
-Open Source	Decisions			X
Sustainability	Accountability		X	
Licensing	Accountability		X	
User Behavior	Accountability		X	
Safety	Accountability		X	
Referee	Accountability		X	
Phasing/Timing	Accountability	X		X
Model-based	Rules			X
Cost	Rules		X	X
Technology	Rules			X
Spacecraft Capabilities	Rules	X		X
Patterns of Behavior	Rules	X		
Burden/Mission Impact	Rules	X	X	
Prioritization	Rules	X		
Disposal	Rules	X	X	X
-25 yr Rule	Rules			X

Groups 1 and 3 felt that the current method of direct coordination is sufficient. Still, some participants in both groups stated concern that as space becomes more contested, primarily in LEO, a faster, more efficient means of coordination will be needed. As mentioned above, all three groups said efforts to consolidate information in data pools but Groups 1 and 3 mentioned using technology and automation to collect and share data from operators. Group 3 stated concerns about using automation, with the expressed fear of automation reducing the amount of coordination between operators. Groups 1 and 3 criticized the automation efforts by companies flying constellations today. Still, participants acknowledged and supported automation in the future, as long as coordination is not precluded.

For data sharing, Groups 1 and 3 described data needs exceeding location information and upcoming maneuvers. Participants in Group 3 noted that some operators are less willing to share their information. Still, there is little patience for those operators with several comments that operators just need to share for sustainability. Other information that would help stakeholders predict future locations to calculate collision probabilities is characteristic of the spacecraft for more accurate modeling.

Group 3 discussed the phases of STM, describing the past as monitoring, with the industry transitioning to consultation, or data sharing, with the third phase being control. The consensus was that the industry is not in a state where space traffic control is appropriate, and the government compelling operators to maneuver is not likely soon. Both groups did have participants who felt that taking an operational management approach would be pertinent and that smartly allocating orbits and managing the orbits appropriately could reduce the chance of collisions in space. Risk was also discussed by

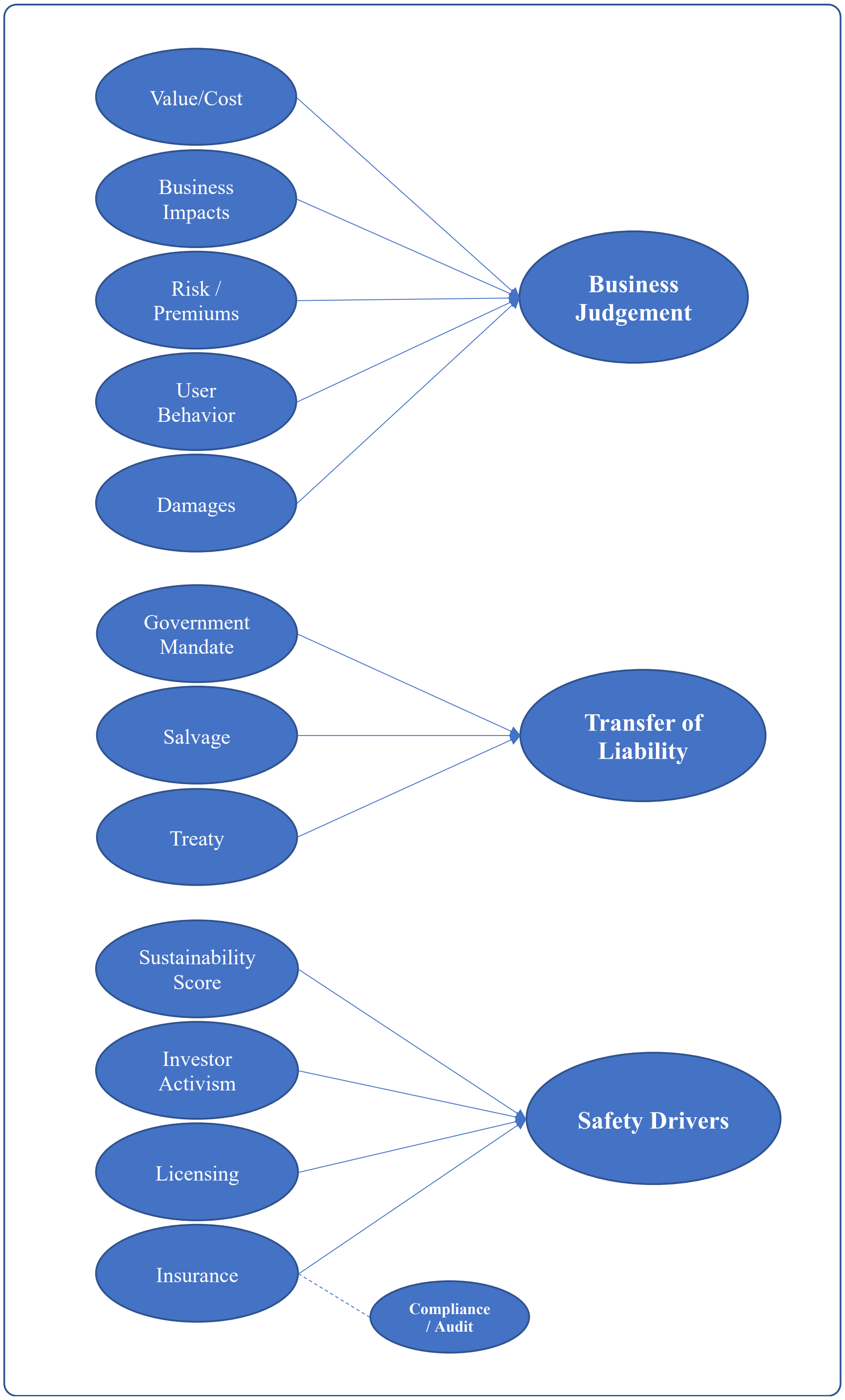
Group 3, with stated concern over risk acceptance by commercial users as a factor of mission phase, number of satellites, and operator culture.

One participant in Group 3 believed that guidelines today have not kept up with technology. Therefore, guidelines need to be refreshed to keep up with technological progress. To that end, another participant mentioned a unique idea of using a system similar to the carbon credit system but for maneuvering in space since maneuvers have a cost associated with them, and safe operations in space require the willingness to maneuver to reduce the chance of collisions.

Research Questions 5 and 6. *What do stakeholders of a future space traffic management system assess as acceptable rules regarding insurance, liability, and compensation for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?* Reviewing participant perspectives across the groups for Research Questions five and six resulted in three themes: Business Judgement, Transfer of Liability, and Safety Drivers, as depicted in Figure 16. Discussions on whether insurance, like for automobiles, should be required to incentivize operators to behave more responsibly in space contributed to the Business Judgment and Safety Drivers themes. The Transfer of Liability theme originated from discussions regarding the Outer Space Treaty and Liability Convention and potential future updates to international treaties to allow for the clean-up of space debris or salvage of derelict satellites. The following sections describe each group's perspectives on the three themes, followed by a cross-case finding. The cross-case findings section includes a theme matrix to identify which groups contributed perspectives for each theme.

Figure 16

Codes and Themes Related to Rules Regarding Insurance and Liability



Space Industry Professionals (Group 1). Responses varied across the group from Participant SPI-1's perspective, "I don't know how [having insurance] would make somebody more responsible," to Participant SPI-3's perspective, "from the perspective of private operators or commercial operators, yeah, seems like a very much a no brainer." Participant SPI-3 did note the caveat that for operators of large constellations, there would be no motivation to purchase insurance because losing one satellite has a negligible impact on the constellation's performance. Participant SPI-2 agreed with SPI-1 that they did not see how having insurance would make operators "more responsible." Still, they did follow up with an interesting point that having insurance "doesn't undue damage and the creation of the debris."

Participants SPI-3 and SPI-4 described how insurance companies could encourage responsible behavior in space by giving rate reductions for responsible design and operations. However, they stopped short of supporting a rule requiring insurance, comparing it to a tax that most operators would not support. If insurance did become a requirement, Participant SPI-3 had an idea of how an automated auditing system could contribute to more transparency in the industry. The concept is that insurers could monitor operators and hold them accountable with their rate at risk of rising if the operators did not follow standards of behavior or design standards.

Participant SPI-6 stated they would support mandatory in-orbit liability insurance "as long as it's affordable." They also provided an alternative to the insurance companies monitoring operators to provide incentives for responsible behavior through a sustainability rating. The premise is that a third-party observer monitors space operators and gives them a space sustainability rating which is widely available for anyone to use.

Participant SPI-7 provided a similar idea of having an “impartial third party, commercial source, that’s able to verify that people are doing what they’re doing or confirm that they’re not.”

Space Insurance Industry (Group 2). Responses in this group also varied, with Participant SII-2 questioning a requirement for in-orbit liability insurance at this time but supporting a gradual phased approach to a requirement and Participant SII-1 supporting a requirement for liability insurance. Participant SII-1 did acknowledge that even with liability insurance, it may not be easy to collect money, particularly with international operators.

In-orbit liability covers liability from damaging another satellite. Only a few nations require liability insurance, but the US does not require in-orbit liability insurance, and globally, very few buy it (Participant SII-2). Forcing liability may work, but operators already have an economic incentive to behave without it because they do not want to destroy their satellites (Participant SII-3).

Regarding an incentive that insurers could provide to encourage responsible behavior, Participant SII-1 does not want to give discounts for good behavior because good behavior should be the norm and expected; instead, they would like to add a surcharge if the operator is acting irresponsibly.

When asked about compensation related to lost business due to another operator’s actions, Participant SII-1 seemed skeptical, “you know we could, but it would be such a vast array of potential threats or perils that’d be pretty hard to kind of break it down and be able to pick apart the different risks that we’d be looking at.” Participant SII-3 echoed the skepticism, “there are the asset policies which would protect against pretty much what we consider all risk. So, unless insurers excluded something, it's covered, but it's typically what they call a multi-trigger policy. First of all, something has to go wrong," which, in the case of a maneuver to avoid another satellite, nothing has happened to trigger the policy, so it seems like a gray area.

Participant SII-2 and Participant SII-3 discussed the more significant issue regarding space insurance. Risk and probability are the basis for insurance, and "probability is based on the law of large numbers, but because the numbers of aviation and even space aren't big enough, probability does not work." Instead, underwriters use "cash flow underwriting. It's not done on an actuary basis because they just don't have the law of large numbers" (Participant SII-3). Participant SII-3 warned that they could see a future in LEO where underwriters are unwilling to underwrite operations in unmanaged orbits or if operators act irresponsibly.

One final comment by Participant SII-2 is that the likelihood of a collision increases with more satellite launches, and there will be an accelerated drive for change in the space insurance industry.

Space Policy Experts (Group 3). Participant SPE-1 and Participant SPE-7 both see the need for insurance as a business decision, but Participant SPE-1 does not see the value in purchasing liability insurance, given the realities in space today. Participant SPE-1 noted that operators must identify the method of indemnification, and if that is through insurance or personal risk, that is their business decision. Participant SPE-7 also indicated that business decisions are not always driven from within but can be influenced externally by investors.

Some other factors that drive the business decision on whether to have insurance are the orbit and size of constellations. When you have multiple satellites, you manage your risk by the numbers, and in a big constellation, you can risk losing one or two in your constellation (Participant SPE-4, -7). “That’s different than the old GEO model where the GEO birds would buy insurance for business interruption so they would ensure the viability of their satellite because that one bird is tied to millions or billions of dollars revenue” (Participant SPE-7).

Participant SPE-4 mentioned the use of insurance companies to promote responsible behavior in space by providing financial incentives for responsible conduct and following guidelines. Participant SPE-7 also noted it, but they said the concept would only work if everyone were required to have insurance. If governments required liability insurance and the insurance companies required specific capabilities to acquire insurance or reduce insurance premiums, insurance companies could become policy drivers (Participant SPE-7). If insurance is not required, then “the alternative is people would say, I’m just gonna proceed without insurance” (Participant SPE-7). A shared view by two participants is that the insurance industry does not want the role of policymaker (Participant SPE-7, -8).

Suppose insurance companies do not want to become policymakers. In that case, a couple of participants still see a role for the insurance industry, “if you have something that emerges as kind of a best industry practice and when companies don’t follow, then they find that insurance companies, go, why aren’t you doing that” (Participant SPE-2). Participant SPE-6, eager to involve the insurance industry, shared a similar view that insurance companies could hold operators accountable for their actions. They think that insurance companies are better suited to penalize bad actors because they can better assess the risk and damages. Participant SPE-8 disagrees that the insurance companies understand the risks well and that for the insurance companies “to jump in, they need a better way to understand the risk.” The government would require everyone to have insurance, so insurance companies could collect data to understand the risk better (Participant SPE-8). Even so, it would be challenging to understand risk with many unique systems (Participant SPE-8).

The respondents’ statements were related to third-party liability. Still, Participant SPE-3 also mentioned first-party liability: “insurance underwriters get a massive amount of technical data about the spacecraft that they insure. If for whatever reason (spacecraft design, operations, following of industry standards) they deem you as higher risk, they will charge you more money.” So, insurance companies already provide some accountability measures to spacecraft manufacturers and operators.

A comment from Participant SPE-8 minimizes the need for third-party liability while still highlighting a case for first-party liability, “I just don’t consider the satellites themselves to be the primary problem. I consider debris to be the problem, and performance and liability insurance and so forth doesn’t really help me with the debris, particularly debris that I can’t really attribute.”

Two additional topics related to liability came up but outside the topic of insurance. The first was from Participant SPE-2 regarding government-compelled action on operators and the potential transfer of liability to the government. Second was a discussion with Participant SPE-1 regarding the transfer of liability from the launching state to a third party or third-party state for salvage and environmental clean-up.

Currently, international treaties do not allow for such a transfer of liability between countries.

Cross Case Findings. For Research Questions 5 and 6, there was overlap on a few topics and many unique issues within each group. All three groups had wavering support for the value of requiring liability insurance. The space insurances expert group (Group 2) had a participant that fully supported the notion. In contrast, others questioned the value or thought that a rule requiring insurance should be something that happens over some time. The space industry expert group (Group 1) had participants that saw no value in having insurance or requiring insurance and others who saw corollaries to the auto industry and using insurance premiums to incentivize responsible behavior in space. Group 1 and the space policy expert group (Group 3) discussed the value of having insurance only if required, but the value is questionable if not.

Table 9

Research Question 5 and 6 Theme Matrix

Category	Theme	Group 1	Group 2	Group 3
Value/Cost	Business Judgement	X	X	X
Business Impact	Business Judgement		X	X
Risk/Premiums	Business Judgement		X	X
User Behavior	Business Judgement	X		
Damages	Business Judgement		X	
Government Mandate	Transfer of Liability		X	
Salvage	Transfer of Liability			X
Treaty	Transfer of Liability			X
Sustainability Score	Safety Drivers	X		
Investor Activism	Safety Drivers			X
Licensing	Safety Drivers	X		X
Insurance	Safety Drivers	X	X	X
-Compliance/Audit	Safety Drivers	X		

Another area that both Groups 1 and 3 discussed is how the value of insurance is different based on constellation architecture and orbit. Large constellations are naturally less reliant on any one satellite, so losing a satellite has little impact on business (these would be in LEO). In GEO or older business models, one or a few satellites perform the entire mission, and the impact of losing one satellite is significant, so insurance becomes more important. Group 3 was the only group that focused explicitly on the decision to have insurance as a business decision and mentioned how internal culture and external factors might decide whether insurance is purchased. An example of an external factor mentioned by Group 3 was investors in a company. Group 1 noted that a third party could verify that operators act responsibly in space. Also, a participant brought up the idea that insurers could use data-driven analytics and automation to audit operators to make sure they are operating responsibly.

A unique topic discussed by Group 1 included that insurance may provide a payout for a damaged satellite. Still, the insurance claim will not fix the issue with the debris that is now in orbit due to a collision. Group 2's unique topics focused on insurance-specific concerns, such as the lack of data to determine risk and develop actuarial tables to create accurate insurance premiums. They also warned that in the future, underwriters might be unwilling to insure satellites in LEO due to environmental conditions and risk.

Group 3 highlighted that insurers do not want to be de facto policymakers and do not want to drive policy through insurance mandates. Group 3 did mention a lack of understanding of risk without mentioning actuarial tables. Still, one participant noted that they thought that insurers are better suited to penalize bad actors as compared to the government.

Lastly, participants in Group 3 discussed two topics that were related to liability but not related to insurance. The first topic was related to changes in international liability treaties to make salvage possible. The second topic was related to compelled action by the government to avoid collisions and the potential transfer of liability from the operator in those cases.

Summary

This chapter describes the research process, including summarizing the three groups, the sampling technique used to select participants, and a detailed description of the credentials of all the participants. Furthermore, this chapter discussed the detailed process of conducting the interviews, the coding process, and a summary of the collected interview data. The chapter went through each research question for each group, summarizing the relevant participant perspectives in direct quotations from the interviews. Lastly, for each interview question, a cross-case summary was written comparing the themes and perspectives of the three stakeholder groups.

The next chapter will discuss the results for each research question and provide conclusions, recommendations, and recommended work on the subject.

Chapter V: Discussion, Conclusions, and Recommendations

The results in Chapter IV reviewed the data associated with each research question but did not extrapolate and provide any discussion beyond the data collected. Chapter V will discuss the results from Chapter IV for each research question and the common themes across the questions. Additionally, Chapter V will describe the theoretical and practical contributions and future research opportunities.

Discussion

Research Question 1

What do stakeholders of a future space traffic management system assess as acceptable rules regarding the maneuvering of orbital space vehicles for minimizing risks of collisions with manmade, active space objects??

The initial vision of Research Question 1 was to gather perspectives on a maneuverability requirement focusing on using the maneuvering capability to perform collision avoidance maneuvers. Through the interviews, it was clear that the driver for a maneuverability requirement was not for collision avoidance but for deorbit. There was a broad consensus across the groups for a requirement to have maneuverability in orbits that are sufficiently high in altitude. There must be a near guarantee that the spacecraft will not be in orbit for decades. Operators can accomplish that by launching into a low enough orbit so that the satellite will deorbit in an appropriate period, or the satellite has the maneuverability to get down within a specific time frame. This discussion focuses on satellites in LEO, as satellites in GEO are already managed and require propulsion to move the satellite into a graveyard orbit at the end of the mission.

Over the two years of interviews, the language participants used changed. Towards the end of the interview period, the term *very low earth* orbit or VLEO started being used by participants. There is no agreed-upon definition of what VLEO is in terms of altitude. Still, a recommendation is that the altitude for VLEO is associated with the altitude limit where maneuverability is required. A shared value heard during the interviews for the boundary for a maneuverability requirement was 400 km. This value was referenced to the altitude of manned spaceflight's primary outpost, the International Space Station, and was not associated with a deorbit timeline requirement. NASA is likely to deorbit the ISS within the next decade. They are busy working to get man back to the moon, so using manned spaceflight activity as the boundary for maneuverability does not make sense. The altitude boundary needs to be associated with a deorbit timeline requirement. Participants broadly consider the current standard of 25 years as too long and not a practice that should continue if sustainability is mankind's goal. The specific values given by participants varied from weeks to 5 years or even a dynamic duration that is a factor of the satellite's mission lifetime.

The performance requirement for timely deorbit can be sufficient to reduce the risk of environmental destruction because the consequences of a collision due to the inability to perform a collision avoidance maneuver in VLEO will have fewer consequences so long as the deorbit timeline is set sufficiently low. Put another way, if two satellites collide at a low enough orbit, the environmental effect is short-lived, and the consequences will be less devastating. The system could minimize catastrophic consequences due to one operator's action or one accident. The FCC is already proceeding in this direction by reducing the 25-year guideline in the most recent orbital debris mitigation guidelines (Wiquist, 2022).

One point that participants stated as a concern regarding creating new rules or guidelines is the risk of stifling innovation and investment in the industry. Participant SPI-6 was one participant who did not share that concern. They stated that people need to get on board with sustainability and innovate around it. Incremental, data-driven, and thoughtful rules can stoke directed innovation. As an example, participants stated the biggest concern in space is debris. The government could create rules to encourage innovation and development of new deorbit technologies to reduce cost and drive action in orbital environment clean-up.

Another topic related to the discussion of timely deorbit is reliability standards. Reliability standards were not part of the research questions but were discussed by many of the participants. Reliability standards are related to Research Question 1 because if a satellite can maneuver but that capability fails, then the operator is unable to remove the new piece of space debris from the environment and is unable to remove the future collision hazard. If maneuvering does become a requirement, a reliability standard may need to accompany the maneuverability requirement (Participant SPI-4). The new FCC orbital debris mitigation rules require disclosing the lifetime probability of collision (including the deorbit phase) and assessed the risk to be less than 1 in 1,000 (Dodge, 2021). If the satellite can maneuver, then the probability is assumed to be zero, but this does not consider the reliability of the spacecraft.

One final comment on Research Question 1 relates to a statement from Group 3, which was that a maneuver needs to be defined. A definition is less important if the driver for a maneuverability requirement is for a deorbit purpose. Still, if the maneuverability requirement stems from a requirement for collision avoidance, then a performance requirement for what can be considered a maneuver will need to be defined. Further, the responsiveness of the satellite and a sufficient magnitude of maneuver will need to be determined.

Research Question 2

What do stakeholders of a future space traffic management system assess as acceptable rules regarding identifying tracking technologies for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?

Space domain awareness is the foundation of STM, and tracking and identifying all objects in space is critically important. Participant SPE-8 described STM as having three phases: monitoring, consulting, and controlling, where monitoring is equivalent to SDA. Included in monitoring are detection and prediction, using a ground network of sensors to detect where the objects are. Since the sensors cannot watch continuously, operators must predict where the objects will be in the future and later make corrections with new data. Participants discussed detection along three topics: beacons, tracking networks, and data pools. The impression given by participants was that technologies are available that can be easily accommodated by satellites. Still, the primary use case is for identification purposes on launches with many satellites. There is no need to have large satellites or launches with one or only a few satellites include a beacon because they are sufficiently easy to identify (Participant SPE-2, SPI-8).

Two options exist to improve the ability to monitor space traffic and debris (Participant SPI-5). The first option is to increase the frequency and accuracy of tracking all objects in space or to improve the ability to model and predict future locations with infrequent observations. Predicting the future positions of satellites is like predicting what the weather will be in the future; it is not easy or precise due to many complex and confounding variables. The easier path is to build out a more robust ground-tracking network with the help of commercial companies. Tracking networks will require an expansion in tracking sensors as the number of satellites proliferates.

Debris tracking depends on improvements in tracking sensor technology but tracking networks can track active spacecraft without proliferation and advancement in tracking sensors by requiring operators to share ephemeris data. Tracking networks could focus their resources on tracking debris. There was more support for this among participants than expected, but an agreement was not universal. Participants commented in interviews that some companies think their precise ephemeris information provides some business leverage over competitors. It is unclear what advantage that information provides these companies or why it is more important than safe and transparent operations. Transparency, communication, coordination, and safety ought to be the priority. Therefore, a rule requiring timely reporting of precise ephemeris information of all satellites should be a priority. Several participants noted that some operators have the impression that this would be a burdensome requirement, but it is unclear from the interviews how a reporting requirement provides a substantial burden.

Moreover, at some point, the researcher recommends that the community evaluate a burden-to-benefit ratio. For a slight burden on operators, there is a significant benefit to the community by operators being transparent with their data. The more precise objects' locations are known, the smaller the error ellipses are, which will reduce the number of conjunctions to evaluate, saving the operator time and resources. The burden saved by reducing the number of evaluated conjunctions outweighs the burden of being transparent with ephemeris data. Operators can automate sharing of this data, and after an initial investment to set up automatic reporting, the maintenance of that capability will be minor.

There is a fundamental reliance on the DOC getting a data repository setup to house all the shared data from operators. The vision is there, but progress has been slow to accommodate such a system primarily due to a lack of funding from Congress (Participant SPE-4). Congress must prioritize this funding and empower the DOC to perform the role defined in SPD3 (Participant SPE-4). This system must accept and merge the shared data with commercial and DOD tracking data. To enable that, reporting and data standards will have to be defined. Also, modeled similarly to data provided through the National Weather Service, access to the orbital data needs to be provided, which will drive innovation in the industry. Companies can process that data to provide products and services to give thoughtful insights to operators so they can make sound decisions to minimize the risk of orbital debris-creating events.

Research Question 3

What do stakeholders of a future space traffic management system assess as acceptable rules regarding zoning or the creation of spaceways as a means for minimizing risks of collisions between manmade, active space objects?

The concept of spaceways, or the space equivalent of classes of airspace with minimum standards required to operate in specific volumes of space, is supported based on responses to Research Question 1. At a minimum, there are three spaceways: VLEO,

LEO, and then GEO, with the requirements to operate in those realms getting more stringent as you go through the list.

The required capabilities to constrain access to certain orbits include requirements related to reliability, resiliency, maneuverability, identifiability, data sharing, orbit allocation, and debris-mitigating design standards. Other research questions discuss these in more detail.

One final point relevant to Research Question 3 is related to a comment from a participant about being skeptical about getting a consensus across the international community and a harmonization of rules globally. It is true that to get the full benefit of STM, including spaceways, the international community would have to sign on to the concept and adopt similar rules. Participant SPE-8 said that Europe and other major space actors were waiting for the US to figure out a plan for the international community related to STM strategy, but Europe has grown impatient and is moving forward. Nonetheless, a recent example of the US leading was Vice President Kamala Harris' announcement at Vandenberg Space Force Base that the US would no longer conduct anti-satellite tests and that the US would lead by example. The researcher agrees that the US needs to do more of that; make the tough decisions, prioritize space sustainability, and lead by example.

Research Question 4

What do stakeholders of a future space traffic management system assess as acceptable rules regarding the definitions of right-of-way in space for minimizing risks of collisions with manmade, active space objects?

The discussions regarding right-of-way rules were the biggest, most complex, and where much of the suggested future work should be focused. Right-of-way rules are also lower on the priority list of the research questions to address with new rules. There will come a time when monitoring and consultation will not be sufficient, and space traffic control will be required. Right-of-way rules are a significant aspect of space traffic control.

The first step is to create a platform and data pool for operators to contribute to through the DOC. The DOC started an effort to combine commercial data with DOD data with the OADR, but there needs to be an accompanying requirement to share data and interface standards. The majority of participants felt strongly that operators should be transparent, and they failed to understand why some operators found it burdensome to send data to a data pool. The intent of a data pool is to provide everyone with a common operating picture so that operators can responsibly make appropriate decisions on their own. The data pool is to encourage coordination and make coordination easy, efficient, and reliable. Multiple participants noted that the current ad hoc coordination has been sufficient but will not be adequate in the future. Ad hoc coordination is a stop-gap measure until someone implements a better system. If operators can coordinate easily, they will coordinate. Operators can automate some coordination, but many participants noted that operators must prioritize active coordination. There was a stated concern about automation reducing coordination and predictable behavior reducing coordination.

Additionally, the move to automated maneuvering by some companies created some consternation for several participants because they cannot predict the maneuvers, and no coordination happens with other operators. The benefit of predictability of behavior outweighs the risk of lack of coordination due to coordination automation. However, system architects understand the importance of active coordination when designing future systems. Using the aviation industry as a model would be a good starting point. Each aircraft automatically broadcasts its position, heading, and speed and the pilots make real-time decisions on operating their aircraft, prioritizing safety. The next step of STC is similar to pilots coordinating with air traffic control and other pilots in the area and following right-of-way rules, including following a pre-defined path and minimum separation distances between aircraft. The system is complex but works very well, creating an incredibly safe industry that continues to innovate.

A long-term step is analyzing and designing concepts to begin an operational management (orbital allocation) system. Watson (2012) focused on orbital designs to maximize density which is a first step. Still, a holistic approach to the design of many different constellations, with the existing systems and constellations already in orbit, needs to be evaluated. Participant SPI-8 discussed the high burden of an overlapping constellation with a current constellation. A system could require future operators to operate in certain orbits where the risk of collisions between active spacecraft could go to zero. A participant also discussed the use of frozen orbits to actively manage particular orbits to minimize the volume of space that a spacecraft will ever occupy. The community must utilize more concepts like frozen orbits to reduce the probability of collision in an inherent way. If operators launched satellites smartly so that the risk of a collision between them was always near zero, then the tracking assets on the ground could focus on the actual threat of debris.

With the creation of more rules or guidelines, operators must be held accountable and there must be a means for conflict resolution. Three good ideas for holding operators accountable were using the licensing process as leverage to encourage compliance, rating each operator with a space sustainability score, and using insurance premiums with an insurance mandate. Participants did not support an insurance mandate at this point. When clear and concise rules of the road exist, conflict resolution is less of a problem, and operators are held accountable to those rules.

To the actual right-of-way rule definitions, the obvious rules are straightforward and broadly agreed upon but are a tiny part of the scope of future rules of the road. Some of the rules mentioned were that the burden to maneuver is on the satellite in a non-operational orbit. If two spacecraft are going to collide, but only one has a maneuvering capability, then that satellite must maneuver. Technical experts must provide more analysis and feedback to inform policymakers on the best path forward.

Overall, coordination must be the first step, but a system can reduce the risk of collision by smartly designing and operationally managing orbits in the long term. The rules of the road will eventually be the way to resolve conflicts if coordination does not reach a resolution. Still, regulators will not create such a system until the space industry is ready to move from monitoring and consultation to active space traffic control. Space traffic control is not needed today but will be required earlier in the relative maturity of the industry to protect the long-term sustainability of the space environment.

Research Questions 5 and 6

What do stakeholders of a future space traffic management system assess as acceptable rules regarding insurance, liability, and compensation for orbital space vehicles for minimizing risks of collisions with manmade, active space objects?

There is not a convincing case for having in-orbit liability insurance. There are two contributing factors to that. First, the insurance industry has no desire to become de facto policymakers by requiring specific capabilities to reduce premiums. Second, there is not enough accident data (and cannot be enough accident data) to create actuary tables to drive premium prices. Eventually, insurance in LEO could be helpful for companies and could be used to drive responsible behavior in space but not until policymakers have defined rules or guidelines.

Insurance is based on probability and the law of large numbers so the insurance industry will have to innovate to determine how to set premiums with few insured and accidents being avoided at all costs (Participant SII-2). The space environment cannot support the probabilistic approach used in other traffic regimes. A zero-tolerance policy for collisions does not allow it. A push by the insurance underwriters into the modeling realm to quantitatively determine risk is a likely path to pursue. Premiums currently have huge swings, but a model and a broader pool of premium holders could stabilize the industry. Another option is using a model similar to models used for floods, fires, and hurricanes.

Additional Discussion

Participants made several interesting and important points unrelated to the research questions throughout the discussions. This section will discuss some of those points because they are essential and provide context to the results of the research questions.

The first interesting comment was about a recent rebranding of STM to space traffic coordination. The participant who mentioned this was unsure if the rebranding was simply to assuage the community, but the scope and long-term intent of the STM is the same, or if the language change also changed the desired long-term scope and mission of the DOC. If it is the latter of the two, this is a mistake, as most participants supported some form of rules beyond just coordination, particularly in the long-term.

A comment made by several participants was that operators in space have an incentive to be safe because they do not want to destroy the expensive asset in space. These comments were connected to conversations about right-of-way and conflict resolution if both operators refused to maneuver. Both operators would indeed like to keep their spacecraft healthy and operate for as long as possible. Still, the counterargument to this point is that in all other traffic domains, operators also would like to keep their assets from being damaged and in an operational condition, yet we have rules in those domains. A desire to safeguard one’s assets does not preclude the creation of a high-risk situation where inaction is the selected course of action.

Multiple participants made another comment about the relative risk of active satellites colliding compared to the risk of satellites colliding with debris. The relative risk of a collision with debris is orders of magnitude larger than the risk of two active satellites colliding, but this study focused on operational satellites for three reasons. First, we cannot control debris, but we can control satellites. Second, as we launch more satellites into space, the risk of collision between them increases. The industry must move toward requiring behavior that minimizes the risk of more debris-generating events. Lastly, the risk of colliding with another active satellite is mathematically unlikely but operationally relevant, especially with tracking technology and operational constraints from satellites' capabilities in space today.

A common complaint of regulations is that they will stifle innovation. For space, companies like SpaceX are breaking that mold and showing that self-imposed rules are not hindering their innovation. SpaceX is one of the most innovative companies in the space industry despite its self-imposed restrictions. An example of this is how SpaceX is deploying its Starlink constellation. Since the spacecraft are being built cheaply and with expected reliability issues, SpaceX launches the spacecraft in batches into VLEO. If a spacecraft fails, it will deorbit in a matter of weeks and will not clog up LEO. The healthy spacecraft rise to their operational orbits, where they can operate while experiencing less drag, reducing the fuel required to maintain their orbits. GEO is an example of a regulated domain where innovation still flourishes.

Participant SPI-1 shared a final comment about vocabulary in space. On the oceans, we have tankers, container ships, sailboats, speed boats, windsurfers, etc. They are all very different; most can imagine and describe the differences and have some knowledge of what each can and cannot do. In space, everything is just a satellite. Part of the STM issue is to educate people on what it means to operate in space and more precise definitions of the variety of capabilities in space.

Conclusions

Most stakeholders are opposed to regulations for the space industry but are open to best practices, guidelines, and standards of behavior. Factors contributing to this position are fear of stifling innovation, imposing a burden on operators, killing businesses, space being expensive and complex, and the nascency of the commercial space industry. Some participants support a broad set of regulations and favor prioritizing the sustainability of the space environment over the concerns listed in the factors of the opposition. Higher than anticipated support for regulations was across all three groups but still in the minority. The majority preferred best practices, guidelines, and standards of behavior. Paradoxically, participants also vented frustration with bad actors and the inability to hold those actors accountable.

There are circular arguments that operators prefer best practices, guidelines, and standards of behavior over regulations, and people will follow them out of self-interest. There is not support for regulatory bodies creating rules, but there is support for developing best practices, guidelines, and standards of behavior with the expectation that everyone will follow them. If that is the case, there is no difference in creating and enforcing regulations. The current state of mind by many is that the ability to make one’s own decisions is more important than safety and sustainability.

Advancing technology through innovation and increasing access to space will drive the need for regulations. At some point, the environmental risk will outweigh the benefit of further rapid innovation, and society will purposely inhibit some innovation to protect the environment. The trick will be to accurately identify the inflection point to ensure regulators do not implement laws too early or too late. The inherent nature of the space environment will mean that the industry will reach the inflection point earlier than in other traffic regimes. Remnants remaining in the environment after an accident will increase the risk to the entire community. Stakeholders must understand that relative timing comparisons to other traffic domains are inappropriate.

Society will need regulations in space for many of the same reasons that society requires regulations for all traffic domains. At some point, rules will become a reality, and this study intended to discover rules that are most agreeable and effective in attaining sustainable operations in space. A widely agreed-upon method of avoiding over-burdensome regulations is to use performance-based regulations that provide a stated intent but allow for flexible solutions to be innovated around by operators. Regulations will stifle innovation. Smart regulations will encourage innovation in strategic areas while reducing innovation in areas of low impact. The most significant problem in space is debris. Requirements that promote innovation around debris issues will help create efficient and creative solutions to benefit the space environment.

Another argument against regulation is that the probability of a collision in space with another active space object is low. That is true today, but the likelihood of active objects colliding in space will exponentially increase as the volume of traffic increases. Moreover, uncertainties of object locations in space, due to limitations in tracking and modeling, at present traffic levels already incur a cost to operations. A low probability of collision does not mean there is no effect on the industry when collision avoidance is still operationally relevant.

A final argument by detractors of regulations is that space policy is an international issue, and this mindset inhibits progress in making rules at a domestic level. The viewpoint is if it is unsolvable globally, then why solve it at a domestic level? For the foreseeable future, nations will continue with the polycentric governance of space, with the key word here being governance. Here is an opportunity for the US to proactively lead the international community.

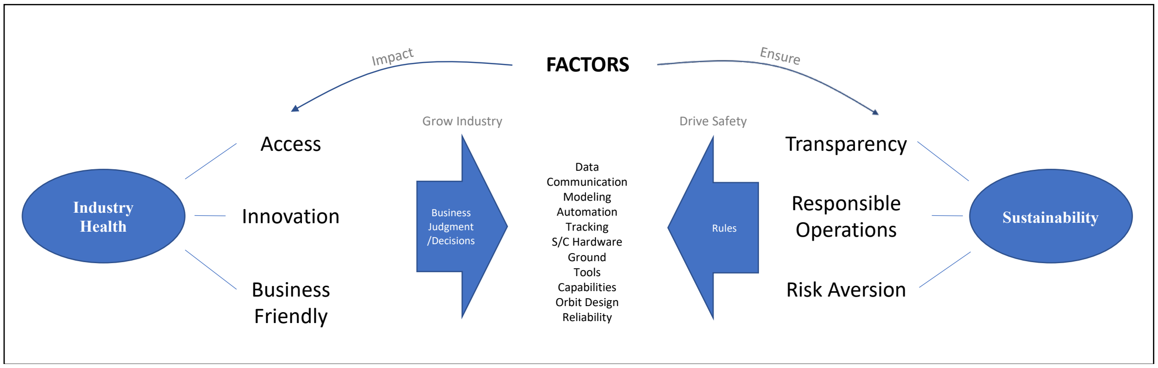
Theoretical Contribution

Researchers construct grounded theory from the collected data via well-developed categories and explanations of the respective linkages between the categories (Corbin & Strauss, 2015). Recall from Figure 9 that from the categories a theme or a higher level, abstract concept is defined and called the *core category or concept* (Corbin & Strauss, 2015). Researchers can then state assertions or theories from this core category (Corbin & Strauss, 2015).

Figure 17 is a high-level, cross-question depiction of the linkages and relationships between most categories derived from the data for each of the six research questions. It is clear from the data that there is a conflict between the determination to create a thriving and healthy industry and the drive and imperative for the sustainability of the space environment. Critical metrics for industry health were ease of access to space for various operator classes, the freedom to innovate, and keeping the industry business-friendly to encourage investment, innovation, and growth. Sustainability depends on responsible operations where operators are transparent with their data and intentions and operate with an appropriate level of risk aversion to avoid generating more debris. The conflict comes down to factors where many interviewed participants would like to retain their ability to use their business judgment to make their own decisions. Opposed to that is the group of participants who would like to create rules to control those factors to assure a safe environment, even if it impacts the operations of space operators. The vital question is how do we drive safety while growing the industry as a community? What rules minimize the impact on access, innovation, and business, and what business decisions must operators make to assure transparency, responsible operations, and risk aversion? The key to accomplishing this balance is the introduction of accountability in the industry.

Figure 17

Linkages and Relationships of Categories



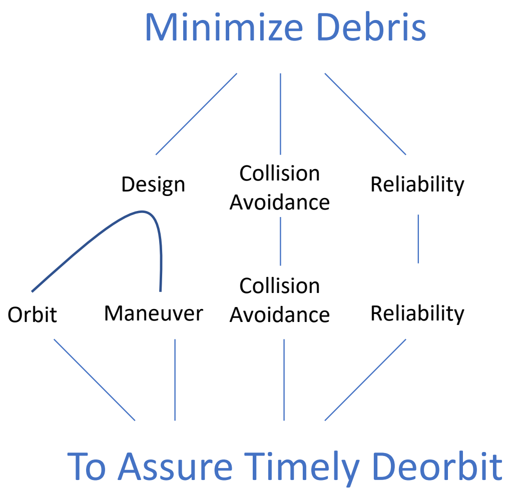
Several participants discussed their frustration with the lack of accountability in space operations and offered several solutions. The first was using a third-party space sustainability rating system to publicly shame operators into following best practices, guidelines, and standards of behavior. The rating system would be publicly available and could be used by investors to determine investments and to provide a financial incentive for operators to behave. Second was the use of insurers to encourage good behavior, but until there is a requirement for operators to have in-orbit insurance, the power of insurance companies is minimal. Lastly, many participants across all three groups pushed to introduce a limited set of performance-based incentives.

At a simplified level, in the aviation domain, aircraft movements are very prescribed, and there are varying levels of required capabilities to fly in different classes of airspace, including communication requirements. For autos, guides are abundant to help traffic, and there are standardized ways to communicate to facilitate the safe flow of traffic, but drivers make their decisions at the individual level. For maritime, right-of-way rules are defined and understood; otherwise, it is a free-for-all with standardized communication forums. For space, the desire for some is not to prescribe movements, do not standardize communications, and do not force right-of-way rules. The space industry will eventually have to pick at least one that works best for the space domain. The consensus from participants is that communication and coordination are essential, meaning that a safe system is possible without prescribed movements and right-of-way rules so long as communication and coordination occur. How can operators be encouraged to communicate and cooperate? How can operators be encouraged to follow other best practices, guidelines, and standards of behavior in a minimally invasive way?

One idea derived from a consensus of U.S. regulatory actions and participants of this study is that *accountable deorbit requirements will innovatively drive sustainable space operations*. The most significant risk in space, agreed upon by all participants, is debris and generating more debris. Minimizing debris generation and ridding the environment of debris is the highest priority. There are three primary considerations for reducing the generation of more debris: design, collision avoidance, and reliability. The three considerations of minimizing debris map nicely to the four considerations to assure timely deorbit, shown in Figure 18 below.

Figure 18

Connections Between Debris and Timely Deorbit



For accountability, this concept means that fines may be levied or licenses restricted, but only if operators do not meet a deorbit requirement. The deorbit requirement is that operators must remove their *entire object* from the environment in a defined period after the completion of the nominal mission. For every other aspect of space operations, each operator can utilize their business judgment and determine their risk tolerance to make decisions about how they operate, about how closely their operations align with the best practices, guidelines, and standards of behavior. Operator behavior will naturally tune itself as the traffic volume and risk of operating in the environment increases. When traffic volumes are low, operators can take more freedom, but when traffic increases, operators begin to police themselves. A regulator can also tune the system to encourage better behavior by changing the required deorbit timeline. As previously discussed, debris is the most significant issue in space today, and not all debris is trackable. Spacecraft can be destroyed by unknown and unseen objects that the operator cannot control. Those instances would not be punishable.

To understand how this might work, let us look back at the research questions. First, regarding the topic of maneuver, it was clear from the data that the driving force for a maneuvering requirement is for deorbit, not to perform COLA maneuvers. Depending on the deorbit timeline requirement and the desired mission orbit, the imperative for maneuver capability is levied second-hand. No one needs to define maneuver if the maneuver method can reliably remove the object from the environment in a particular timeline.

Reliability was a topic several participants mentioned as a significant concern for the large constellations. A 1% failure rate in a constellation of 5,000 satellites means 50 dead satellites drifting uncontrolled in orbit and having a minimal impact on that operator's mission. Suppose a dead satellite in space prohibits an operator from launching more satellites, impacting their mission and business. In that case, that operator will ensure they can remove their spacecraft from orbit in a reliable manner. They can innovate around the need for reliability to ensure the success of their future business ventures. Or they can fly lower, and physics will guarantee they will deorbit in the required timeline.

For tracking, objects will continue to be tracked by the network of sensors. The government and commercial companies will continue to perform COLA analysis to inform operators of potential risky conjunctions. Errors in the measurements will still exist, and predictions of future locations will degrade over time. The aspect of tracking that a majority support is the idea of operators self-reporting position and intent so that the impact on operators is reduced proportionally with orbit uncertainties via operator truth. How can operators be incentivized to share their data? One way is to associate a long-term consequence with short-term decisions. In today's paradigm, if an operator's satellite destroys another object, there is a short-term financial hit by losing the asset, but the operator can launch another asset. In a future paradigm, if decisions made by the operator (e.g., not to share data) result in a collision and their resultant debris cannot deorbit in the required timeline, then that operator is facing the prospect of regulators withholding licenses for future launches. The longevity of that business' prospects will dim, and because of that, the operator is more likely to behave responsibly. That may include being more transparent by sharing location, intention, probability of collision assumptions and errors, and automated algorithms. Operations must be predictable and determinate.

Several participants discussed self-interest as a reason for avoiding mandatory data sharing and coordination. The concept is that operators are not purposely dangerous because it also puts their assets at risk. Self-interest can be a driver for safety, but self-interest can also be the driver for unsafe behavior, such as leaving a spacecraft in orbit without disposing of it to eke out as much profit as they can. When does safety outweigh profits? When fines hit profits for not disposing of as required.

Another factor discussed by participants related to transparency, data sharing, and coordination was automation. Several participants pushed for openness in automation algorithms and a system where automation does not circumvent coordination. Operators would need extremely high levels of confidence in their automation to avoid collisions if they were unwilling to share those algorithms and unwilling to coordinate actively.

In the long term, most participants thought more regulations will arrive and that the industry would need STC at some point for the same reasons other domains required them. The expectation is that best practices, guidelines, and standards of behavior will naturally evolve into easily palatable regulations, including STC.

Practical Contribution

From a practical perspective, this study provides regulators with a summary of many perspectives from three stakeholder groups so that as regulators prepare potential future rules, they can approach that process better informed. Additionally, the results of this study provide insights to operators on the possible future of space traffic management so that they can prepare their plans and constellation designs for potential future regulations. More importantly, if there are regulations that operators think would be detrimental to the industry, this study will give them adequate time to prepare their perspectives and comments to share their concerns with regulators during comment periods.

Limitations of Findings

The findings of this study are limited to the three stakeholder groups whose perspectives were shared in Chapter IV. Additionally, the results are valid only during this point in time. As the dynamic industry evolves, technology progresses, and space traffic increases, the stakeholders' perspectives will likely change. A significant factor that will change views is if more collisions happen more frequently and the environment becomes more dangerous in which to operate. A last aspect that may change stakeholders' perspectives is the actions of other countries. Since space is a global domain and there needs to be international coordination, efforts by foreign governments will impact how the U.S. approaches regulating space.

Recommendations

Recommendations for Target Population

For regulators, the industry is more accepting of some moderate rules than expected. There is also this fear that regulations stifle innovation, but intelligent regulations can help drive and direct innovation. Regulators must identify where they want to drive innovation and set regulations accordingly. Additionally, be straightforward regarding what will remain a guideline and what aspects of space operations will see future regulation so operators can predictably comply. Create and plan for phased rules so that everyone can prepare and to provide stability and predictability for licensing. If the government, in coordination and communication with industry, wants to delay the creation of laws (as has happened with regulations related to space launch), that is fine, but set a vision and update the community frequently. If guidelines are indeed recommendations, there is no reason not to shoot for the stars. Set minimum regulations, such as a disposal requirement, that operators must meet and then guidelines for what the best of the best should achieve. Rate the operators so the industry, investors, and the public can hold bad actors accountable. Society uses ratings for many other products and services, and there is a place for ratings in the space industry. The space industry should not be afraid to act and to be agile. If regulators create a law that does not work out and has unintended consequences or a negative impact, consider an adapt-and-change mindset but also weigh the risk to regulatory uncertainty. There is a need to be conservative for space because accidents should be avoided at all costs, and a zero-tolerance policy is required.

Recommendations for Future Research Methods

For social science research methods, the recommendation is to conduct an industry survey to gain perspectives from a larger population and objective metrics on what stakeholders want and what they think is fair. The results from this study provide many insights to help create the survey instrument. Another recommendation is to analyze comments made during federal rulemaking related to STM. Such a study may provide additional insights, and the data is currently available.

Recommendations for Future Work

Research related to STM is broad and nearly endless. A few recommended future research topics are research regarding:

- Standards and interfaces for data exchange for automation of coordination.
- Technical analysis of orbital allocation design with an emphasis on the impacts to space operators.
- Impacts to users in reducing the 5-year deorbit rule.
- Impacts to users by requiring a maneuver capability.
- An altitude where a maneuver requirement makes sense.
- Tracking identification technologies.
- Limits in modeling to predict spacecraft movements with the associated minimum tracking network requirements.
- Research into reliability standards for spacecraft operating in non-VLEO orbits.

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Appendix A

Tables

Table A1

Summary of Foundational Space Treaties and Agreements

Title	Year	Key Participants	Summary
Outer Space Treaty Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies	1967	Canada, China, France, Germany, Japan, Iran, Iraq, U.K., U.S., U.S.S.R.	• Outer space, and the exploration thereof, shall be to the benefit of all mankind and all states have the freedom to explore. • States may not appropriate or claim sovereignty in space. • Nuclear weapons or other weapons of mass destruction are not allowed to be placed in space. • States are responsible for national space activities originating from their jurisdiction. • States are liable for damage cause by their space objects and they should avoid contaminating space.
Rescue Agreement Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space	1968	Canada, China, France, Germany, Japan, Iran, U.K., U.S., U.S.S.R.	• Elaborates on Articles V and VIII of the Outer Space Treaty. • States are responsible for assisting and/or rescuing an astronaut in distress, regardless of statehood. • The astronaut must be returned to the launching state. • Space objects must be returned to the launching state.
Liability Convention Convention on International Liability for Damage Caused by Outer Space Objects	1972	Canada, China, France, Germany Japan, Iran, U.K., U.S., U.S.S.R.	• Elaborates on Article VI and VII of the Outer Space Treaty. • Launching states are absolutely liable and compensation is due for damages caused by space objects: o On the surface of the Earth. o To aircraft. o To other objects in space. • Provides a means for settling claims.

Title	Year	Key Participants	Summary
Registration Convention Convention on Registration of Objects Launched into Outer Space	1975	Canada, China, France, Germany, Japan, Iran, U.K., U.S., U.S.S.R.	• Elaborates on Article VIII of the Outer Space Treaty. • Basic information regarding objects launched into space must be provided, including a designator, orbital and launching parameters and general function of the space object. • States must provide assistance in identification of space objects that have caused damage.
Moon Agreement Agreement Governing the Activities of States on the Moon and Other Celestial Bodies	1979	France, Guatemala, India, Romania	• Not signed by the major space powers (China, U.S., U.S.S.R.) • Expands on the Outer Space Treaty. • Covers only the moon and other celestial bodies within our solar system. • These bodies are to be used for peaceful purposes and no weapons of mass destruction or military installations are allowed. • Exploration is for the benefit of all mankind and no national appropriation. • Freedom of scientific investigation and sample collection but recommend sharing samples with the international community. • Respect the environment of the bodies. • Bases can be built on or below the surface, as long as those bases do not interfere with the activities of other State Parties. • Safeguard human life, regardless of nationality and offer shelter.

Note. Adapted from *Exploring the Competitive Advantage of the U.S. Commercial Space Transportation Industry: A Qualitative Case Study* [Doctoral dissertation, Northcentral

University] (p. 127) by S.A.H. McMullen, 2015, ProQuest Theses and Dissertations (https://www.proquest.com/openview/8f7b01e7f205f0c3aa5885eb07b685bb/1.pdf?cbl=18750&pq-origsite=gscholar).

Table A2

Summary of Findings and Recommendations from an AIAA Workshop in 1999

	Finding	Recommendation
Orbital Resource Management		
Number 1	Both commercial and government operators need accurate, timely and dependable information regarding allocation and location of space resources.	A new international clearinghouse of information services is needed to collect, maintain, interpret, and facilitate the distribution of data regarding planned and existing satellites in orbits.
Collision Avoidance		
Number 1	A mechanism is needed to warn satellite operators when there will be close approach or potential collision and to provide real-time guidance.	An internationally organized entity should be developed to provide reliable, timely, generally available collision warning and mitigation service for launch, in-orbit and end-of-life operations.
Number 2	Governmental and commercial satellite operators are willing to pay for the service described above.	The service provider concept should be reviewed and refined by an international body or committee that includes representatives of both industry and government.
Orbital Debris		
Number 1	If prudent measures to reduce the formation of space debris are not instituted in the near term on a worldwide basis, the hazards are expected to escalate significantly within 10 years.	Support work is being done by the UN, IAA, and others to develop guidelines designed to minimize the creation of new debris.
Number 2	Technologies exist to incorporate de-orbiting capabilities into satellites.	Government and the commercial sector are encouraged to promote the application of technical solutions to the de-orbiting of spacecraft.

	Finding	Recommendation
Number 3	Removal of existing small, untracked debris would reduce the risk of collisions.	Development of debris removing technologies should be encouraged. Governments are strongly encouraged to invest basic pre-competitive technology that could be further developed and applied to commercial operators.
Regulatory Framework		
Number 1	Only 40 States adhere to the Registration Convention.	Action should be taken to implement the Registration Convention.
Number 2	Not all states have the same standards regarding licensing and regulating launches and on-orbit operations.	An appropriate organization with international outreach should survey existing organizations and practices for regulating launches and space objects; estimate probable future expansion of these activities; and identify and analyze options for an international regulatory framework.
Number 3	Existing legal instruments for space do not use the term space debris and do not differentiate between valuable objects in space and worthless space debris.	IISL is requested to study the definition of space object and other relevant terms and recommend appropriate steps to the UNCOPUOS.
Number 4	A more comprehensive system of identifying and tracking spacecraft and orbital debris and the establishment of collision avoidance services, raises a number of issues related to international liability.	The IISL is requested to study the issues of liability and to initiate appropriate steps.

(Bittles et al., 1999)

Appendix B

Interview Protocols

B1 Initial Interview Protocol

Orbital Coordination Study

Purpose: This document is an interview protocol that will be used to gather perspectives from multiple groups of stakeholders on appropriate rules for reducing the risk of collision between active spacecraft.

Create a participant ID number by:

- Group
  - S = Space Industry
  - I = Insurance Industry
  - P = Policy
- Sequential Value
- E.g S03
  - Space industry participant number 3

Introduction:

Hello <participants name>! Thank you again for agreeing to spend some of your time to participate in my dissertation research.

Introduce yourself (Name, School, Program, Work)

As I have mentioned to you before, my study seeks to understand perspectives of experts and users of a future space traffic management system to find a general consensus among different groups for rules to minimize collisions between operational spacecraft. From the consensus, the goal is to create a list of recommended rules of the road for future space operations. Your perspective will go directly into forming those rules! The interview today should only take about an hour of your time. It will first cover some basic information about you, your background, and your experience before moving into a few different constructs related to safe space operations. The questions are open ended in nature, so I ask you to speak freely and at length to give me a full understanding of your perspective. If you need me to repeat or clarify the question, please do not hesitate to ask.

As a human subject, the interview process has been reviewed by Embry-Riddle's Institutional Review Board, and in compliance with their rules, your identity will remain confidential, and you will not be named, or your perspectives identified in my results or conclusions. You have been assigned an identifier with the only decoder stored in a password protected location on my personal computer and encrypted cloud-based folder. Additionally, by signing the informed consent form to participate in this interview, you acknowledge and approve the use of audio recording of this conversation. The audio file and transcriptions will be named only using your identifier, and they will be saved in a password protected folder on my personal computer and encrypted cloud-based folder. I will be providing you an opportunity to correct my interpretation of your comments by sending you a copy of the transcription of our conversation along with a summary of my understanding. This will come via a link to the encrypted cloud storage for you to access securely from your home computer. I will use the email address we have corresponded with prior to this interview unless you have a different email you would prefer I use.

Review consent form with the participant

If you have any concerns over your privacy and the precautions I am taking to protect your information, please do ask those questions. Are you still ok with me recording this conversation today and agree to be a participant in this study?

___Yes ___No

If yes: Excellent! Thank you again for agreeing to participate! If at any time you would like me to halt the recording, please let me know.

If no: Thank you for letting me know, and I am sorry to have taken up your time. As stated earlier, your name will not be associated or reported in the research, and the contents of this conversation will remain protected.

Alright, before we get started with the interview, do you have any questions for me?

Answer/Address any questions or concerns

If any questions pop-up during the interview, please stop me and ask your question. I am more than happy to answer your questions and to make sure this process is as easy for you as possible.

Interview Questions:

Demographic Information

1. Can you please state your name, age, current position, and/or title?

2. Can you please describe in detail your education and professional background?
3. Do you have any publications? Are they related to STM/space operations/space policy?
4. How familiar are you with the topic of space traffic management?
5. Do you think you are a qualified person to discuss the topic of Space Traffic Management? Why or why not?

Constructs

Ok, onto the core of the interview questions. The questions are broken up into three different thematic groups with some overlap between the three. Some of yours may bleed into other areas, and that is totally fine! If we get to later questions and you feel that you have already given an answer to that question, please say that and we can move on to the next question. If you have some thoughts outside the questions, please feel free to share and speak freely. This is your time to help me understand your perspectives!

Spacecraft Systems (tracking, maneuvering)

1. From what you know, how are satellites tracked today, and do you think those tracking methods are sufficient for a future STM system?
    a. What are your thoughts on government versus commercial SSA data collection and distribution?
    b. Do you find tracking or identification of spacecraft as a tough problem to tackle? Why or why not?

    c. How do you see space operator self-reported information contributing to the knowledge base built from sensor measurements? Which will be more important?

2. What improvements do you think could be made to help track active spacecraft?
    a. Are we technology or funding limited?
    b. What requirements would a suite of advanced sensors be required to meet the demands of a future STM system?
3. Are there improvements that could be made on the spacecraft itself to help improve tracking?
    a. Can you share any spacecraft technologies that you are aware off that may make it easier for the ground sensors to track and/or identify spacecraft?
    b. Should funding be spent on better ground sensors or on spacecraft technologies to help track and/or identify spacecraft?
4. Do you think it should be a priority to improve tracking technology of spacecraft? Why or why not?
    a. What importance do you place on SSA in the big picture of STM?

<u>ConOps (maneuvering, zoning, right-of-way, spaceways)</u>

1. If two spacecraft operators were notified that they were going to collide into each other in the near future, what should the rules be (right-of-way rules) as to who is required to maneuver out of the way?

    a. If both have propulsion systems?
    b. If only one has a propulsion system?
    c. Any economic considerations that could be made?
2. What could be a good metric for determining when one or both spacecraft need to maneuver?
    a. Collision avoidance is all about reducing probabilities; is there a threshold where moving spacecraft to reduce the risk of collision should be mandatory?
    b. What other criteria might one use to require movement aside from probability of collision?
    c. How would operators communicate and coordinate their collision avoidance efforts?
3. I am going to read a scenario to you, and I want to know your thoughts on it and ideas for policies that could help address the scenario:

    Imagine a scenario where two commercial co-orbiting spacecraft have been identified by the Joint Space Operations Center (JSpOC) as being on a highly probable collision course. The first spacecraft is an advanced low earth orbiting (LEO) commercial imaging satellite with a mission of taking photos of the earth for commercial and government users. The second spacecraft was recently launched and is a small, cheap commercial spacecraft without means to maneuver out of the way. The larger spacecraft is able to maneuver but must stand down on their mission to perform the maneuver.

4. Can you explain if it should or should not be mandatory that all future spacecraft should have the capability of maneuvering?
    a. What would some of the pros and cons of that requirement be?
    b. Are technologies being developed to make this requirement more feasible?
5. Do you think some orbits are more valuable than others?
    a. Why or why not?
    b. If yes, which orbits do you think are more valuable?
6. How would you recommend regulating orbits of different values, if different at all?
    a. Have you heard of concepts of orbital allocation?
        i. If yes, what concepts for allocation rules/processes have you heard of?
7. What are some other operational requirements or constraints you think would help foster safe and orderly operations in space?
    a. Announcing pre-planned maneuvers?
    b. Timeline for reporting sudden movements?

Legal (liability and compensation, insurance)

1. How familiar are you with space liability law?
    a. Internationally?
    b. Nationally?

2. Do you think there are liability related laws that could be created to help foster responsible and safe operations in space?
    a. Do you think insurance, in particular, mandatory insurance could play a role in helping foster safe and responsible uses in space?
    b. Aside from physical damage due to collision, what are your thoughts on monetary liability due to placing undue burden on other operators?
3. Thinking back to our scenario before, do you have some ideas related to insurance and liability that could help resolve that scenario?

Final questions:

1. Do you have any other information that you find useful and/or relevant to today's topic that has not been addressed yet?
2. Do you have anyone you would recommend that would be willing and suited to participate in this research study?

B2 Interview Protocol version 2

Orbital Coordination Study

Purpose: This document is an interview protocol that will be used to gather perspectives from multiple groups of stakeholders on appropriate rules for reducing the risk of collision between active spacecraft.

Create a participant ID number by:

- Group
    - SPI = Space Industry
    - SII = Insurance Industry
    - SPE = Policy
- Sequential Value
- e.g., SPI-3
    - Space industry participant number 3

Introduction:

Hello <participants name>! Thank you again for agreeing to spend some of your time to participate in my dissertation research.

Introduce yourself (Name, School, Program, Work)

As I have mentioned to you before, my study seeks to understand perspectives of experts and users of a future space traffic management system to find a general consensus among different groups for rules to minimize collisions between operational spacecraft. From the consensus, the goal is to create a list of recommend rules of the road for future space operations. Your perspective will go directly into forming those rules! The interview today should only take about an hour of your time. It will first cover some basic information about you, your background and your experience before moving into a few different constructs related to safe space operations. The questions are open ended in nature, so I ask you to speak freely and at length to give me a full understanding of your perspective. If you need me to repeat or clarify the question, please do not hesitate to ask.

As a human subject, the interview process has been reviewed by Embry-Riddle's Institutional Review Board and in compliance with their rules, your identity will remain confidential and you will not be named, or your perspectives identified in my results or conclusions. You have been assigned an identifier with the only decoder stored in an encrypted cloud-based folder. Additionally, by signing the informed consent form to participate in this interview, you acknowledge and approve the use of audio recording of this conversation. The audio file and transcriptions will be named only using your identifier and they will be saved in an encrypted cloud-based folder. I will be providing you an opportunity to correct my interpretation of your comments by sending you a copy of the transcription of our conversation along with a summary of my understanding. This will come via a link to the encrypted cloud storage for you to access securely from your home computer. I will use the email address we have corresponded with prior to this interview unless you have a different email you would prefer I use.

Review consent form with the participant

If you have any concerns over your privacy and the precautions I am taking to protect your information, please do ask those questions. Are you still ok with me recording this conversation today and agree to be a participant in this study?

___Yes ___No

If yes: Excellent! Thank you again for agreeing to participate! If at any time you would like me to halt the recording, please let me know.

If no: Thank you for letting me know and I am sorry to have taken up your time. As stated earlier, your name will not be associated or reported in the research and the contents of this conversation will remain protected.

Alright, before we get started with the interview, do you have any questions for me?

Answer/Address any questions or concerns

If any questions pop-up during the interview, please stop me and ask your question. I am more than happy to answer your questions and to make sure this process is as easy for you as possible.

Interview Questions:

Demographic Information

6. Can you please state your name, age, current position and/or title?
7. Can you please describe in detail your education and professional background?
8. Do you have any publications? Are they related to STM/space operations/space policy?

9. How familiar are you with the topic of space traffic management?
10. Do you think you are a qualified person to discuss the topic of Space Traffic Management? Why or why not?

Constructs/Topics

Six question topics: tracking, maneuvering, zoning/spaceways, right-of-way, insurance, liability and compensation

Three constructs: ground/spacecraft (tracking) systems, spacecraft operations (ConOps), law

Ok onto the core of the interview questions. The questions are broken up into three different thematic groups with some overlap between the three. Some of yours may bleed into other areas and that is totally fine! If we get to later questions and you feel that you have already given an answer to that question, please say that and we can move on to the next question. If you have some thoughts outside the questions, please feel free to share and speak freely. This is your time to help me understand your perspectives!

What I want to focus on: mid to long term issues. Not near-term issues. Many folks focused on debris/environment in general, understandably so. But once that is figured out, once traffic is significantly increased, what rules then?

Ground/Spacecraft Systems (tracking)

5. Tracking of large space objects is relatively easy and done all the time

  a. What improvements, if any, do you find tracking or identification of spacecraft requires? Why or why not?
    i. Are we technology or funding limited?
    ii. What requirements would a suite of advanced sensors be required to meet the demands of a future STM system (on ground)?
    iii. Would improved persistency help? Why or why not?
    iv. Could there be a standardization measurements to be more predictable? Ideas on those standards?
    v. Should more sensors be added to track objects more frequently/always? GEO monitoring vs ground (i.e., similar to ADS-B)?
    vi. Should funding be spent on better ground sensors or on spacecraft technologies to help track and/or identify spacecraft?
    vii. Improvements to ground processing/dissemination systems?
  b. Do you see space operator self-reported information contributing to the knowledge base built from sensor measurements? Which will be more important?
6. Are there improvements that could be made on the spacecraft itself to help improve tracking?

    a. Can you share any spacecraft technologies that you are aware off that may make it easier for the ground sensors to track and/or identify spacecraft?

7. Do you think it should be a priority to improve tracking technology of spacecraft? Why or why not?
    a. What importance do you place on SSA in the big picture of STM?

<u>Spacecraft Systems and ConOps (maneuvering, zoning, right-of-way, spaceways)</u>

8. If two spacecraft operators were notified that they were going to collide into each other in the near future, do you think there should be rules (right-of-way rules) as to who is required to maneuver out of the way?
    a. If both have propulsion systems?
    b. If only one has a propulsion system?
    c. Any economic considerations that could be made?
9. What could be a good metric for determining when one or both spacecraft need to maneuver?
    a. Collision avoidance is all about reducing probabilities, is there a threshold where moving spacecraft to reduce the risk of collision should be mandatory?
    b. What other criteria might one use to require movement aside from probability of collision?
    c. How would operators communicate and coordinate their collision avoidance efforts?

10. Do you think it should be mandatory that all future spacecraft should have the capability of maneuvering?
    a. Altitude limit for differing capabilities?
    b. Would creating a barrier have unintended consequences by potentially driving every to flight right below/above the barrier? If so, what? How to we combat that?
    c. What would some of the pros and cons of that requirement be?
    d. Are technologies being developed to make this requirement more feasible?
11. Do you think some orbits are more valuable than others?
    a. Why or why not?
    b. If yes, which orbits do you think are more valuable?
    c. How do we handle orbit that cross through each other?
        i. Equal Value orbits
12. How would you recommend regulating orbits of different values, if differently at all?
    a. Have you heard of concepts of orbital allocation?
        i. If yes, what concepts for allocation rules/processes have you heard of?
13. What are some other operational requirements or constraints do you think would help foster safe and orderly operations in space?
    a. Announcing pre-planned maneuvers?
    b. Timeline for reporting sudden movements or critical events?

<u>Legal (liability and compensation, insurance)</u>

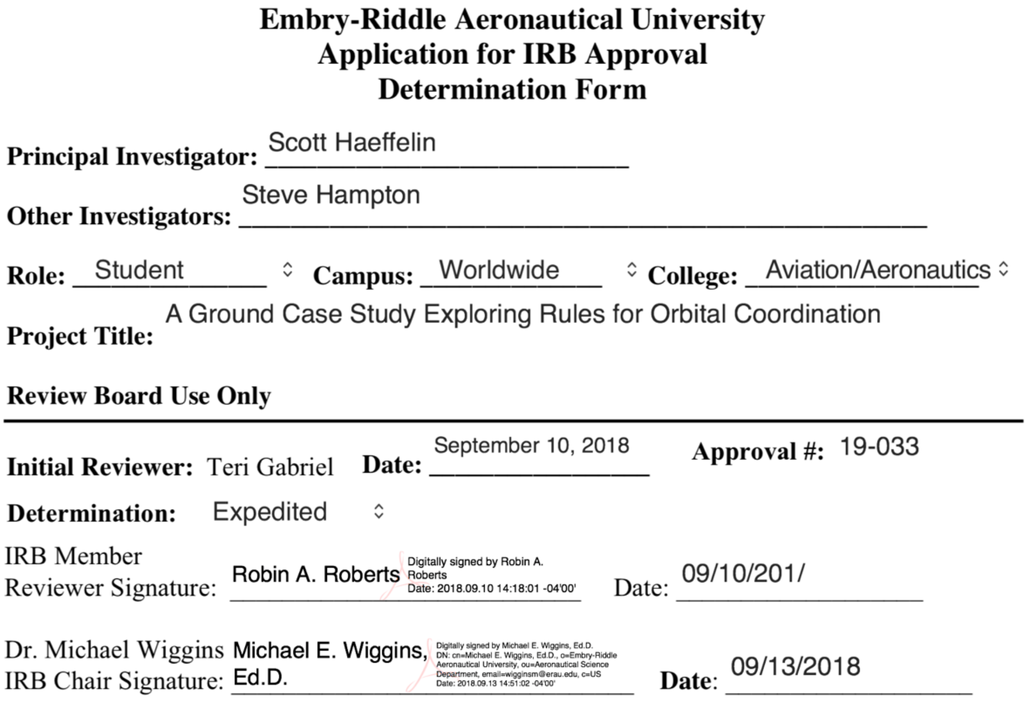
4. Do you think there are liability related laws that could be created to help foster responsible and safe operations in space?
    a. Do you think insurance, in particular, mandatory insurance could play a role in helping foster safe and responsible uses in space?
    b. Aside from physical damage due to collision, what are your thoughts on monetary liability due to placing undue burden on other operators?

<u>Final questions:</u>

3. Do you have any other information that you find useful and/or relevant to today’s topic that has not been addressed yet?
4. Do you have anyone you would recommend that would be willing and suited to participate in this research study?

Appendix C

Permission to Conduct Research



Embry-Riddle Aeronautical University
Application for IRB Approval
Determination Form

Principal Investigator: Scott Haeffelin

Other Investigators: Steve Hampton

Role: Student ⌃⌄ **Campus:** Worldwide ⌃⌄ **College:** Aviation/Aeronautics ⌃⌄

Project Title: A Ground Case Study Exploring Rules for Orbital Coordination

Review Board Use Only

Initial Reviewer: Teri Gabriel **Date:** September 10, 2018 **Approval #:** 19-033

Determination: Expedited ⌃⌄

IRB Member Reviewer Signature: Robin A. Roberts Digitally signed by Robin A. Roberts Date: 2018.09.10 14:18:01 -04'00' Date: 09/10/201/

Dr. Michael Wiggins IRB Chair Signature: Michael E. Wiggins, Ed.D. Digitally signed by Michael E. Wiggins, Ed.D. DN: cn=Michael E. Wiggins, Ed.D., o=Embry-Riddle Aeronautical University, ou=Aeronautical Science Department, email=wigginsm@erau.edu, c=US Date: 2018.09.13 14:51:02 -04'00' **Date**: 09/13/2018

Appendix D

Supplemental Quotations

Research Question 1 Quotations

"No. I don't like mandates. I think that there ought to be obligation to ensure that what you are doing with your spacecraft, you're not interfering with anybody else's freedom of operation or in general the viability of an orbit. I don't think that the issue is so acute that you need to have mandatory regulatory regulations to force companies to have maneuver capability" (Participant SPI-2).

"I think definitely there should be, maybe you want to have some altitude ranges where you require a capability to maneuver" (Participant SPI-3).

"My qualifier to that would be that I think anything that flies above the space station [408 km] ought to be maneuverable" (Participant SPI-5).

"People have been you know, kind of centering around 400 kilometers just because that's the altitude of manned spaceflight right now and it's also a fairly decent number because things that are in a 400-kilometer orbit don't stay in orbit very long. Anything below 600 kilometers is gonna be compliant with a 25 year deorbit requirement" (Participant SPI-4).

"If you're operating above a certain altitude then you must have a plan to deorbit your satellite within 25 years. If you're below a certain altitude, then you don't need maneuverability because atmospheric drag will bring you down" (Participant SPI-8).

"I come down heavily on the side that we are spending an enormous amount of time and energy talking about space traffic management and collision avoidance. It only makes sense if spacecraft are maneuverable and if they are not maneuverable, then effectively you are transferring that burden to operators who have gone through the time and effort and expense of making their spacecraft maneuverable. So my answer is generally, yes, I think everything should be maneuverable. It makes no sense to me that you should be able to license a very low budget program to fly in orbits that could disrupt operations of more responsible and much more expensive assets" (Participant SPI-5).

"I think there should be protection for smaller operators. Precisely because I think that will help innovation" (Participant SPI-5).

"I would certainly say this, a compromise, if you're not maneuvering, you must have some sort of transponder and report your orbit data" (Participant SPI-7).

"Only if it can be done economically cause what's gonna happen is if it becomes so expensive for it to deorbit the whole system that it makes is so that the program doesn't go forward? I'd rather not see a program fail because you couldn't deorbit it than a program, a new program succeeds. So, there's a cost effect to it as well. Requirements for satellite maneuverability should only be included if they can be implemented economically. If the fix is too expensive, it's going to kill programs/businesses before they can be successful" (Participant SII-2).

"In terms of economic incentive I think the economic incentive is for us not to create more debris so the way I describe it is there's responsible space activity and then there's the do-nothing approach" (Participant SII-2).

"I'm reluctant to say that the US government or any government should impose some sort of requirement" (Participant SII-3).

“Have to ensure that your satellites are de-orbited at X time and then let the owner operators or the people putting up the satellite, figure out how they’re going to do that” (Participant SII-3).

“Requiring some sort of propulsion system, what if that fails? There’s always gonna be some level of failure rate? So, what do you do? Maybe that’s okay, we have these little propulsion systems and three or four percent of them are gonna fail and those satellites are just gonna have to decay naturally or whatever” (Participant SII-2).

“The problem that you’re gonna run into there is defining what being able to maneuver means. Notionally, you mean with so much warning, you can move more than a certain distance from an expected close approach and so you have to define fairly specifically how much time they have to allow, which means that’s when they have to make their decision, whether they’re gonna maneuver.” (Participant SPE-6)

“You probably have to add maneuverability capability to re-enter, right? Maybe a drag increase device, maybe propulsive capabilities to re-enter” (Participant SPE-8).

“I think the best approach from a regulatory perspective is if the government can come up with a set of performance-based regulations. They’re written in such a way to allow technology advances and innovation. Don’t be prescriptive about how you tell people to go do that, tell them what they have to go do, and don’t tell them how they have to do it” (Participant SPE-3).

“I don’t think that is realistic because the whole world of cubesats and nanosats would be eliminated it with that requirement” (Participant SPE-1).

“I think depending on the altitude, yes. I think there’s some technology popping up that is for very low earth orbit, VLEO, some different technology that would then also quickly let [the satellite] re-enter. So that might not require maneuverability, but the higher you go up, I think, and the more congested things get, I think we are going towards maneuverability" (Participant SPE-8).

"Collision avoidance capabilities should be a requirement for every satellite over 400 kilometers. It's ridiculous that we have a term space traffic management [when] we don't require them to make their… having the ability to manage their risks from the traffic. We should require people to put collision avoidance on every satellite. Then you actually have something to manage. Otherwise, you just hold, crossing your fingers and hoping for the best" (Participant SPE-4).

"We probably have to have some level of maneuverability above 400 or 600 kilometers altitude" (SPE-2).

"Yes. Yeah. I would say that's my personal opinion on it is that there should be like a point at which you get high enough that you are not going to naturally demise in a short period of time. So, if you're talking about like cubesats and such then great ... That have no maneuverability, then, you know, great to drop them at a VLEO. It seems like [not having maneuverability] is okay below the space station" (Participant SPE-7).

"If they can't maneuver, then you know, we're just putting the entire environment at risk. So, I think there should be some capability. At some point you have to get, not only from the perspective of what are the consequences for me, but you know, what are the consequences for the environment?" (Participant SPE-6).

"There was that kind of opposition and frankly not a lot of technical analysis to support one way or the other, is why we asked the commission to shove that question off into a further notice of proposed rulemaking, rather than just making a kind of arbitrary decision. We just didn't really have enough evidence to require that" (Participant SPE-2).

"Everyone gives way to the lesser maneuverable vessel and that is for practicality more than anything else. The most maneuverable can move out of the way most efficiently the problem with that for the long term, actually even the short term, is it creates a perverse incentive to design a less maneuverable satellite because you'll be less likely to be required to move and that is not a good condition moving forward" (Participant SPE-1).

"Having requirements will always add cost and weight and schedule complexity to the system. So, it always adds something" (Participant SPE-8).

"Depending on your [satellite] size, which will automatically increase with the complexity of your satellites, the added risk of more complex systems are they have more are failure points" (Participant SPE-8).

"In a field where there is rapid innovation in technology you need to be very careful when it comes to constraints. If you standardize too early, you risk limiting your ability to take advantage of operational enhancements" (Participant SPE-1).

Research Question 2 Quotations

"Yeah, I think the idea of having a transponder like they do with aircraft, is a good one, as long as it's not a very large heavy instrument, that's why I think it should be voluntary" (Participant SPI-2).

"I think there needs to be something on the satellite so, if there's an anomaly, even on rocket bodies, right. Put something on there where you can now track that from a ground element" (Participant SPI-6).

“Some sort of beacon that makes them more observable. Now certainly like if you’re a big, large satellite, opticals are gonna see it no matter what, but when you start getting some of these cubesats they can get difficult to see” (Participant SPI-7).

“There might be certain circumstances where having some form of beacon that identifies where a satellite is advantageous. Maybe that beacon is just simply so that the satellite is visible through a radar, which we already see everything, which is greater than 10 centimeters” (Participant SPI-1).

“There are a few ways that you can go about [making a complete catalog with higher accuracy]. One is, is encouraging folks to include beacons particularly on smaller satellites” (Participant SPI-5).

“Yes, it absolutely would. There’s different types of those. Some are optical, some can be like a unique radar signature and that sort of thing” (Participant SPI-8).

“Some sort of beacon that makes them more observable. Now certainly if you’re a big, large satellite opticals are gonna see it no matter what, but when you start getting some of these CubeSats they can get difficult to see. Obviously from an RF standpoint having some sort of transponder obviously certainly would help the whole ecosystem if everybody, like aircraft, have this kind of equipment on your spacecraft before you put it up” (Participant SPI-7).

“Some means of being able to figure out you know, which small satellite is, which small satellite should exist. Larger satellites, I don’t think it’s really much of a problem. And if it’s small there needs to be a better way of figuring out which is which, and it’s not so much for space traffic management or collision avoidance. It’s actually just the help of operators themselves contact and have a working satellite” (Participant SPI-4).

“I think with some recent trends with the proliferation of CubeSats, for example those tend to be a little more difficult to identify upon initial deployment and keeping track of those is a little difficult given their size. So, I think inclusion of beacons is probably a good idea or some kind of mechanism” (Participant SPI-5).

“With CubeSats it’s a little more problematic. SpaceX deployed over a hundred satellites and they’re still trying to figure out which satellite is which satellite. So, the future improvement could be some means of passively figuring out which satellite is, which satellite like a RFID tag or something like that. With the CubeSat, especially since they tend be a little less sophisticated and they’re relying upon the government to tell them where their satellite is” (Participant SPI-4).

“If you have a way to get information from some type of an optical or RF sort of beacon, that has a unique identifier in it. Yeah, then the identification part of the problem is solved immediately” (Participant SPI-8).

“The problem you’re trying to solve in general is a more complete catalogs with higher accuracy data. You wanna see as much stuff as you possibly can, and you’d like those trajectories to be as accurate as possible” (Participant SPI-5).

“I believe that they should integrate commercial data sources because that’s just much more persistence” (Participant SPI-6).

“There are now some commercial actors like LeoLabs and ExoAnalytics, for example, that are providing tracking services both to government clients and to the commercial industry” (Participant SPI-5).

“More sensors are definitely better, but one of the limitations that we have right now is that most sensors are in the northern hemisphere. So, more sensors in the Southern hemisphere would definitely help” (Participant SPI-4).

“We’ve seen some evidence that with LeoLabs that adding commercial sensors could be beneficial because these sensors are actually designed for space tracking as opposed to detecting missile stripes” (Participant SPI-4).

“I think getting those [space based] assets to be able to add an additional data source from a space-based kind of perspective would be key as well” (Participant SPI-6).

“You need to be transparent. I believe that everybody should be transparent” (Participant SPI-6).

“We believe in transparency, so our ephemerides are available to any operator that wants to have access to them. We also send our ephemerides to the space data association” (Participant SPI-4).

“If you have better data than the government or better data than what’s being made public, voluntarily disclosing that would be helpful” (Participant SPI-2).

“Providing that data is potentially beneficial to people tracking objects in space if they know where your object is, they don’t necessarily need to track your object as often as they track the debris” Participant SPI-4

“In general operators are likely to know where their assets are more accurately than trying to track them remotely” (Participant SPI-5).

“I know that there have been a number of studies looking at operator provided data, and sometimes it has biases and inaccuracies baked into them. But there are ways to compare that with validated tracking sensors and to work out those biases and make corrections" (Participant SPI-5).

"There ought to be other ways of self-reporting by companies so that there's not one solution set that, you know, one size fits all that could be detrimental to some operators" (Participant SPI-2).

"They should also report that [data] to a central agency such as a government data pool or a commercial data pool or multiple pools. We're sort of coalescing around the idea of data pools where both operators and folks that have the radar sites and sensors all send data to some centralized data pool. Data pools are important, and I think an international data pool where people are comfortable sending their data to knowing that it's not controlled by any one country is probably the future you know" (Participant SPI-4).

"Encourage data sharing and potentially mechanisms for hosting information about spacecraft" (Participant SPI-5).

"I think it's better to have some like standardized reporting system. Normalized machine-to-machine connections between and requirements for machine-to-machine connections between some sort of centralized tracking system" (Participant SPI-3).

"I think the commercial guys get a little, I think they're worrying about just sort of intellectual property, like how do we do business. But that data could go in like a central repository, like if [Department of Commerce] starts actually doing what they've been told to do then that seems like the likely place it's sort of a neutral sort of government thing that just says, hey, you just post your stuff here" (Participant SPI-7).

“If we don’t have [a database] for ships, why should we have one for satellites? We don’t have one for aircraft either. We just established that the density of satellites is something like two to three orders of magnitude less than the density of ships or planes. We don’t have a database for ships, and we don’t have a database for planes. Why would we need, what’s like the justification for having a database for satellites?” (Participant SPI-1).

“There’s tracking persistence and there’s accuracy of the sensors. Depending on the altitude of the object, a lot of it is gonna be in modeling the orbital environment, the atmosphere drag and the ballistic coefficients of the objects that you’re tracking. So, the way you counter that is you take more data with more accurate sensors and then there’s an element of this also of modeling and having more accurate physical models of the environment” (Participant SPI-5).

“When you have a sensor network and you’re measuring objects, you’re supposed to know the errors and uncertainty sources or levels in your sensors. And then what you do is you take your measurements for an object and then it goes into orbit determination algorithms” (Participant SPI-8).

“What we’ve seen is the way the co-variance is computed, at least by the government, is not sufficient for the future that we have” (Participant SPI-6).

“For a debris catalog, the biggest bang for the buck is improving accuracy as opposed to seeing more stuff. If you’re gonna do STM, the goal would be to, to know where something is within say, a hundred meters or something and then maybe do the propagation that takes you out only as far as it is still accurate to some prescribed level. Or you could take the best information that you’ve got and then just publish the accuracy and let folks determine whether they think it is useful. Additionally, information about the physical characteristics of the spacecraft so that you could do trajectory projections and propagations. The whole STM problem is about predicting, knowing where an asset is and knowing what its predicted trajectory is gonna be" (Participant SPI-5).

"I think that the current mode of coordination or the coordination that is possible now, operator-to-operator is more than sufficient" (Participant SPI-5).

"I think it's more about just communication between the two operators and having systems in place so that you don't have to have an email, or a phone call every time it comes up and then sort of, what do you want to do?" (Participant SPI-8).

"I don't think it's sufficient down to the level that is needed to protect against all collisions" (Participant SII-1).

"I think it would be reasonable, more than reasonable to, to have a system where you track the path of everything in space, on a constant basis" Participant SII-2

"On a national basis, yeah, you could [make a requirement to self-report], a requirement would be good, but it would disadvantage to those nation's operators compared to the operations of other countries" (Participant SII-1).

"In LEO they may have a mission that they don't particularly want everyone to know exactly what they're doing" (Participant SII-1).

"It [beacons] can be a RFID tag or it can be an active beacon. These beacons would do essentially what, they would be like an ADS-B for space or an AIS which is the maritime equivalent. I think if everyone had a beacon then would be a lot smarter. We happen to be big believers in beacons we think every object that's launched every intact object should have a beacon. We're getting a lot of push back and obviously people are saying well, I don't want people knowing where my satellites are" (Participant SII-1).

"[If you're] gonna have something that's gotta emit a signal, you're not guaranteed that it's gonna work, you could always have some failure. Some sort of reflector, then pretty much you can say that's not gonna fail, but requiring extra stuff to go on the satellite may not be the best way to go" (Participant SII-2).

"The Space Data Association was [emphasis added] a very useful forum for that not everyone has bought into" (Participant SII-1).

"It [number one priority] is getting the basic SSA data for civilian operator to make decisions" (Participant SPE-2).

"SSA is really the foundation of everything that we do in outer space, because you need to kind of know where things are, right?" (Participant SPE-8).

"The construct and policy for space surveillance is appropriate, and it is appropriate moving forward the amount of data and the types of sensors is where we will continue to evolve to get more accurate and higher fidelity data" (Participant SPE-1).

"It's more of commitment to safety, just becoming normal, being required. I don't think the limitation of any technology at all. It's just the limitation of people going, ah, I need to do this to be safe and it needs to be a requirement" (Participant SPE-4).

"I think what we have right now is, I think it would be sufficient if people did a better job of sharing. So, I think it's really a combination of technology and people and processes. So, I would say it is sufficient but not with the current processes" (Participant SPE-4).

"We will produce a few hundred thousand conjunction alerts a year that result in just a few hundred maneuvers. This amount of false information, it's not false information, imprecise information, has a cost in the industry" (Participant SPE-1).

"The fidelity and quality of data continues to need to evolve and improve to meet the needs of an increasingly congested space environment" (Participant SPE-1).

"One of the things that we talked about a lot, there was the need to have higher fidelity information" (Participant SPE-7).

"We're going to need both government and commercial systems and one of the important reasons for going to commercial is that there's more opportunities to incorporate new sensors and systems than there is with legacy governance systems" (Participant SPE-2).

"The primary difference between the government and commercial systems, it's not quality of the sensors or anything. It's really the inability of legacy architectures" (Participant SPE-2).

"It's much easier for me to figure out how to incorporate those into a secure cloud architecture with commercial than it is to figure out how to incorporate that into the existing legacy systems" (Participant SPE-2).

"When you look at the existing systems for tracking you realize pretty quickly that with what the number of satellites in the sky is gonna be, it breaks the system pretty quickly" (Participant SPE-7).

"[LeoLabs data] is so much better than CSpOC data, but CSpOC is free. People should stop complaining about it being bad, you get it for free" Participant SPE-4).

“The optical network that we rely on for tracking things in GEO, it is barely adequate” (Participant SPE-6).

“There are additional companies and governments that are bringing on new information for the tracking and detection in terms of different earth observation, digital telescopes, electronic detection means so as they add new sensors” (Participant SPE-1).

“Commercial networks like ExoAnalytic could fill that gap” (Participant SPE-6).

“There are no companies that’re saying, yes, we collected it, we’re going to hand it to the government, it is sold to the government the government is a customer so can you structure it in a way that the government as the customer is providing adequate commercial incentive for the industry to continue to build those sensors. A mixed-use, mixed-customer, mixed-payment system has actually proven itself in space over the last 7 years pretty efficiently” (Participant SPE-1).

“There’s also telemetry data where the operators are tracking their own space objects and provide that into the space situational awareness catalog” (Participant SPE-1).

“There are operators that are willing to share, we’ve got 30 of them, and some of those are more than willing to share” (Participant SPE-6).

“I honestly don’t understand it. There is this sense that operators think that there’s something magical about knowing where their satellite is and that they don’t wanna release their, I’ll say good data” (Participant SPE-6).

“I think it could be that first of all, how do people realize that it’s out there?” But that if “there’s a forcing function, maybe it could work” (Participant SPE-3).

“Absolutely, [operators, self-reporting their ephemeris should be a requirement, in a future system]” (Participant SPE-4).

"What we need is all of the sources available contributing to a common data picture" (Participant SPE-1).

"Open Architecture Data Repository (OADR) is basically just information of where everybody's at, that people can go access and add to that incorporates all kinds of things that says we want to have space weather information, environmental information, total electron count measurements, spacetrack.org numbers and updates from optical and radar commercial systems. A very, very large cloud environment that people can interrogate" (Participant SPE-2).

"The Russians, for example, have always advocated to expand the registration convention, to have more active understanding of where the objects are, what their maneuvers are and so forth. The Department of Defense has always advocated for, no, we will maintain the authoritative catalog. [Gen. Hyten is] not, he was not willing to give up that catalog. I think that's an old view" (Participant SPE-8).

"It's now sort of operator-to-operator and that happens sort of on an ad hoc basis" (Participant SPE-4).

"It strikes me as that, coordination between companies is pretty ad hoc" (Participant SPE-7).

"I think it needs to be a little bit more automated. Not that maneuver should be automated, but that the notifications and the discussion should be more automated and not manual" (Participant SPE-4).

"Department of Commerce is starting to take on in a larger sense. That's the sharing of data, the coordination part" (Participant SPE-8).

“The other thing that’s a challenge in the space situational awareness realm is not just the detection but the prediction” (Participant SPE-1).

“As soon as we stop looking at [the satellites], then they’re somewhere, but we don’t where cause it’s in space, it doesn’t move in a direct line, right. So, it’s very much a conversation about how do we do the best that we can to model where things are going and to engage in capabilities to track them maybe with like a little bit less fidelity but more regularity” (Participant SPE-7).

“Because there’s no way to share [ID information] other than the operators doing their own independent orbit and saying, here’s our orbit, and then trying to match it, what they need is an ability to be able to have some kind of passive sensor on the satellites, you know, sort of like an RFID tag, that when it goes to the radar, it says, oh, I’m satellite X” (Participant SPE-6).

“Objects need to be better monitored. That could be they could be using some sort of system, a beacon system for identification, but also making them more visible when they’re smaller. We need to be able to take better measurements and so there’s a component on the ground that can help with that, but there is also a component in space, like through adding on beacons or you know, GPS sensors” (Participant SPE-8).

“[A beacon should] absolutely be a requirement. I think more of active, but there’s a very nice low power RF. There’s several prototypes that have flown that are active and I would prefer an active one. I mean, I think passive is a low-end option. I think they should be active and there’s not a lot of SWAP that you have to worry about” (Participant SPE-4).

“Many of them would really benefit from having something like a beacon that basically full-time reports where they are because you have a situation where if they become dead, nobody has high accuracy ephemeris because GPS is onboard and is dead. And so, a beacon could give an identifiable, like an RFID tag” (Participant SPE-4).

“Do I find traffic tracking, identification of spacecraft, a tough problem, absolutely not. Actually, spacecraft are easy. You can make it hard if you’re say deploying a bunch of CubeSats rapidly from the space station, if you don’t space them out enough then it takes a while to assign unique identifiers to the numbers” (Participant SPE-2).

“The first thing I’ll say is that tracking the large objects is not easy and that’s, I think, a misperception that a lot of people have is that if it’s big, you can see it, then you know where it is, and the problem is if it’s big and you can see it, it’s probably performing a mission and it’s maneuvering all the time to stay within its mission parameters and so the Space Data Center, in particular, was set up exactly because of that problem, that the hardest things to track were the ones that were maneuvering all the time” (Participant SPE-6).

“I’m sure you’re aware of the launch from a week or so ago. 143 satellites, almost all of them CubeSats, and we’re still going through the process of trying to ID ‘em. Now, the 18th is coming out with IDs. I can assure you that they are not all correct” (Participant SPE-6).

“I’m a firm believer that automation typically improves things. So, taking humans out of the loop usually, I have a lot of confidence in automated software solutions, and taking humans out of the loop” (Participant SPE-3).

Research Question 3 Quotations

“You might imagine like a couple layers that are dedicated, just like air traffic control” (Participant SPI-3).

“Yeah. I could see at least slightly different rule sets and maybe constraints or lack of constraints based on your orbit. There might be different rules for GEO, you know, maybe say low LEOs” (Participant SPI-7).

“Layers that are dedicated to high tech, science payloads that maybe are slightly above your big constellations, where you might put future Hubbles and James Webbs and things like space station” (Participant SPI-3).

“Maybe you want at some point [where] you’re far enough away that the risk is high enough and the duration of a debris field is long enough that you’ve gotta be able to de-orbit yourself” (Participant SPI-3).

“Once you get up to… at some point, the volume of space gets so huge that COLA, the risk of COLA, goes away” (Participant SPI-5).

“Then obviously at GEO, you gotta be able to put yourself in a disposal orbit” (Participant SPI-3).

“Obviously some satellites are not in circular orbits, you probably wanna require some sort of special license to be in some very eccentric orbit” (Participant SPI-3).

“I think it doesn’t have to be an exclusive allocation” (Participant SPI-5).

“Well, what happens if [Company 1] or [Company 2] overlaps our constellation and the answer is it’s very burdensome. It would be a big problem. And so, I think for space traffic management, it’s very important that constellations have some kind of altitude separation from one another” (Participant SPI-4).

“There’s also already a precedent for allocating orbits in GEO, they already do allocate orbital slots by longitudes” (Participant SPI-5).

“You influence to get people not to overlap in their orbit, but if we’re thinking very long term then yeah, eventually we’re gonna have to get to a system where like in GEO, there’s some kind of slotting, there’s a certain number of satellites that go through a certain altitude at a certain inclination. We may have to get there in the long-term future if the mega constellations are really coming, which it looks like, you know, one is” (Participant SPI-4).

“Getting government cooperation, I’m kind of pessimistic on that, so, I would say we’re decades away” (Participant SPI-4).

“We control to frozen orbits it’s an orbit where you park over the north pole and minimize the altitude variation. It’s an effective mechanism of minimizing the amount of volume that you’re flying through which minimizes the probability that you’re gonna have a conjunction. If you’re not in a frozen orbit, then you would need more separation” (Participant SPI-4).

“Reliability, maneuverability, I think orbit selection, separating large constellations, for example, I think is so that they’re not overlapping in altitude deorbit reliability timelines” (Participant SPI-5).

“We probably will have to eventually get to some kind of reliability requirement” (Participant SPI-4).

“If you have an anomaly or something, then yeah, you should be able to at least deorbit” (Participant SPI-6).

"I think [maneuverability should be required] in all orbit regimes…from a space sustainability perspective, you can't just leave your crap up there anymore" (Participant SPI-4).

"Now those rules, even today aren't necessarily always followed. People will just launch and go to whatever slot" (Participant SPI-6).

"I don't like mandates. I think that there ought to be an obligation to ensure that what you are doing with your spacecraft, is not interfering with either anybody else's freedom of operation or in general the viability of an orbit" (Participant SPI-2).

"I just think people need to get on board and we have to sustain space as an operation. I think they just need to get over it and innovate around that" (Participant SPI-6).

"I think the requirement should be that the possibility of a conjunction shouldn't exist meaning that altitude separation has been applied" (Participant SPI-4).

"I don't think any should be less or more stringent. I think they should all be stringent" (Participant SII-2).

"Certain operators have started launching large amounts of satellites into particular orbits because they want to claim squatter's rights to those orbits and I think that's a very dangerous, kind of slippery slope to go down because then people are gonna start launching things into orbit just to be able to claim ownership of a particular orbit, I think that's wrong" (Participant SII-1).

"I'm not sure if there's certain orbits that would be more interest from a regulatory point of view or a control point of view than others. And how it would be managed? What's gonna drive the space economy is where putting up satellites, I wanna make money or where do I think I can make what sort of business idea do I have, and that's gonna define where that satellite needs to go. So, I would not want government impediments or interference with that, because then that's gonna be a drag for that economy, but it's gotta be well-managed right. And, what's the best way to manage that is through industry, associations and things like that. Some sort of top-down government mandate would probably be by people who have zero experience in the real world" (Participant SII-3).

"You design areas where certain orbits would require maneuverability. This is where we can look to aviation as well because think about airspace classes. Airspace classes require minimum equipage levels in order to participate in that airspace class so could you create an environment where there is sort of space classifications. To be in this orbit you need this level of maneuverability, this orbit is available for others" (Participant SPE-1).

"The requirements that you're going to operate in this particular congested domain is there's a minimum standard of maneuverability that is required" (Participant SPE-1).

"Having maneuverability in GEO seems like a no brainer with your low near the atmosphere doesn't seem like maneuverability is really gonna be that important. So, it's an argument of where you draw the line and what level of Delta-V you would require" (Participant SPE-2).

"This is like bicycles not being allowed on the freeway. Allowing them on the freeway would raise the risk" (Participant SPE-7).

"When we talk about these rules we need to look backwards and see where there needs to be some standards in the design phase" (Participant SPE-1).

"During review and licensing, should look at reliability and have some standard that they must meet, whether they have maneuverability or not. Want to make sure if you have propulsion that it works when it needs to" (Participant SPE-7).

"If you're required to remove your object out of orbit within one year after operational life, I think you pay a little more attention to the reliability and your post-mission disposal" (Participant SPE-4).

"You would say something like, you have to have something to identify yourself in orbit or provide data into the system that is coordinating all of these things. And we're not going to tell you what, so it doesn't have to be an ADS-B. It doesn't have to be a beacon. It doesn't have to be this, but it's going to be something that is compatible with our system and let them figure it out. I see that as an eventuality for, for sure. It seems to me like that's something that's going to happen" (Participant SPE-3).

"This will have a significant impact on the low-end users particularly when it comes to research university non-commercial small satellite operators because it could restrict their access because it makes the cost of the satellite more expensive" (Participant SPE-1).

Research Question 4 Quotations

"You need to be transparent. I believe that everybody should be transparent. I even think our exclusion list should be transparent now with all the capabilities that are out there today, everything can be seen so there's no reason to do that" (Participant SPI-5).

“We believe in transparency, so our ephemerides are available to any operator that wants to have access to ‘em. We also send our ephemerides to the Space Data Association cause we believe it’s important and providing that data is potentially beneficial to people. If they know where your object is, they don’t necessarily need to track your object as often as they track the debris” (Participant SPI-4).

“We’re sort of coalescing around the idea of data pools where both operators and the radar sites and sensors all send data to some centralized data pool that generates conjunction data messages but part of that data that would be flowing there would be the maneuver plan” (Participant SPI-4).

“I wouldn’t say that I have a super strong preference on an actual set of rules. I think it’s more about just communication between the two operators and having systems in place so that you don’t have to have an email, or a phone call every time it comes up. That’s what we have and certainly something the industry needs to move away from. Obviously, there’s a mixture of maneuverable and non-maneuverable satellites up there. If you have a maneuverable versus a non-maneuverable, then that’s a pretty clear-cut choice. But then in the scenario where you’re both maneuverable, this is where communication becomes key. What you don’t want to happen is a scenario where there’s a close call and the two operators don’t talk to one another and then they both maneuver their satellites because there is a world where you could both maneuver into each other” (Participant SPI-8).

“Maintaining an email list is not a great way of sharing information. Nothing else exists. So, until something else exists, that was the best way to do it” (Participant SPI-4).

“I think that the current mode of coordination or the coordination that is possible now, operator-to-operator, is more than sufficient. Creating specific rules of the road, I think may be necessary at some point in the future, but I think that’s a solution looking, you know, in search of a problem to some extent. I think the starting point is just to make sure that 24/7 operational points of contact are identified rather than specific email addresses for individuals, they could be position email addresses, a mission director, so that no matter who happens to be on duty” (Participant SPI-5).

“There’s no way for owner operators, government, or military or civil to be able to actually come together on a platform and communicate right now” (Participant SPI-6).

“[Program] is meant to use additional analytics so that the operators, it shrinks down to what I need to pay attention to today from a conjunction perspective, do I need to plan a maneuver? I’m seven days out. I see there’s a high-risk junction. Could I plan a maneuver? And de-risk all these other conjunctions. And so, in that we actually asked the owner operators for their onboard ephemeris and if you have both of the owner operator ephemeris together, you’re able to do that analysis that makes a pristine result” (Participant SPI-6).

“Have required standards for ground systems to receive information and normalized maneuvering, normalized practices at ground stations” (Participant SPI-7).

“I’m going to deorbit a satellite, or I’m going to put it out in a graveyard, or I’m going to change. I’m going to get close to somebody else. It’s making intentions known. I think that sort of activity by the private sector, that transparency will be helpful in an environment” (Participant SPI-2).

“I think the uncertainty around actual position, which feeds into those probabilities, may be better known by a company or a government, better known than another company or another government. We’re not just getting a ping once every once in a while, we’re tracking our satellite all the time. I think that there has to be a way that factors into it” (Participant SPI-2).

“The other danger I see in having set rules for who should move and who shouldn’t is that I think there is a real chance that it then discourages coordination. I think it is still the safest mode of practice for the two operators to coordinate, to talk to each other. It could be an automated conversation, or it could be a person-to-person conversation where they convey their understanding of the situation and their intent and to coordinate action or inaction by either party. But if you set rules of the road there’s a risk that people act unilaterally or presume that the other party is gonna act unilaterally” (Participant SPI-5).

“I am a fan of automation as long as the automation does not exclude coordination” (Participant SPI-5).

“[Constellation] sometimes maneuvers and doesn’t really mention it. At some point there’s a disconnect there. I think satellites should be able to maneuver last minute and autonomously. But to avoid each other, that maneuver should be recorded in a timely manner. I think that that doesn’t have to be in advance” (Participant SPI-2).

“They have thousands of satellites there’s not a scenario where they’re gonna send out an announcement for each maneuver. It’s more kind of fluid than that, but I think what they have done is share the criteria under which their system will do an automated maneuver” (Participant SPI-8).

“Normalized electronic machine-to-machine connections between and requirements for machine-to-machine connections between some sort of centralized tracking system” They also would like to take the concept to space, “I wish everything could be space-to-space and I wish we could just do things without the ground. Cause then if you could do that you can wait till later to do anything and 99% of these problems resolve themselves” (Participant SPI-3).

“[constellation] does automated collision avoidance with their spacecraft and I personally think that’s a horrible idea because they’ve taken the coordination out of the operation. Their attitude is we’ve automated the whole thing so if we have a conjunction with you, don’t worry about it. We’ll take care of it. They don’t give the other operator an opportunity to discuss the situation with them or to coordinate a maneuver that they might have planned or that they wish to make in order to avoid the conjunction. That’s a problem on a couple of levels, right? One is you gotta trust them when you don’t really have any insight into how they assess the conjunction or how they go about determining what kind of maneuver to make. You don’t have any sense for the reliability of their system. You don’t know whether the, the object you’re encountering is a live Starlink satellite or not. So, if you have a conjunction with one and SpaceX says, don’t worry, we have automated collision avoidance, but it’s a dead spacecraft. You don’t have any way of knowing that. And, lastly that’s the sort of system that even if you could solve all of those problems, it’s the sort of thing that only one operator gets to do, because as soon as the second operator does it, if those two operators have a shared conjunction, they both have uncoordinated independent and unilateral automated decision processes, so now they’re both gonna move” (Participant SPI-5).

“I actually believe in the future, it should be autonomous. I know [Company] is doing it. I’m not sure I believe in the way they’re doing it, but I think we can get to a place, machine-to-machine, where you have an autonomous maneuvers that optimize those or when a conjunction comes up, it just happens autonomously and that they’re able to sense like their surroundings” (Participant SPI-5).

“I don’t wanna be too critical of [Company], but what I’ve seen over time or over the last decade is that it’s dangerous to completely trust the data that you’re getting, if you don’t actually own the sensors” (Participant SPI-4).

“There’s a whole collision avoidance and collision probabilities and co-variance realism and all that good stuff, people get crazy about it. It’s such a hot topic about how to calculate it all correctly” (Participant SPI-8).

“You can kind of report based on the collision probability and then each operator has their own sort of preference about what metric they use to base maneuver decision off of. Some operators really rely on collision probability and they’ll just look at the value that the 18th reports and they’ll say, okay. Others ignore that completely and they’ll look at other values or they’ll recompute the collision probability using some other tool, or they can look at values like one is called the Mahalahobis distance, which is a representation of the relationship between the miss distance and the covariance size. There’s two main factors that go into how that collision probability number can sort of vary and this is where you can get into differences where like the 18th calculates it this way, cuz they use these assumptions. But this other company they calculated this other way and they use these assumptions. And so neither one is wrong, but you have to understand the assumptions that went into the calculation and that’s often sort of ignored.

I still think PC is the best metric but it's a very sensitive metric to use and when sharing the information, I think it's very important that whoever issued that alert, whoever calculated that collision probability needs to be very transparent in saying the assumptions that they used to actually calculate it, because then the operator can take that into context" (Participant SPI-8).

"There's tracking persistence, there's accuracy of the sensors, a lot of it is gonna be in modeling the orbital environment, the atmosphere drag, for example and the, the ballistic coefficients of the objects that you're tracking. Small stuff has higher ballistic coefficients. So, the way you counter that is you take more data with more accurate sensors. And then there's an element of modeling" (Participant SPI-5).

"Things get a bit more congested because you're having to spend more and more time assessing conjunctions and reacting to them. As that happens, you'd like to think that the data gets more accurate to keep the problem manageable" (Participant SPI-5).

"The whole STM problem is about predicting, knowing where an asset is and knowing what it's predicted trajectory is gonna be; information about the physical characteristics of the spacecraft" (Participant SPI-5).

"You could have a satellite operator who gets the most dangerous conjunction alert ever. We live in a world right now where the operator could have a maneuverable satellite and chooses to ignore it and chooses to not maneuver and there's no repercussions whatsoever. There's no penalty. And what's worse is that the general space community wouldn't even be aware that the close call ever happened in the first place. So, there's just like a total lack of visibility into like what's happening, who are being responsible space actors that sort of thing. I think space should be like the other domains of land, air, and sea where you can't just drive or, fly an airplane or whatever, like wherever you want, whenever you want sort of thing. Like if you mess up and go outside the bounds that dictated by like federal or state law, there's consequences for that" (Participant SPI-8).

"I think we're at least five to 10 years away. I say that because in practice that sort of coordination has not been a problem. I've never encountered a situation where two operators impact each other and are involved in a conjunction, and they have some disagreement about who should move. It's in both party's best interests to, to coordinate so, I've never seen it become contentious" (Participant SPI-5).

"We actually overlap in altitude with [another system] because we're both in frozen orbits, the possibility of collision is zero. It doesn't take a lot of altitude separation to work depending on the orbit. So, we're in frozen orbit so you need much less separation, but if you're not in a frozen orbit, then you would need more separation" (Participant SPI-4).

"I don't see any harm in establishing a standard or a or even a rule that one spacecraft ought to be the one to maneuver. The problem with doing that prematurely before it really becomes an issue is that you establish rules for the road that might be less efficient or less convenient than if you just let the operators coordinate" (Participant SPI-5).

"In most scenarios, what happens with collision avoidance is that the closer you get to the time of post approach of a given event the more accurate the data gets. The closer you get the more that error goes down. So that's the choice that operators are faced with is the more I wait, the closer I wait to the last minute, the more likely it is that the collision risk will go down and I won't have to maneuver it all" (Participant SPI-8).

"The burden of maneuver is on the satellite that's transitioning from its injection orbit and its mission orbit or moving between mission orbits or deorbiting" (Participant SPI-4).

"I think what's gonna have to happen is a set of rules that are agnostic of who it is. If you are this, then this, and that's not going to be easy. If you had a little better set of rules of the road that everybody could kind of agree on like, it seems reasonable to say if someone is more maneuverable than others or has, you know, a greater percentage of fuel left or life left or whatever that they would be the one more likely that, it's less costly for them to move. A set of rules that are about like, who is hurt the least by having to move" (Participant SPI-7).

"We were playing with the suggested traffic rules and said, well what happens if [Company 1] or [Company 2] overlaps our constellation and the answer is it's very burdensome. It would be a big problem. And so, I think for space traffic management, it's very important that constellations have some kind of altitude separation from one another" (Participant SPI-4).

"One spacecraft operator can't say this entire orbit is mine. Orbits tend to not be so defined that you can't have [a satellite] 50 kilometers higher that has almost zero probability of potential collisions that wouldn't work from a business case" (Participant SPI-2).

"Beginning with a sort of simple approach, people could start adopting like this year, ground rules as far as who maneuvers and how they maneuver and if no one can maneuver, then obviously you don't have any options, but if only one can maneuver, it's pretty easy to build a tree" (Participant SPI-3).

"I think good stewardship is a start, right? So, people ought to remove their hardware from orbit as soon as practicable afterwards with some really tight timelines" (Participant SPI-5).

"I would love it if it's enforced it's not enforced. They're trying to force us little guys but all the big guys and all that forcing it, there's lots of spacecraft launch and they have no chance of being out of orbit in 25 years. And there's no punishment if you launch a satellite and it goes dead after seven years and you can't maneuver it out of orbit, and it's going to stay there for 200 years. There's no cost to that" (Participant SPI-1).

"A company] is a big proponent of reducing that. We signed on to the space safety coalition doc, where I believe we said five years" (Participant SPI-4).

"That's a tough one. If they both have on-orbit propulsion, then I think they just have to work it out I think as long as there was no intent in terms of setting up the collision probability, but I think satellites should have propulsion if they're above the ISS so if they're above the ISS then I would say they have to work it out. It's pretty hard to say well the spacecraft on the right has the right-of-way. Which ones on the right? So, there are a lot of issues with that it's more a matter of cooperation if one is just a derelict then obviously the one who's active needs to take action" (Participant SII-1).

"If everyone had a beacon then would be a lot smarter about where things are I think the LNTs will always be a problem and, but I think you know again it's pretty hard to have rules of the road in terms of right away even if it's big and small or active against derelict or whatever it’s pretty hard to have rules. Just at this point I don’t I haven’t seen any good solutions to that” (Participant SII-1).

“The space data association WAS [emphasis added by participant] a very useful forum for that but not everyone has bought into it, and I think something similar would be good but again it’s a matter of who’s data do you use. Space Data wants you to use [Company]’s data and there’s other data out there that might be equally useful so it’s pretty hard to say exactly what the standard should be you know what group should be the clearing house” (Participant SII-1).

“As you get more and more crowded and then start being disposed of, now I’m not controlling that satellite anymore. Now it’s uncontrolled. It’s just on its decay. So that’s to me where the biggest issue is. I’m not too concerned of satellite constellations colliding into each other. I think it is pretty settled before they launch, they know where they’re going and you can prevent a lot of that by, with a launch license. You gotta show that you’re not gonna be an issue for existing constellation” (Participant SII-3).

“What you could do if somebody’s a bad actor you could not give them a launch license” (Participant SII-3).

“What they can do is better time their maneuvers. They can either delay a maneuver or advance a maneuver. So, I don’t know that it’s become something that’s a burden where they have all these extra maneuvers, they just have to time the maneuver properly based on the conjunctions that they’re getting” (Participant SII-3).

“It would be very beneficial to have the industry very involved and figuring out what people think makes sense from a traffic management point of view, rather than have some dictate come from some bureaucrats” (Participant SII-3).

“Maybe there’s some other way to do it. I would not want to say impose a top-down sort of one size fits off solution for every satellite. There might be the requirement. It might just say, you just have to ensure that your satellites are de orbited at X time and then let the owner operators or the people putting up the satellite, figure out how they’re going to do that rather than imposing a solution of you need to carry a thruster or whatever” (Participant SII-3).

“Maybe it’ll become a requirement that you need to be able to deorbit your satellite in a matter of I don’t know, a couple months or something, or a couple weeks. I don’t know maybe you have to require that any satellite that goes into these orbits has some method of quickly deorbiting itself. So, it doesn’t become an issue for others. During its operational life and its operational orbit, it should not be an issue, right. That should all be very well coordinated. I think the issue comes in if there was some inadvertent collision” (Participant SII-3).

“That goes back to looking at who’s, who’s really participating in space, right. And the analogy from ground traffic in the street you have all these various different participants, you have potholes, you have walkers, you have bikers, you have you know, debris on the streets or, or a tree fell over. So, you have kind all kinds of things going on, but you also have modern cars, autonomous vehicles, and it’s the key component there. Why is it working on the ground? It’s because you have solid understanding and anticipation of who’s doing what. And you have communication exchange. You have rules of the road, and you can transport goods and services and people from one end to another end very much quicker, right? Because you have that better understanding. And so, I think in space, there isn’t something similar necessary today. We don’t have really a good understanding what the rules of the road are. We do a little bit of, of sharing of data, but we don't have that clear understanding. And if you really want to grow the economy to the trillion-dollar economy, that some consulting companies have proposed, you really need to have a better understanding of what the behaviors are so you can anticipate who's doing what, a clear understanding of the data sharing that's going on. And similarly having that clear, better understanding will contribute to the growth of these space economy because ultimately society as a whole really depends on it depends on the value that space provides through GPS, remote sensing, and missile defense. You have space debris, you have small satellites, you have small satellites without propulsion, larger satellites, more experienced operators, and also now autonomously moving satellites, right? So, it's really having, you need to really take all these various different capabilities into account and assure if there is a good understanding of who's to do what, when there is a conjunction predicted, right" (Participant SPE-8).

"We need more collaboration. We need, we need more transparency. That means that we need to have ways to openly share using standard data products and give people the ability to do their own assessment of what's going on as to how to trust somebody else's assessment. The more communication and transparency you have with the people that are operating in that environment, the less likely you're gonna into things that cause conflict or misinterpretations or whatever. And so, it requires sitting down and sharing some of it and realizing that it's probably more important to share where your satellite is to protect the environment or protect your satellites than it is to necessarily protect some competitive advantage that you think you have" (Participant SPE-6).

“My impression has been that the coordination between companies in particular is pretty ad hoc” (Participant SPE-7).

“There is still a strong incentive for two operators to figure out [what to do] because they have very costly assets in space” that they do not want to lose in a collision with another satellite” (Participant SPE-8).

“Hey guys, this is one of my older ones, can you do it this time? I think that’s fair. If you don’t have a lot of recurring [conjunctions], you don’t have a chance to put any money in the bank. Cause I would say, I don’t have any, Goodwill in the bank that you’d like to say, hey, last time, remember, I took the maneuver in his last year of operation, can you do it this time? So, I think that’s a real good question” (Participant SPE-4).

“That’s really the key next step to develop those common understanding so you can speed up that part of, hey, we’re having a maneuver planned. We see your planning also one, there’s a conjunction predicted based of that. Are you planning to not go, or maybe could you delay, or how are you gonna raise your orbit? At what time scale are you gonna go fast or slow, right. That conversation takes too long. There has to be a much faster, better way of exchanging that information, but also have a better understanding of what can happen, what will happen next, right?” (Participant SPE-8).

“I just don’t know that you can achieve the transparency and the communication that you want to, if you don’t have a really integrated system that brings up, I acknowledge, so many legal and policy issues. But I think for the system to really be robust and really service as many users as possible and let me be clear that the overarching goal here is safe operations in space, that is what the end goal here is and I think you would choose that by a really transparent integrated system that spans the entire globe of users" (Participant SPE-3).

"Yes, self-reporting is very important. And [Company] has actually been a strong advocate of that and it's actually one of the best practices listed in the Space Safety Coalition best practice document, that operators should not only maintain a good a fix on where their satellites are but they should also report that too to a central agency such as a government data pool or a commercial data pool or multiple pools you know" (Participant SPE-7).

"There are operators that are willing to share. We've got 30 of them with [Company 1] and [Company 2] and some of those are more than willing to share their data. There is this sense that operators think that there's something magical about knowing where their satellite is and that they don't wanna release their good data" (Participant SPE-6).

"People are coordinating amongst themselves, there's not necessarily reason to coordinate through an entity" (Participant SPE-2).

"People have been looking at a singular platform, for example, COPUOUS. The Russians, for example, have always advocated to expand the registration convention, to have more active understanding of where the objects are, what their maneuvers are and so forth. The Department of Defense has always advocated for, no, we will maintain the authoritative catalog. He's not, he was not willing to give up that catalog. I think that's an old view" (Participant SPE-8).

"Space traffic management to me is a term that includes things like monitoring, consultation, coordination all the way to the other side of the spectrum that is more a space traffic control. And that's the analogy to air traffic control, where somebody's actually telling you, you have to turn left or right. Or raise your orbit or go down. We're sort of shifting that from what we do today, from the monitoring like we did in the past to that of consultation where we exchange perhaps some maneuver plans. Where we exchange conjunction messages to something that slides a little bit more over. It's a stronger coordinated effort in how we operate, rather than we'll just send you messages and then you go off and do your own thing. So, we're sliding over from monitoring, not all the way over to control, but just getting a little bit closer to having a solid understanding of who's doing what and what is everybody's plan. It's not sufficient anymore to just have everybody independently operate. There is a need for more coordination necessary, not yet control, I think that may be a bridge too far, but coordination" (Participant SPE-8).

"We're a long way away from compelling people to take actions, the way people think of air traffic control. We don't have space traffic control. We're not likely to get it. Space traffic management itself is still a far bridge so it's getting the basic SSA data for civilian operator to make decisions" (Participant SPE-2).

"We have a whole lot of people going to space still, they've chosen to engage in a very like highly hazardous activity. I do think that's the important piece, with people having to make good decisions, people having to achieve certain levels of technology to have access. And then right now it's kind of work it out amongst yourselves, but once we get some level of capability and tracking capabilities as well, all of that has to then have the operational like management approach" (Participant SPE-7).

“I think that we’re gonna see analogs in space to what happens on the ground and in the skies. I think that there’s a reason why that has made sense in multiple modes and activities in the past. And it probably continues to make some amount of sense in space, even though it is a very different environment. That’s when you start talking about the traffic, it’s why there’s a default to the idea that it’s a role for the government, similar to air traffic control that the industry should be very much involved in helping it and contributing to it, and it’s gonna have to be part of the solution, but at the end of the day, it’s likely gonna be a government entity, that’s having to make the call based on some set of principles and rules of the road” (Participant SPE-7).

“Everybody has different algorithms, different cutoff rates for acceptable risks. There’s not always agreement on what the actual risk is and if somebody needs to maneuver. It’s an open question because it’s necessary to create that understanding of each other” (Participant SPE-4).

“Unfortunately, just like any time when you have risk acceptance and then you have to change the threshold because you start to realize I can’t make all these maneuvers, so therefore I’m going to accept a higher level of risk. I think ten to the minus three is probably a good number a [for probability of collision threshold], but I will tell you, I know for a fact that current operational constellations will start to accept greater risk when they’re getting closer to end of life” (Participant SPE-4).

“I’ve got a hundred of these satellites and they don’t really cost a lot so if I lose one, no big deal. And the other one, you know, it’s like, well, I got 10 of ‘em and they cost, you know, a hundred million apiece. And it’s the same physical results for the collision, same two objects, same distance, relative, velocity, whatever. And because they will have a different risk profile, they will make a different decision" (Participant SPE-6).

"If you want the government to define those boxes, they're probably always going to be more conservative than the commercial sector and I don't think that necessarily means that the commercial actors are being more flippant or disregarding safety. I think in a commercial sense, you're going to get folks that collect up as much data as they can get their hands on, and they're going to try to make data-based decisions and they have a bit higher risk tolerance than the government traditionally does" (Participant SPE-3).

"I think [Constellation], the way that they do autonomous collision avoidance is a horrible thing. It sounds like it's safer and good, but nobody else is doing it and I think it actually makes it less safe. It's kind of like self-driving cars. I think eventually it will be safe, but just don't have a self-driving car out there and telling anybody else, you know, good luck. I think it's actually less safe. I think in the short term, it should be something that there's a man in the loop of operating in the loop until we start to understand things better cause I actually believe in the future, it should be autonomous. I think we can get to a place, machine-to-machine, where you have an autonomous maneuvers that optimize those or when a conjunction comes up, if it's between two objects, it just happens autonomously and that they they're able to sense like their surroundings" (Participant SPE-4).

"It's more than just sharing the current location. It's also sharing maneuver planning but that becomes more difficult when the satellite is maneuvering autonomously. So, you might need to have the algorithm written shared so other people know who's gonna move first. Companies like to hide behind intellectual property. They say, well, we developed the algorithm we can't share, but when I think first step is to create more mutual understanding and transparency, like maybe through a common lexicon and make more companies more comfortable with sharing, perhaps maybe initially some more top level understanding of while you don't share the code or the source code, maybe just the decision tree on what goes into it right" (Participant SPE-8).

"You see this in the challenger crash there were too many entities that had too much at risk if the answer was no go so if the answer is maneuver or don't maneuver and there is this external pressure we risk compromising the safety equation for space is a very unique construct when it comes to collisions or … space is a very unique construct when it comes to collisions so aviation rules in aviation safety is built on a whole lot of crashes thousands of plane crashes to get to the safest environment but when the plane crashes that plane is no longer a hazard to aviation. Space does not have that luxury a collision between two objects in space create an exponential hazard for the future of space to sustainability so the model where rules are based on reaction to accident is not a viable model for space traffic management because the consequences of an accident are long term for the operating environment not just for the industry" (Participant SPE-1).

"We are about reusability and sustainability and these kinds of technical solutions are, they are the key to the future of the industry and so just having a spacecraft that just kind of die and put her out in orbit and becomes space junk. I just can't buy into that. We are better than that. We're smarter than that. And I certainly don't think legal issues will get in the well we'll stop those types of progressions" (Participant SPE-3).

"The first step in ensuring long term sustainability and safety would be to address this question of debris generating behavior and how do we reduce the likelihood that new debris is created by new operations in space and our rules to mitigate debris are out of date and also not complied with. Things like the 25-year rule was based on a certain promulgation of satellites in space that we have already exceeded so those sorts of rules need to be addressed in the first stage in order to ensure the continued safety and sustainability of the space environment" (Participant SPE-1).

"It seems really an unfair number having 25 years, right? Let's say your mission life is only six weeks. Why would you be allowed to remain in orbit for 25 years? It just doesn't connect really. I think down the road, what people have started talking about is making that permissible lifetime in orbit as a function of how long your mission is. So, if your mission is for 20 years, maybe 25 years is a reasonable number. But if your mission is only for two or three years, maybe you should be required to re-enter and clear out the orbit after your mission has ended" (Participant SPE-8).

"The 25-year rule, I believe we should have a one -year rule and a one -year rule would put you at about a four-hundred-kilometer altitude. All the math issues about, we can't do a one-year rule, but can only afford to do a 25-year rule was all true in the nineties technology space technology. Especially with the modular nature of electric propulsion has changed that completely. And the regulations have not kept pace with the changes in space technology. So, I think that we really don't need to be talking about graveyard orbits a lot anymore. We need to be talking about putting in electric propulsion systems as post mission disposal and making people responsible and not pushing off the risk to the next generation is my opinion" (Participant SPE-4).

"Somebody who purposely burned their fuel down to the end of life, to do an operation to get another billion dollars of revenue, and then they couldn't do their post mission disposal as they were supposed to. Should they be held liable for a collision? Absolutely, they should be! But right now, there is no call for that. So, actually what happened with [satellite], they knew they were getting close to the very end. They knew! And they had fuel onboard for post mission disposal, but they kept operating and then they ran out of fuel, and they're stuck. So, I think that was purposeful. They said they were gonna remove it in 25-years. They said what they were going to do at a certain point. They didn't do it! They didn't do it, but there's no teeth in the mitigation guidelines just because it's not a law, it's a guideline" (Participant SPE-4).

"I don't know yet and we haven't figured that part out who is required to move at the moment. I would say those two operators really have to figure it out, right? We do not have that common understanding of based on X, Y, and Z maneuverability, size, capabilities. We don't have that best practice or that norms of operations developed and who's gonna maneuver, or who's gonna move first. So, we don't know yet, but it will have to depend on different factors" (Participant SPE-8).

"Obviously, I think the priorities should be the folks that are in their operational altitude. So, if you're transiting somebody else's operational altitude, then the operational altitude should have priorities and not have to move. That's the first level and then the second level is probably going to be a little bit more difficult, right? If you're both in your same operational orbits, which is going to happen, then I believe it's probably going to have to be something where they agree that whoever has the smallest Delta-V to make the maneuver should make the maneuver and I think that would be the second filter. Obviously, that requires a lot of sharing of data and a lot of common of algorithms to be able to say for sure which that would be, but that would be my second filter" (Participant SPE-4).

"If you were a satellite operator encountering another satellite operator, then someone has to move. To determine who must give way to the other is where we have complexities and issue because there is a commercial cost to maneuvering a satellite so once there's a commercial cost the decision of who is required to give away falls to a decision of standards possibly a regulation and that is where the difficulty in reaching international agreements will come in" (Participant SPE-1).

"There needs to be, and I like the best way I can think of it right now would be some kind of an exchange sort of like what they do with carbon limits, like, somebody else can buy extra credits from somebody that's producing less or whatever. You might need something like that and some set of best standards on who should move because there's just gonna be so many different cases that you run into where, when this happens, this is who maneuvers is not a gonna be straightforward. And sometimes it's fairly clear cut, if one satellite can maneuver and the other one can't then it's either you're gonna move or we're just gonna ride this thing out with risk" (Participant SPE-6).

"We've got to understand the benefits and the liabilities of electric propulsion. A lot of people are making decisions about collision avoidance with a heritage of chemical propulsion and they're not the same, they're drastically different of their responsiveness and capability" (Participant SPE-4).

<u>Questions 5 and 6 Quotations</u>

"I don't know how [having insurance] would make somebody more responsible" (Participant SPI-1).

“From the perspective of private operators or commercial operators, yeah, seems like a very much a no brainer. Especially, like a lot of companies do this for cars, right?” (Participant SPI-3).

“After the fact of a collision it doesn’t undo the damage to the orbit. It may payback a company for their loss, but it doesn’t undue damage and the creation of the debris. I mean, if somebody could better tell me how that would help but I don’t see it obviously” (Participant SPI-2).

“So, you can imagine some similar sort of organically market driven network where the insurance company insurers give breaks on rates” (Participant SPI-3).

“That could be a mechanism or stipulation that if you’re required to have insurance, then your insurance company might cut you a better rate if it’s demonstrated that you’re not gonna be an issue or your satellite is unlikely to fail, versus if you’re just doing something risky. So, it could be [a solution] but we don’t go out there pushing people to do it because asking the government to tax you is not something people tend to do” (Participant SPI-4).

“If your satellite is in their data sharing network, it doesn’t have to be centralized and you could imagine like insurance companies have auditors that would go and say, look, your orbit tracks are typically a kilometer off, not good enough. Or like, you know, things like that. Or like, you’re not reporting, you’re not updating them frequently enough that, that sort of stuff. You can easily just have automated processes go and do the audits for [the insurance companies]” (Participant SPI-3).

“SpaceX loses one satellite out of, out of like, whatever, 10,000, they don’t care. Like if there’s utterly no regulation and it’s the wild west, which I think would be unwise then, and all insurance is doing is protecting your own assets and not protecting you from liability for damage cause to other people's assets. Then there's not much motivation for insurance, especially for big guys to get insurance" (Participant SPI-3).

"As long as it's affordable, right, it's gotta be affordable. If it's cheap enough all should have. If all have, it should drop costs" (Participant SPI-6).

"There's a working group that is doing a space sustainability rating and what that would allow is where I think if people are transparent with their data, then now you can start applying some machine learning and you get those norms of behavior. Hey, this satellite maneuvers every whatever, so they are safe. So, you're able to now see that you kind of get like you do on a vehicle. I get a good driver discount. So long as that operator is operating in a safe and sustainable way" (Participant SPI-6).

"Impartial third party, commercial source, that's able to verify that people are doing what they're doing or confirm that they're not" (Participant SPI-7).

"You don't have to necessarily have in-orbit liability right off the bat. I would prefer more of a gradual process than suddenly creating that requirement. I just don't think it's necessary yet" (Participant SII-2).

"I think liability insurance should be required and that's not necessarily a popular viewpoint but that's my that's my viewpoint" (Participant SII-1).

"You may not be able to collect anything because of where it's adjudicated or international treaties or whatever but if you were to sue me, I still have to defend myself I have to spend money on attorneys and that sort of thing to defend myself so that's what liability insurance would be for" (Participant SII-1).

“I think the operators have an incentive cause they don’t want their satellites to be destroyed” (Participant SII-3).

“I prefer to say that we’re not gonna give you a discount for doing the right thing we’re gonna give you a surcharge if you don’t do the right thing” (Participant SII-1).

“There’s the asset policies which would protect against pretty much what we consider all risk. So, unless something is excluded, it’s covered but it’s typically what they call like a multi trigger policy. First of all, something has to go wrong” (Participant SII-3).

“Probability is based on the law of large numbers but because the numbers of aviation and even space aren’t big enough, probability does not work” Instead, underwriters use what is called, “cash flow underwriting. It’s not really done on an actuary basis because they’re just don’t have the law of large numbers” (Participant SII-3).

“In the GEO orbit, you’re kind of out there in a very well managed orbit. For the LEO, some of the underwriters have started to express concern. Like they’re not gonna underwrite because the collision issue is becoming something they can’t really get their head around. They can look at the satellite and go, okay, you’ve got margin, you’ve got redundancy. Maybe I’m not really too worried about your satellite failing, but I’m worried about maybe something hitting it right. Or some other cause of damage beyond normal environment like micro meteorites or something like that. So, I think as some of these other constellations start to launch, that might become more of an issue for more underwriters to understand how [orbits are] managed and how they’re gonna take some sort of action to ensure that these orbits are well managed” (Participant SII-3).

"Nobody should buy insurance. I mean sure...you… that's a business decision whether you self-insure like for example. So here is the thing in your license is that indemnification is required so the person who licenses you, the operator, is responsible to assure that you the indemnification requirements. You have to identify the method you use. To do that indemnification it is a business decision whether it's through an insurance group or self-insurance they're still indemnification so that indemnification I think needs to be done and that is done on a state by state basis; the state of launch gets to determine what indemnification is required and in the U. S. there's a certain level of indemnification and then the U. S. liability kicks in after that, that's a public policy decision" (Participant SPE-1).

"I think it's all a business decision. It's absolutely a business decision for the company and I would say that has to do with the personality and culture, like there are some company cultures that are not big into insurance and there are others that are" (Participant SPE-7).

"The other piece of that is, is the company publicly traded because sometimes the risk tolerance is less when you're a publicly traded company than it is if you're privately held. Or even if you're held by private equity, right? Like what's the culture of the private equity investor or the major investor in your company. Do they wanna see insurance or do they not?" (Participant SPE-7).

"A big constellation where you can risk losing one or two and your constellation still survives, that's different than the old GEO model where the GEO birds would buy insurance for business interruption so they would ensure the viability of their satellite because that one bird is tied to millions or billions of dollars worth of revenue. And so, if something were to happen and it was 25% ineffective, they would insure against that 25% performance loss, or if it was lost entirely, they would insure it" (Participant SPE-7).

"Insurance is about managing risk. If you have one satellite, your one satellite insurance is really important. When you have multiple satellites, you really manage your risk by that, by the numbers. I think there'd be less [need for insurance] when we have these larger constellation, because they're kind of going eh we're launching 60 today, if 58 work that's still good. Why should I, insure for those two? That's not the case when you have a single satellite. So, I think that some of the concept of operations will make insurance in LEO for some of these groupings of satellites, whether it be two, three, four, five, a hundred that may make it less likely that that would be a big deal. So, I think the best thing that I think the best thing insurance can do is say, I'll charge you less, if you're responsible, so I think they can provide an incentive. But I don't think they're gonna make money off it, but I think they can be a thought leader in that area. So, I do think insurance can be the one to highlight. You know, I'm going to give you a break. If you follow a good guideline, that's overall, that'll end up helping the insurance community to not have such a risky environment" (Participant SPE-4).

"If insurance becomes required. One argument for how you get people to be responsible in space is if all the insurance community came together and said, we're not going to provide any insurance for any satellites that don't have maneuverability" (Participant SPE-7).

"All of a sudden if insurance were required, then everybody essentially, because the effective requirement for maneuverability, [has to have maneuverability]" (Participant SPE-7).

“I insurance is not required then, “the alternative is people would say, I’m just gonna proceed without insurance” (Participant SPE-7).

“Our conclusion was that the purpose of insurance, or let’s say the motivation for the business for insurance is, is not to regulate or develop best practices or rules of the road. The reason their insurance companies is because they wanna make money. Right. So that that’s the ultimate goal. Um, so their insurance is always going to be hesitant to step into, uh, a more authoritative viewpoint” (Participant SPE-8).

“The insurance communities today have said they don’t want to be the reason, that it doesn’t wanna be the driver for responsible activity in space” (Participant SPE-7).

“If you have something that emerges as kind of a best industry practice and when companies don’t follow then they find that insurance companies, go, why aren’t you doing that” (Participant SPE-2).

“I’ve been a big proponent for getting the insurance guys involved just because when we go through all the analysis, [operators] come up with a number, there’s this theoretical probability that something bad will happen and so you’re sitting there going, well, it could happen, or it couldn’t happen so it’s not a tangible loss at that point. Whereas when you have insurance you’re either paying higher premiums because you’re not taking actions to prevent these types of occurrences and then you have the potential issue of well if you do hit something, it’s not gonna be like the Iridium-Cosmos [collision] where they never went to court and they just kind of walked away from it and left all sorts of debris in orbit. If there was some kind of a penalty and the insurance guys are probably better to be able to assess a penalty than say a regulatory body at this point.

That might make it a much more tangible decision for a lot of these operators to try to behave more responsibly" (Participant SPE-6).

"Insurance underwriters get a massive amount of technical data about the spacecraft that they insure. If for whatever reason (spacecraft design, operations, following of industry standards). they deem you as higher risk, they will charge you more money" (Participant SPE-3).

"I just don't consider the satellites themselves to be the primary problem. I consider debris to be the problem and performance and liability insurance and so forth doesn't really help me with the debris, particularly debris that I can't really attribute" (Participant SPE-8).

"I think [compelled maneuvers] is kind of unlikely, that we would want to assert that control because if it doesn't happen, is the government liable to pay for the cost of maneuvering? Right now, if a collision does occur then we have the standard international liabilities to come back to the launching state and if we would then go back and recover against the company. So, they have already, to some extent, internalized that risk through liability and insurance regimes. If the government had a more active role, we would be taking that liability risk on, and it'd be unclear as to what benefit" (Participant SPE-2).

"Some latitude in the liability laws could be very helpful. Right now, ownership and continuing supervision remains with the state of launch and that precludes concepts like salvage where a third party can remove large bodies from an orbital environment. We have some models in maritime law that could be helpful the law of salvage and removal of wrecks and if we had latitude under the liability structure that created a process by which a derelict object could be removed by a third party and with that removal, liability transfers to the person taking the action and exempts the state of launch from any liability then we can create an environment where clean-up of space could be easier and more efficient" (Participant SPE-1).