

5-2016

Space Traffic Safety: Is Global Space Traffic Control the Answer?

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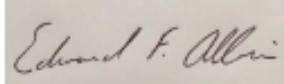
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Space Traffic Safety: Is Global Space Traffic Control the Answer?

A Master Thesis

Submitted to the Faculty

of

American Public University

by

Leslie Harris Jr.

In Partial Fulfillment of the
Requirements for the Degree

of

Master of Science

May 2016

American Public University

Charles Town, WV

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ABSTRACT OF THE THESIS

Space Traffic Safety: Is Global Space Traffic Control the Answer?

by

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American Public University System, January 3, 2017

Charles Town, West Virginia

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This study explores the concept of a Global Space Traffic Control as a possible means to enhance the safety of outer space traffic. Space debris, the addition of new spacefaring entities and the ad hoc nature of current space traffic control measures are all factors contributing to the hazardous conditions for space travel today. The space community, writ large, has made strides in improving the safety of space operations by instituting debris mitigation measures. However, these efforts may be too-little-too-late as the debris problem continues to worsen to the point where certain prime orbits may be unusable in the near future. This study consists of a qualitative review of data to provide detail on the current condition of space traffic and future concerns. It also presents a quantitative analysis consisting of a Gap Analysis, which compares the current ad hoc space traffic control process with the proposed Global Space Control Concept. The results of the study reveal the implementation of a Global Space Control could support improved safe space operations in the areas of space situational awareness, command and control, and notification. Also, the study reveals significant challenges dealing with the sharing of proper information to safeguard spacecraft and management of secret military satellites within a transparent structure. These issues will need to be overcome in order for a Global Space Traffic Control concept to be realized.

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I. Introduction

Man-made satellites zoom around in Earth's orbits at 17,000 mph. These satellites are owned by different organizations whose operators have no idea of where other satellites, operational or not, are located. They are virtually flying blind through space. Though satellite collisions haven't been frequent, the potential for more frequent collisions is ever-increasing due to the space debris environment and new actors solidifying their role in the space industry.

One of the most recent events in outer space that provides evidence of an increasingly hazardous space traffic environment was the collision between a U.S.-based Iridium satellite and a Russian-owned Cosmos satellite in February, 2009. The Russian satellite was a derelict but still intact and the Iridium satellite was operational prior to the incident. This collision added as much as 2,000 pieces of debris at least 10cm in diameter and thousands more smaller pieces to Low Earth Orbit (LEO) significantly increasing the potential of future collisions (Weeden 2010). This incident is just one of several catastrophic events ranging from rocket body explosions to purposeful collisions, which have contributed to the current orbital debris environment.

Orbital debris consists of an estimated 23,000 pieces of debris the size of baseballs and hundreds of thousands more smaller pieces (Hildreth and Arnold 2014, 449). Debris 10cm in diameter can destroy a satellite on impact and create thousands more pieces of debris. Debris greater than 5cm in diameter can cause severe damage or catastrophic failure of a spacecraft making it a sizeable piece of debris as well. The increasing debris population has become a serious issue for space operators, which

have implemented mitigation measures, but it has yet to be seen whether they will be effective in preserving Earth's orbits for future use.

Another factor contributing to the hazardous space traffic environment is the burgeoning commercial space industry. What lays ahead for commercial space entities is uncertain and will probably depend on the magnitude of their success. Several space companies have experienced success establishing niche services. One company is SpaceX was founded by entrepreneur Elon Musk in 2002 and entered the space market with a goal to develop a reusable rocket to send humans to space. SpaceX eventually won a contract to resupply the ISS in 2008, along with Orbital ATK, and accomplished its first resupply mission to the ISS on April 21, 2012 with its Dragon capsule and Falcon 9 rocket (Gebhardt and Bergin 2016). Orbital accomplished the same feat in January 2014 with its Cygnus capsule and Antares rocket. Both companies have been resupplying the ISS ever since.

Unfortunately not all the upstart space companies have been as successful. One example is Virgin Galactic, which was founded in 2005 by Richard Branson and Burt Rutan with a goal of becoming the first space-liner to routinely shuttle people to and from space. The rocket-plane, named SpaceShipTwo, they plan to use was designed to transport people to space at a low price of \$200,000 a-piece (Howell 2016). The program was plagued by multiple delays until finally completing three test flights in 2013 and 2014. Unfortunately, on the fourth test flight the rocket-plane broke apart killing the co-pilot in October 2014. SpaceX was not without setbacks as it experienced a catastrophic failure of a Falcon rocket intended to resupply the ISS in 2015 and three

failures out of four attempts to land its reusable rocket on a sea-borne barge (Carl 2015; Grush 2015).

These start-ups may have had difficulties getting started, but it is only a matter of time before commercial companies are successful in carving out niche services in the space industry. This could ultimately result in increased space traffic and human space presence. Considering the current state of orbital debris, this additional traffic becomes an even greater concern when human lives are involved. Protecting commercial space endeavors from this threat must be added to the equation when assessing current and future space traffic safety issues.

There are several space traffic safety techniques being used today to protect equipment and human lives. Debris mitigation is a reference used to describe techniques used to reduce the creation of debris, to include avoidance measures, when conducting space operations (Orbital Debris Mitigation n.d.). Examples of orbital debris mitigation include designing spacecraft in such a way that debris generation is minimized during deployment and the chances of rocket body explosions are removed, or disposing of satellites via decay or parking orbits. Debris remediation is a term used to describe techniques to reduce the amount of debris already in Earth's orbits. (Orbital Debris Remediation n.d.). Examples of remediation including atmospheric drag devices in satellite design or using lasers or tethers to deorbit satellites. Many space faring nations have integrated orbital debris mitigation techniques into routine space operations and there are several entities investigating remediation technologies. However, studies have shown that though mitigation is helping to reduce the amount of

new debris, it would take significant effort to reduce the amount of debris already in orbit thanks to previous collisions and breakups.

Conjunction assessment and collision avoidance, which is a subset of orbital debris mitigation, involves several steps to include keeping track of Earth satellite objects and conducting satellites maneuvers when necessary. These operations are accomplished by nation-states, commercial entities and other organizations to ensure safe space operations. The process can be loosely compared to air traffic control; however, not every space operator has the capabilities to accomplish all STC processes and those that can, do not coordinate well with other space operators. One example of this poor coordination was during the Iridium-Cosmos collision of 2009. Prior to the collision the U.S. and Russia did not routinely share space situational awareness data. This lack of awareness was likely what caused the two satellites to collide. Since the incident, the U.S. and Russia have agreed to work together and share data, which proved valuable later when the U.S. helped Russia during the re-entry of the failed Phobos Grunt Mars probe in January 2012 (Listner 2012).

Considering space traffic is only expected to increase in the coming decades, space stakeholders should be concerned with the sufficiency of current space traffic safety processes to maintain safe space operations now and in the future. One possible concept that is worth exploring to help with this problem is the consolidation of current STC processes under a Global Space Traffic Control (GSTC).

Several studies have been accomplished regarding space traffic safety that recommended STC as one solution to the increasingly dangerous space traffic safety

problem. However, most fall short of describing what it would actually consist of or how it would improve upon current processes. The purpose of this thesis is to describe the concept of a Global STC through literature review and current data evaluation. Global STC is not specifically defined; however, the concept to be proposed in this paper refers to a construct by which to centrally coordinate STC processes on a global scale. Not only could a global STC reduce equipment and monetary loss to those vested in space industry, but it could also prevent the potential loss of human life and contribute to the preservation of Earth's orbits for future use. The following questions will be explored in order to investigate the potential of a Global Space Control concept:

- What are the space traffic safety concerns?
- How does the current STC structure work?
- What gaps exist in the current STC structure?
- What would a Global Space Control structure consist of?
- How would a Global STC enhance space traffic safety?

To answer these questions, this study begins with an extensive literature review of the current space traffic environment and future space traffic concerns, which is provided in chapter II. Chapter III explains the sequential mixed methodology used to determine the construct of the current STC system and process gaps that would require improvement for a GSTC concept. Chapter IV discusses the results of the analysis providing a description of the GSTC concept, a depiction of the current STC construct and the gap analysis results. Chapter V wraps up the study with a brief discussion on

the GSTC concept and concludes with some thoughts on some possible areas of further research.

II. Literature Review

Insight into the Current Space Traffic Environment

During the early years of space travel, the perception that space is “big,” was pervasive; however, during the 1970s that perception began to change as the number of objects being thrown into space grew exponentially. In 1979, the NASA Orbital Debris Program was established to characterize the space traffic environment and the growing threat of debris to space flight (NASA Orbital Debris Program n.d., 4). By this time, over 5,000 objects were being tracked by the U.S. Space Surveillance System (NASA Orbital Debris Program n.d., 27). Almost 40 years later, over 23,000 objects--four times that of 1979--have been catalogued at 10cm in diameter or more and most of it is orbital debris. Many space-faring nations have implemented debris mitigation techniques which is codified in the Inter-agency Space Debris Coordination Committee (IADC) Mitigation Guidelines published in 2007. However, the space traffic environment continues to grow more dangerous despite these concerted efforts. This section of the literature review provides an impression of what the space traffic environment looks like today.

Current Orbital Debris Environment

Orbital debris is defined as human-made space objects that no longer serve a useful purpose. (Orbital Debris Frequently Asked Questions 2012). Orbital debris can consist of any object ranging from minor fragments from explosive bolts to large rocket bodies or defunct satellites. Once created, a piece of orbital debris can remain in space

for years becoming a 17,000 mph projectile just waiting for an unsuspecting victim to wander into its path. It can be generated either intentionally or unintentionally. Intentional space debris is created when spacecraft shed components, such as rocket stages, fairings, bolts or other materials during launch and early phases of operation. Another situation that can lead to intentional debris is purposefully colliding with other objects in outer space. A spacecraft can become a piece of orbital debris when it is no longer operational, which could also be the result of intentional or unintentional actions. In either case, if it cannot be moved into a disposal orbit or deorbited, it can remain a threat to other spacecraft that transgress its orbit for years to come. Unintentional debris results from fragmentation events like rocket body explosion or accidental collisions in outer space. The review of the documents forthcoming will provide a general understanding of orbital debris environment.

The History of Space Debris provides a good overview of the evolution of space debris since the launch of Sputnik (Hall 2014). This paper was prepared for the Space Traffic Management Conference held at Embry Riddle University, Daytona Beach, Florida, on 4-6 November 2014. The purpose of the paper was to provide the audience with background information on the status and source of space debris, its impact on the space environment, and its potential impact on future space operations. This study describes the current space traffic environment as being debris free almost 40 years ago to a current environment that is dangerous to human space flight and spacecraft. According to this paper, the space debris threat consists of over 21,000 softball sized objects, an estimated 500,000 marble-sized objects, and possible over 100 million smaller objects (Hall 2014, 1.). It also mentioned the current environment is due to

mission-related actions, accidental events and intentional acts that resulted in the creation of debris. A summary of the debris environment can be seen in Table 1.

Types of Space Debris	Examples	% of Total Space Debris
Mission-related – Debris generated as part of satellite deployment.	<ul style="list-style-type: none"> - Solid fuel exhaust - Explosive bolts - Protective shields 	12 percent
Accidental - On-orbit explosion spontaneous release of fragments or collisions.	<ul style="list-style-type: none"> - 2012 Briz-M explosion - 2007 Cosmos1818 coolant release - 2009 Cosmos-Iridium Collision 	73 percent
Intentional Acts - Deliberate destruction of space objects creating space debris or the purposeful deployment of space objects that become space debris.	<ul style="list-style-type: none"> - 1968-1985 American and Soviet anti-satellite tests - 1961 & 1963 West Ford Passive Reflector deployments - 2007 Chinese anti-satellite test 	7 percent

Table 1. Space Debris Environment (Hall 2014, 2-5)

The study also mentioned that the growth of space debris has resulted in a 50 to 67% chance of a collision between spacecraft and a piece of debris each year (Hall 2014, 7). The consequences have been felt on the ground as well as in space as space debris fall to earth weekly and on-orbit spacecraft routinely conduct avoidance maneuvers. Another point mentioned was that LEO has reached a point where collisions will create debris faster than what will deorbit. So, new space debris will be created even if current mitigation techniques continue.

Lastly, the study revealed that 100 satellite maneuvers were conducted to avoid orbital debris in 2010 (Hall 2014, 8). Additionally, the ISS made 19 avoidance maneuvers between 1999 and 2014, with the two maneuvers recorded in within three weeks (Hall 2014, 8). This seems to be a slight increase within a short period of time that would signal the increasing debris threat; however, this was not mentioned in the paper. Furthermore, the study goes on to mention that there were several debris threats to the ISS that were noticed too late prompting the astronauts on-board to take shelter in the Soyuz crew transportation vehicle, which could be used as a lifeboat during emergency evacuation situations. All of this is evidence of a deteriorating space traffic environment that increasingly threatens human life and space equipment. Improvements in Space Situational Awareness (SSA) and warning will be important to maintain continued access to space. SSA and warning are two areas where a Global STC concept would provide support and enhance the current ad hoc space traffic system.

Space Debris: Conjunction Opportunities and Opportunities for International Cooperation addressed the problem of the space debris environment and its constraining effect on the continued use of space (McCormick, 2013). The purpose of the paper was to provide insight into the causes of the space debris environment and the international attempts at mitigating space debris by the institution of debris mitigation guidelines. It also provided an overview of the disparate STC systems being implemented by the different nations. The position of this paper is that current efforts are not enough to stem the increasing debris situation and to ensure the future availability of Earth's valuable orbits. It also surmised that though human dependence

on space continues to increase, the space community has failed to cooperate on an international regime to govern the use of space. The paper concluded by suggesting the development and implementation of an international review board, an international space surveillance system, and an international space policy to reduce the creation of debris and hold those responsible for space-related incidents accountable.

One area relative to Global STC was comments regarding the U.S. and Russia possessing the most capable SSA systems, with the U.S. SSA sharing program being the most transparent program. Information sharing will be important for Global STC concept to work. The paper also discussed the creation of the European Space Agency SSA system and the commercially-based Space Data Association was in response to the Iridium-Cosmos collision. It was evident by these last examples that though the SSA information exists, it may not be immediately accessible all the time prompting organizations to the development their own space traffic safety systems. However, these are disparate efforts that if brought under one concept, enhanced SSA data could be provided to stakeholders.

Current Debris Mitigation Efforts

Stability of the Future LEO Environment is a study conducted by six IADC members; NASA, European Space Agency (ESA), Agenzia Spaziale Italiana (ASI), Japanese Aerospace Exploration Agency (JAXA), United Kingdom Space Agency (UKSA) and the Indian Space Research Organisation (ISRO) (Liou et al 2013, 1). This study was a follow-up to a series of studies conducted between 2006 and 2009 to investigate the instability of the debris population in LEO. The intent of this study was to integrate the original studies with the more recent debris generated by the 2007

Fengyun-1C and 2009 Iridium-Cosmos collisions. Each organization used their own modeling capabilities to perform analysis on 10cm or greater debris in LEO covering the 2009 to 2209 timeframe. Debris maneuvers and on-orbit explosions were not considerations when performing the projections. The results of the analysis verified the concern that LEO was unstable. Debris in altitudes of 700 km to 1000 km was predicted to increase by 30 percent over the 200-year timeframe. Additionally, the study predicted a likelihood of a catastrophic collision every 5 to 9 years (Liou et al 2013, 17). Each of models conducted by the different organizations was in general agreement, though there were slight variations in the data. The study concluded that active debris removal would be required to reduce debris in LEO even if nations complied with debris mitigation procedures aimed at reducing debris during operations.

The data in this study is sobering; however, it does not depict some realities that when factored into the analysis would likely paint a direr situation than what was revealed. One issue was the 90 percent rate of compliance with mitigation standards that was applied to the analysis. It was mentioned in the study that the rate of compliance was actually less than 90 percent at the time the study was being conducted. Use of the true compliance rate would have likely yielded more realistic results as the true amount of mission-related orbital debris would have increased the number of debris introduced in the models. Another issue with the study was that it did not seem to factor in the amount of debris smaller than 10cm into its calculations. Though this may have been outside the scope of the study, some mention of this threat would have been prudent. Orbital debris of this size is more numerous and harder to detect than the 10cm debris population, therefore the threat is actually worse than

depicted because of this. The study concluded by suggesting more aggressive orbital debris removal techniques and other alternative methods be investigated; and more importantly, points out that these additional efforts will require international cooperation.

Threats to U.S. National Security Interests in Space: Orbital Debris Mitigation and Removal described the orbital debris environment and the current mitigation and remediation efforts. The purpose of the paper was to inform the reader about the current orbital debris environment and to proposed establishment of more aggressive mitigation and remediation techniques by space operators (Hildreth and Arnold 2014).

The paper mentioned that prior to the 2007 destruction of the Chinese Fengyun-1C satellite, the primary cause of space debris was rocket body explosions. However, the aforementioned event and the 2009 Iridium-Cosmos satellite collision significantly raised the amount orbital debris. This was the first collision of two intact satellites. The paper predicted future collisions like this will present a threat to U.S. national security. This notion was inferred from studies that surmised that the debris environment will continue to increase due to random catastrophic collisions predicted to occur every five to nine years (Hildreth and Arnold 2014, 452-453). The paper recommended the use of more aggressive mitigation techniques to help reduce the overall amount of orbital debris. However according to the study, there is evidence that adherence to these mitigation techniques will not have a significant effect on reducing the threat. Therefore, remediation--the physical removal of space objects--was recommended as the next feasible option; however, there are issues with this as well. The first is that remediation techniques have proven to be expensive to employ and many techniques have not gone beyond the design stage. The second issue is that remediation would only target larger

pieces of orbital debris for removal and leave behind smaller pieces of debris that would still pose a serious threat to space operations. There would be other issues to deal with as well, such as legal issues with ownership of debris. In other words, just because a satellite is no longer operational does not mean that the owner has relinquished ownership. Ultimately, the study recommended a multi-faceted approach would be the best approach to improve the orbital debris threat environment and ensure the future use of space.

Considering the predictions of the worsening orbital debris environment, it would be agreeable that multiple solutions be applied to the orbital debris problem to ensure safety. An additional consideration would be the institution of a GSTC. The current large debris population and the potential for future collisions is a major threat to sustaining Earth's orbits. Barring a significant breakthrough in technology that allows a serious remediation push, a GSTC could be an integral mitigation measure to help improve space traffic safety in an orbital debris threat environment.

Earth Satellite Population Instability: Underscoring the Need for Debris Mitigation is a paper that detailed the results of a study by NASA scientists regarding the current instability of the LEO orbits (J. C. Liou and N. L. Johnson n.d.). The purpose of the study was to investigate the condition of the space debris environment. The study concluded that the current mitigation and post-mission remediation techniques implemented by space-faring nations would not be enough to decrease the amount of orbital debris within next 200 years. This finding was based on data from NASA's LEO-to-GEO Environment Debris (LEGEND) satellite modeling tool. The study predicted the satellite population will not change drastically through the year 2055, if there were no additional

collisions. However, when a predicted 18.2 collisions (between now and 2055) are added to the model, the satellite population drastically increases due to the creation of collision fragments significantly out-pacing the predicted number of decayed debris. The study proposed the use of additional remediation techniques, more specifically the removal of large debris, in order to assure access to valued regions of space. The paper went on to mention more aggressive mitigation techniques would not be practical or cost effective; and a collaborative effort between commercial and government entities was required to resolve the problem.

While the study did address the satellite population in general, it primarily focused on the space debris population and did not include data on active satellites, which is a subset of the satellite population. It would have been more informative to provide expected active satellite populations along with the debris population discussed to provide a more holistic picture of the satellite population. Nevertheless, the paper did provide insight into the increasing danger of orbital debris and revealed that current mitigation techniques would not be enough to assure safe space operations.

Commercial Space Flight

Commercial Space Travel: Security and Other Implications addressed the issue of commercial space traffic security within the international law framework (Abeyratne 2013). The purpose of the paper was to explore the different security enterprises including air traffic safety and space traffic safety that would provide the best support to the burgeoning commercial space travel sector. The paper hypothesized that the air traffic security regime, such as that managed by the International Civil Aviation Authority (ICAO) would possibly support relevant aspects of current developments in the

commercial space travel sector. However, adding legislature specifically to address commercial space travel to current air traffic security regime would be problematic due the fundamental premise of sovereignty in which air law is based. The paper also postulated that the space domain is similar to maritime and that it would probably be more appropriate to utilize certain aspects of the “freedom of the high seas” concept managed by the International Maritime Organization’s as a template for a separate and distinct security system for commercial space travel.

Security, in the context used by this study, referred to the safety of commercial space entities from a political perspective. This is a topic that surely needs to be addressed as the commercial space industry is set to expand at any time. However, Abeyratne (2014) fell short in defining why there would be a requirement for threat assessment, intelligence and prevention concepts in the proposed security framework (Abeyratne 2014, 269). Nevertheless, in a GSTC concept, the security of commercial space traffic would need to be addressed within established agreements to ensure the rights of commercial entities in case of incident.

Federal Aviation Administration: Commercial Space Launch Industry Developments Present Multiple Challenges was a report conducted by the Government Accountability Office (GAO) for the Chairman, Committee of Science, Space and Technology, House of Representatives (Dillingham 2015). The data collection and analysis was conducted by several GAO staff members through site visits to commercial and government space transportation organizations and interviews with senior representatives. The period of discovery was January 2015 to August 2015. The purpose of the report was to evaluate how far the commercial space travel industry has

progressed over the years since the establishment of the Commercial Space Launch Amendments Act of 2004. This act granted the Federal Aviation Administration licensure authorities over commercial space launches. The report was very broad in scope covering the investigation of five areas: 1. competition amongst commercial launch entities; 2. FAA licensing and regulating challenges; 3. commercial launch industry standards development; 4. budget forecasts; and 5. the effect of changes in the industry on government support for commercial space launch (Dillingham 2015, 3). The GAO report revealed that the commercial launch industry is growing, albeit at a slower pace than many experts had expected. The industry experienced \$1.1 billion in profits during 2014 and was responsible for more orbital launches (11) than Russia (4) and Europe (6) combined (Dillingham 2015, preface). One of the reasons for this growth has been NASA's support to the commercial launch sector, which has provided contracts to companies like SpaceX and Orbital ATK to ferry supplies to the International Space Station. Even though both companies experienced setbacks only months apart in 2014 and 2015, their growth continued and may grow even more as NASA plans to utilize commercial providers to transport astronaut crews to the ISS in the future. On the other hand, the space tourism sector has shown slower growth than expected by some analysts. Even with the tragic destruction of Virgin Galactic's SpaceShipTwo and the loss of its pilot in 2014, several companies continued to develop reusable means to transport space tourists who also continued to sign up for flights. According to the GAO report, no space tourism licenses have been issued as of the publishing of the document; however, six companies possessed 17 active launch licenses and 10 launch sites are licensed for use by commercial providers (Dillingham 2015, 11). It may be only

a matter of time before the FAA begins to realize a significant uptick in activity with so many commercial launch companies developing new ways to transport people to space. In anticipation of the increased licensing workload the FAA has requested a \$1.5 million budget increase and an additional 12 personnel for their Commercial Space Transportation Office for 2015 (Dillingham 2015, 10).

When commercial space tourism begins to take wing, the FAA will likely be ready to deal with issues domestically. However, one issue that will be difficult to resolve is the protection of commercial space transport entities outside national boundaries. The transit of the orbital and sub-orbital flights of these spacecraft will cross several lines of responsibility. How the different elements of traffic control work together will be important to the safety of the participants. Again, here is where a GSTC can likely fill a gap acting as a bridge between regional and global operations ensuring tourist safety as the spacecraft transits from Earth's atmosphere, to space and back.

Insight into Future Space Traffic Concerns

Small Satellites and State Responsibility Associated with Space Traffic Situational Awareness was a paper that addressed space traffic safety concerns posed by increased deployment of small satellites (SmallSats). The purpose of the paper was to describe the current growth of the small satellite population in LEO and the responsibilities of nations in the management of the additional traffic small satellites present. According to the paper, SmallSat is a category of satellites that encompasses several sub-categories of satellites weighing less than 500kg (Long 2014, 1). According to this paper, these satellites have generally been used by the governments and militaries of space-faring nations; however, the low cost of deploying SmallSats has

resulted in increased use by non-state actors, such as academia and other economically constrained entities. The paper explained that states are liable for any damages caused by its nationals, according to Article VI of the Outer Space Treaty. The paper discussed three different issues that would necessitate state regulation of SmallSats to help avoid liability issues. The first was that the increased deployment of SmallSats could increase the probability of collisions. To reduce numbers, it was recommended that states should establish protocols to validate operators' need to deploy SmallSats. The second was that most SmallSats lacked shielding for space weather protection. This should prompt concern that SmallSats could become debris as a result of significant weather events causing additional collisions and debris. The third concern was related to the integration of propulsion systems in SmallSats to increase maneuverability. While this is not a bad thing when it comes to operational control and collision avoidance, it should create concern with regard to "hijacked" satellites threatening other satellites. The paper concluded with a recommendation for states to mandate SmallSat plans include post-mission actions, shielding against space weather, and protocols to maneuver and reacquire satellite control.

This paper is primarily focused on the regulation of the SmallSat issue; however, it presents a valid point that SmallSats could have a significant effect on the satellite population. Additionally, increased deployment of SmallSats increases the probability of collisions due to their small size and difficulty in tracking them due to gaps in the current STC structure. If these SmallSats are disabled, they could contribute to the debris environment, which is already at a critical state.

Suborbital Reusable Vehicles: a 1—Year Forecast of Market Demand is a study that forecasted the future activities of and demand for commercially offered launch services (Tauri Group n.d.). The report focused on suborbital reusable vehicles (SRV) that would be capable of transporting equipment or people to and from space. The report covered a 10-year period and detailed the analysis conducted in eight different areas of the space market where SRVs could be utilized. The market areas of concern were: commercial human spaceflight, basic and applied research, aerospace technology test and demonstration, media and public relations, education, satellite deployment, remote sensing, and point-to-point transportation. The study used interviews, surveys, polls, and open source information that resulted in a seat/cargo (1 seat=3 ½ cargo lockers) equivalent to reveal the level of demand across the different markets. A three-scenario forecast that was based on different trends such as consumer interest, economic and political environment, and marketing, was also developed to depict the best- to worst-case scenarios. The growth scenario reflected an upward trend due to the variables such as successful marketing or price drops. The baseline scenario depicted the expected results based on currently observed trends. The constrained scenario revealed the lowest demand compared to the baseline due to downward trends that could result from variables such as rough economy or unsuccessful launches.

Using the baseline scenario, the results of the study revealed SRV demand would increase from 370 seats/cargo equivalents to over 500 seats/cargo equivalents over the ten-year period. The more optimistic growth scenario estimates demand to grow from 1,100 to 1,500 seats/cargo equivalents over the same period. The least

optimistic constrained scenario would produce a slight increase from 200 to 250 seats/cargo equivalents during the 10-year period (Tauri Group n.d., 9). These results could be translated into an increased amount of traffic if the number of commercial space operators continues to grow. However, the report only assessed the demand, not the number of vehicles or flights that would be required probably because many of the SRVs are still in development.

Forecasts such as these are important to organizations such as the FAA to determine future license requirements, which translate into future FAA resource requirements. With regard to space traffic safety, obviously the concern is the predicted increase in SRV demand that can be translated into a probable increase in commercial space traffic. Not only would this increase be a concern with regard to controlling this additional traffic, but it would also be a concern with regard to protecting the human and material capital being transported.

Relevant STC Concepts and Documents

Space Traffic Control: Technology Thoughts to Catalyze a Future Architecture, written by a team of authors on behalf of the American Institute of Aeronautics and Astronautics, Inc., provided a look at resolutions for STC implementation from a technical perspective (Boone et al, 2009). The purpose of the paper was to provide an idea of the current space traffic environment and to propose a STC construct. The paper identified space debris and gaps in SSA, which is based on cold war requirements, as issues that reduced the safety of current space operations. This paper proposed the integration of active and passive on-board sensor technologies in future spacecraft would allow autonomous STC improving space traffic safety. These sensors

would provide information, such as ephemeris data, maneuver plans, and data about other spacecraft or objects around the satellite, among other things. The paper proposed several technologies that could be used to provide the information above. The suggested technologies are summarized in Table 2 below.

Technology	Description of Use
Automatic Dependent Surveillance – Broadcast (ADS-B)	Automatically broadcasts aircraft’s (or spacecraft) current state vector
Radio-Frequency Identification (RFID)	Sat-to-sat communication during close proximity operations or on-orbit rendezvous
Photonic Telemetry	Light energy used for low data rate Sat-to-Sat communication
Nanosats technologies	Increase nanosats radar footprint; enhance deorbit capabilities
Surface Preparations for Attribution	Specific preparation of satellite materials to aide attribution in case of incident
Data Fusion Algorithms	Algorithms used to calculated maneuvers and collision probabilities

Table 2. STC Technologies (Boone et al 2009, 6-11)

In summary, the paper suggested that there needs to be a shift from today’s ground-based sensor methodology of STC to a future construct that is distributive in nature and autonomous. The paper promoted the cooperation of the international community as well as industry to enable the development of such a construct, which would be important in establishing a global STC. Though the paper freely admitted that a STC design is not addressed, some of its ideas can surely support additional STC measures and the advent of a global STC.

The next document *Hearing of the Committee on Science, Space, and Technology U.S. House of Representatives “Space Traffic Management: Preventing a Real Life ‘Gravity’*, provided insight into the findings a technical advisor of the Secure

World Foundation (Weeden, 2014). The testimony mentioned the Cosmos versus Iridium collision of 2009 was a wake-up call for the space community. The purpose of the testimony was to present a clear picture of the space traffic environment and provide recommendations for government consideration to the committee. The testimony reviewed the current debris problem and pointed out that the “Kessler syndrome,” a point in time where collisions in concentrated debris orbits promulgate more and more collisions, is a likely scenario in the future. This would significantly increase the amount of debris in orbits that are already heavily populated. To deal with this problem, it was recommended that policy makers institute debris mitigation measures, promote the development of debris removal technologies, consider the establishment of a space traffic management organization and improve SSA coordination.

Each of the concepts mentioned in the testimony have their merit, however, most relevant to a Global STC was the recommendations regarding the establishment of a space traffic management organization and the improvement of SSA. The testimony mentioned that most important to a space traffic management organization is the ability to perform conjunction analysis and to provide warning to spacecraft. This concept is central to the premise of a GSTC. Additionally, the testimony discussed the gaps in SSA capabilities and how they must be improved. Due to the Cold War, the northerly focus of U.S. SSA coverage has created coverage gaps in the South. The testimony suggested that the U.S. cooperate more with other nations to fill-in the coverage gaps in the southern hemisphere. Also discussed in the testimony were the issues dealing with SSA data provided by military organizations, which has prompted the emergence of civil and

commercial entities that conduct their own SSA. Due to these issues, it was suggested that it may be time to shift the space traffic management role from military organizations to a civil or commercial organization. This would relieve military organizations of any liability issues and allow them to focus on protecting DoD assets, while this other space traffic management organization concentrated on providing data to all organizations.

What these studies reveal is that the current way space traffic safety techniques are carried out will not be sufficient to deal with the increasingly dangerous space environment. The mitigation and remediation techniques, though they should continue, may not be enough to ensure future safe space operations. STC activities, such as SSA and collision avoidance enhance the safety of space operations. However, issues like SSA gaps and civil concerns with military management have prompted some space operators to find other alternatives. These concerns could be alleviated if international partners worked together to create a GSTC utilizing current systems to enhance space traffic safety.

III. Methodology

A mixed methodology, utilizing both qualitative and quantitative data, was used to support this thesis. Mixed methodology is defined as a research design that combines both qualitative and quantitative approaches in one of several complimentary ways to provide a comprehensive representation of the research data. One way to organize a research paper using this method is to present the qualitative data first followed by the quantitative data to validate the qualitative data. Obviously, the same strategy could be used in reverse order to validate the quantitative data. This style of conducting the study is known as the sequential mixed methodology. Utilizing concurrent analysis is another

way of conducting mix method research. This entails integrating one form with the other, for instance, mixing quantitative data with the qualitative data to support the qualitative content. There is a third form of mixed methodology known as transformative, which is intended to pose questions or theories and can be sequential or concurrent in nature.

This study utilized a sequential strategy to address the proposed concept of a GSTC. The first part of the study consists of a review of qualitative information concerning current STC systems. The review was further broken down into five elements of the current STC system; U.S. STC, Russian STC, China STC, ESA STC, and Commercial STC. Three primary processes were investigated for each category, including Space Situational Awareness (SSA), Command and Control (C2), and authorities with associated entities. The analysis resulted in a diagram, which depicts the current construct of today's ad hoc and disparate STC structure.

The qualitative review also enabled the identification of current gaps in the STC structure to include the U.S. and other nations' space safety practices that could likely be resolved by the implementation of a GSTC. The qualitative data analysis also provided insight into the concept of a GSTC that would be designed to improve upon the current ad hoc STC concept. This analysis resulted in a diagram that depicts how the current STC systems could be arranged in order to support to a future GSTC.

As mentioned earlier, the methodology used for this paper was sequential mixed method methodology. A gap analysis was conducted to provide the quantitative portion of this thesis. Gap analysis is a process in which the actual performance of a process is compared to potential performance in order to achieve the highest possible

performance of that process. In this case, the intent of a gap analysis would be to compare the performance of current STC processes to the proposed GSTC concept objectives to identify any processes that would need to be improved.

A three-step process was used to accomplish this gap analysis. The first step consisted of identifying the expectations for each process integral to the execution of a GSTC. This was done by identifying specific objectives that would need to be achieved to accomplish the each process. Table 3 displays a portion of the chart resulting from the GAP analysis. The column labeled “GSTC Objective” identifies the specific objectives to be achieved. The objective is preceded by an identifier, e.g. “S1” for the first objective listed, that was used to correlate the objective on a radar chart (see Figure 4).

Process Name	GSTC Objective	Issues with current STC	Issue Weighted Score	Objective Assessed Score
SSA	S1. SSN capable of global coverage	Lack of Sensors in S.H.	2	5.0
		Sensors are antiquated	1	
	S2. HAC available for conjunction assessment	Space operators use different satellite catalog datasets	1	3.3
		JSpOC HAC accuracy issues	1	
	S3. SSN able to track all objects 1cm+ in LEO	Can't track objects continuously	1	6.7
		Can't track objects <5cm	3	
<i>Weighted Score Scale: 0 = Issue(s) do not prevent objective achievement, 3 = Issue(s) prevent objective achievement</i>				
<i>Assessment Score Scale: 0 = Objective(s) achieved, 10 = Objective(s) not achieved</i>				

Table 3. Example of Gap Analysis Chart

The next step was to identify issues currently affecting the accomplishment of these objectives. This was accomplished through literature review, which was discussed in Section II. The last step consisted of assigning a weighted score based on how much

each issue reduced or prevented the achievement of the respective objective. Table 4 provides a description of each of the weighted scores.

Weighted Score	Weight Description
3	Issue(s) would prevent the achievement of a process objective
2	Issue(s) would significantly reduce achievement of a process objective
1	Issue(s) would slightly reduce achievement of a process objective
0	Issue(s) would not reduce achievement of a process objective / or no Issue

Table 4. Gap Analysis Weighted Scoring Description

This score was displayed in the “Issue Weighted Score” as shown in Table 3. To allow the results of each of the objectives to be compared, the scores of each issue were combined then divided by the maximum potential score. This resulted in a decimal number, which was then multiplied by 10 to translate the number to a whole number that could be plotted on the radar chart. This assessed score was displayed in “Objective Assessed Score” column of the Table 3 example. The closer the assessed score is to 0 (zero) the less impacting the issue or issues would be to GSTC objective achievement. The opposite was true the closer the assessed score was to 10.

The results of the Gap Analysis were also integrated into a radar chart (see Figure 4), to visually display the assessed objectives. A radar chart was used to plot the values of different variables to provide a visual display of the analysis. Once the values were displayed on a radar chart, deviations were easily identified. Also, the use of a radar chart would be valuable in assessing the progress of process improvement in the

future as multiple assessments taken during different time frames could be displayed on the same chart.

There was no specific research timeframe used for the conduct of this study; however, the documents referenced dated between 2005 and 2016. Events mentioned in this study may date back further. The data gathered for this study consisted of a mix of information from several internet sources to include the American Public University website electronic library, which houses several databases allowing access to books, articles and journals to several subjects including space, space debris, space traffic management and much more. Another major source was the International Academy of Astronautics (IAA) website. The IAA is an international organization that is headquartered at Stockholm, Sweden and has been in existence since 1960. The organization promotes international coordination and encourages the peaceful uses of space such as science and exploration. IAA has hosted several conferences regarding space debris, space traffic management and other space interests and has completed several studies, which are stored at their website. The NASA Orbital Debris Program Office's website is another source from which data was extracted. The office is located at the Johnson Space Center and specializes in assessing the orbital debris problem. The website offers a great amount of information regarding the space debris problem as well as space debris mitigation guideline documents produced by the international community and the U.S. Several websites, such as the European Space Agency website, Celestrak.org and Spacetrack.org provided information used to gather details on SSA and C2 capabilities, agreements that are in place, and the processes for ensuring the safety of space traffic.

Definitions

To ensure the mutual understanding of the concepts presented in this paper, a brief section defining a few terms used in this paper is warranted.

Space Traffic, according to a study on space traffic management, is defined as near all space objects' activities from the start to the end of operations (Contan-Jorgenson et al 2006, 19). This definition primarily concerns activities in near Earth space and encompasses activities during launch, on-orbit, and post-mission phases of operation. For the purposes of this paper, space traffic in Low Earth Orbit (approximately 200-900 miles) will be the primary focus as this area has experienced the most traffic growth in recent years; it has experienced the majority of human space flight; and it has been most effected by space debris. Much of the data reviewed for this paper agree that debris is the main concern when it comes to safe space flight operations. Other issues that are concerning with regard to space traffic are the continued success of new space launch companies, such as Space X and Virgin Galactic, and the continued improvements of re-useable rocket and satellite miniaturization technologies. These issues could significantly increase the human space flight presence and satellite population respectively, therefore increasing the amount of space traffic.

Space traffic control (STC) is not specifically defined in any space doctrine; however, one study describes *Space Traffic Control* as the technical element of Space Traffic Management (Boone et al 2009, 1-2). This definition proposes that STC is a subsection of Space Traffic Management, which also considers the regulatory aspects of ensuring safe travel to, operations in, and return from outer space. The document

also mentions that the two terms are used interchangeably. For the purposes of this paper, the technical aspects, related to STC are discussed more so than the regulatory body of Space Traffic Management.

GSTC is a concept that is also not specifically defined in any text. This study did not attempt to specifically define a GSTC; however, the ideas presented in this paper propose that the GSTC concept would expand upon the aforementioned definition of STC to a global scale. In other words, this concept would require international cooperation and commitment to successfully address the global aspects of ensuring global space traffic safety. What organization would best serve as a GSTC is uncertain; however, a few ideas are discussed in sections four and five.

SSA takes on different meanings depending on what organization is queried, but in general it means having knowledge of all activities in the space domain. SSA is a requirement for STC to ensure safe space operations. In order to do so, at a minimum a STC must be able access information regarding the location of objects in space, and perform conjunction assessments. This requires access to a space catalog that houses information collected from a network of sensors (ground-based and/or space-based) and computer processing and modeling capability. For global coverage, a STC would require information from sensors located in different locations around the world.

Limitations of Analysis

Data regarding how each element of the current STC structure actually communicates with each other is not clear in some instances. Information on how the U.S. and ESA coordinate with each other and with other STC entities was readily available and decipherable; however, information regarding how Russia and China

communicate with each other and other entities regarding STC was sketchy at best. What contributed to this was the limited availability of information on the internet and other sources used for this study. This is likely due to the tight control the governments have on all aspects of space operations and the release of information. In order to paint a complete picture of the current ad hoc STC system, some assumptions regarding their local processes were made to fill some information gaps.

Data on how the space community handles global space crises is lacking due to only a few incidents that required international cooperation. The number of events involving nations' satellites and debris are more numerous than satellite on satellite events. Up until the 2009 Iridium-Cosmos incident, there wasn't an apparent need within the space community, writ large, to cooperate on an international level.

There are very few documents that specifically address the GSTC concept discussed in this study. Many of the documents reviewed for this study focus on the concept of Space Traffic Management. Some of the elements of a Space Traffic Management concept were discussed in this study as there would likely be some interrelation between the two concepts; however, this study takes a more technical look rather than a regulatory look at what a GSTC might look like.

IV. Results

A Look at the Current STC Construct

A qualitative review of the referenced documents was conducted to determine the current STC process. In this review three areas were investigated; SSA capabilities, command and control, and authorities. The purpose of this analysis was to reveal how

the current STC system operates today and to breakdown each element to determine what gaps exist. This information will also be used to conduct a gap analysis later in this study.

Figure 1 illustrates the results of the analysis of the current STC construct. The approach for this analysis was to investigate the disparate systems, managed by the different space-faring entities and identify the cross connects that would infer a global process. Data regarding how each of the major stakeholders communicates with each other during routine and crisis environments was evaluated to determine lines of communication. The diagram can be subdivided into five sub-systems; U.S., Russia, China, European Union/ESA, and other Foreign Nations. The solid lines represent routine communications, which usually involves two-way information exchanges and may involve laws that govern interaction or the establishment of an agreement that controls that exchange. The dotted lines represent lines of communication that seem to only occur during a crisis event. A review of diagram follows.

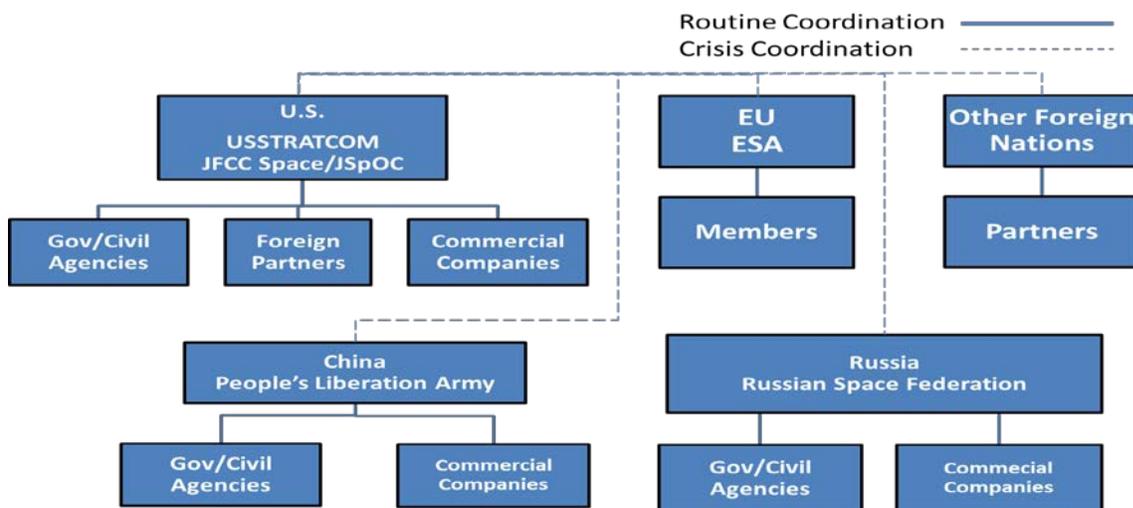


Figure 1. Current STC C2

As mentioned previously, there is some semblance of a STC that is being conducted today; however, the system is imperfect and in need of much improvement in order to ensure future space traffic safety. The term *ad hoc* has been used in this study to describe the current system as it is currently disparate and operates without specific guidelines agreed upon by its participants. Additionally, it seems that some space faring nations, such as Russia and China, which have much to offer to enhance space traffic safety, chose to operate in a vacuum primarily focusing on their own assets. These entities tend to only collaborate with others during times of crisis. Lastly, there doesn't seem to be a clear-cut controller or authority designated to make sound decisions and all actions seem to be voluntary in nature. On the other hand, the U.S. seems to have taken on the role as the world's STC and has made great strides in attempting to improve the safety of space flight.

The U.S. possesses an extensive online SSA program and allows access to all who wish to gain access. The U.S. will also provide enhanced data to those who wish to sign an agreement. For all intents and purposes, the U.S. system is as close as there is to a global or international STC. The discussion below provides insight into the overall concept of today's STC system, which explains the relationships between the major space-faring entities with space traffic safety interests. Additionally, since the U.S. SSA process is a significant contributor to the current STC system, the primary focus will be on the U.S. STC relationships.

The upper left section of the diagram represents the U.S. STC construct. The U.S. STC capabilities are well known as it provides the preponderance of support to the current STC system. It possesses the most sophisticated Space Surveillance Network

(SSN) and SSA Program. The U.S. SSN consists of 29 radar and optical sensors located world-wide, and one on-orbit sensor (Joint Functional Component Command for Space 2011). These SSN is capable of detecting objects as small as 1cm in LEO and 10cm in GEO, although it is only able to routinely track objects larger than 5cm. The system conducts several hundred thousand observations per day to maintain the most complete catalog of satellites that exists today. Protecting U.S. space capabilities, including DoD, NASA and other organizations' satellites by providing SSA and collision avoidance data is of the highest priority.

The SSN also contributes to a transparent SSA sharing program that can be accessed via an internet site at Space-Track.org. This site is managed by United States Strategic Command's (USSTRATCOM). (Documentation n.d.) This SSA database openly shares basic space tracking data with anyone who has an account and shares advanced data with those willing to enter into an agreement with the U.S. The information requested is configurable and determined by the user. Depending on what is requested, the information can be downloaded and used for whatever purposes the user wishes. The user agreement determines the limitations regarding further sharing this information.

The solid lines in this section represent the routine STC coordination that occurs between the U.S. and other parties. As mentioned, the U.S. is primarily concerned with protecting its own satellites as well as its allies and partners, which are represented by the Gov/Civil block in Figure 1. This responsibility has been assigned to USSTRATCOM through military directives. The Joint Functional Component Command for Space (JFCC Space), located at Vandenberg AFB, California, via the Joint Space Operations Center

(JSpOC) is the unit that executes USSTRATCOM's space operations. The JSpOC is the focal point for ensuring the safety of U.S. spacecraft operated by the Department of Defense and by U.S. government agencies such as NASA and NOAA (Joint Functional Component Command for Space 2013).

The JSpOC also provides services to U.S. commercial space operators as well as U.S. foreign partners. Furthermore, there are indications that JSpOC is stepping up support to U.S. commercial and foreign partners by integrating them into the military operations center. One article, mentioned the completion of the Combined Integration Cell (CIC) experiment designed to promote robust collaboration between the commercial sector and DoD. (Henry 2015). The experiment involved companies like SES Government Solutions, Intelsat, Digital Globe, Iridium, Eutelsat and Inmarsat, and involved an increased level of SSA information sharing. According to another article, a participant in the experiment exclaimed, “..having commercial representatives work alongside the military was valuable. It improved coordination response times and helped resolve problems before they became issues.” (Turk 2016). It has yet to be determined whether this construct will become the norm for future military-commercial operations. However, this experiment proved the value of the concept of having operators collocated, which warrants further investigation and may even provide a baseline for a much larger scale GSTC concept.

As of June, 2015, the U.S. has signed SSA sharing agreements with at least 60 entities that include foreign commercial and government partners (Henry 2015). The United Kingdom, France, Canada, Germany, Italy, Japan, Australia, Republic of Korea, Israel, and ESA are just a few of these organizations who are currently enjoying mutual

exchange of SSA data. To further increase SSA collaboration, in 2014 the U.S. entered into agreement with its closest allies in the creation of a Combine Space Operations Center (CSpOC) concept (Pekkanen 2015). This agreement enables exchange of even more sensitive space operational data with the UK, Australia, and Canada. In Figure 1, these relationships are represented by the solid lines drawn from the Foreign Partners and Commercial Companies blocks to the U.S. block.

Another linkage with foreign and commercial entities is represented by the dotted line connecting the USA block to the other organizational blocks labeled ESA, Other Foreign Partners, China and Russia in Figure 1. When the JSpOC detects a conjunction, it sends what is known as a Conjunction Summary Message (CSM) to the parties involved notifying them of the impending close approach. The CSM contains conjunction assessment information that allows the space operator to determine the best course of action (COA) in response to a predicted satellite conjunction (a place and time where two object could intersect). Though JSpOC is not authorized to direct parties to maneuver satellites, it offers its support to ensure maneuvers avoid subsequent conjunctions. During 2013, JSpOC sent anywhere between 20 and 30 of these messages to space operators each day (Florick and Cashin 2013). In the years to come the number of CSMs will likely grow as the space traffic problem continues to worsen. The U.S. encourages entities join its expanding SSA sharing program to meet this challenge.

The upper right-hand portion of Figure 1 represents ESA's and Other Foreign Nations' contributions to the current STC construct. The ESA is headquartered in Paris, France and has facilities in the Netherlands, Germany, Italy, Spain, Belgium, UK and

launch facilities in French Guiana. Created in 1975, the ESA consists of 18 member states and focuses on peaceful cooperation in space, while conducting space launch, space exploration, telecommunications, earth science, and human spaceflight missions. ESA currently has an agreement with the U.S. to mutually share SSA data; however, ESA has plans to field its own SSA system (Space Surveillance and Tracking – SST Segment 2014). Working with the European Commission, ESA plans to utilize SSA capabilities that already exist within member states, in particular space sensors, to form the baseline of its Space Surveillance and Tracking (SST) system. It hopes to be able to consolidate the information the system collects in a central space object database where it can be utilized to provide conjunction and reentry awareness services to its partners.

According to ESA's homepage, the first phase of the plan is complete with the development of its first online application, similar to the U.S. SSA website, which can be accessed via the internet. Additionally, ESA has established a control center at the Space Surveillance Test and Validation Centre, Spain, and two SSA centers in Brussels for Space Weather and in Italy for Near Earth Objects (natural objects). Lastly, ESA has re-purposed an on-orbit satellite mission from solar observation to space-based space surveillance. Phase two of ESA's plan consists of a seven step process focused on the continued development of its current SSA processes and the development of new SST systems, such as satellite laser ranging systems, ground-based sensors systems and IT infrastructure (Space Surveillance and Tracking – SST Segment 2014). At this point, there is no indication that ESA has fully implemented its SST system, based on the data

reviewed. However, once established ESA's SST system would be a significant contributor to the current STC system as well any future GSTC concept.

There may be other nations that have an interest in protecting their assets in space, but may not have indigenous SSA capability or may not have sought an SSA sharing agreement with the U.S. This is represented by the dotted line from the U.S. to the Foreign Countries block on the upper right-hand side of Figure 1. These nations would be eligible to receive assistance from the U.S. SSA sharing program by either accessing the SSA website or receiving conjunction warnings via the CSM at no charge. The JSpOC keeps track of over 1100 active satellites and has the ability to contact 98 percent of these satellite owners (Florick and Cashin 2013). The JSpOC will attempt to contact satellite owners in the case of close approach situations, regardless if there is an agreement in place.

The two sections at the bottom of Figure 1 represent the relationships between the Russian and Chinese STCs and the rest of the current STC system. Russia is known to have an extensive Space Surveillance System (SSS), second only to the U.S. The Russian SSS is run by the Russian Space Federation and based on missile defense requirements of the Cold War, much the same as the U.S. system. The SSS consists of as many as 4 optical and 11 radar systems located across Russia and in former Commonwealth of Independent States (CIS) countries of Kazakhstan, Azerbaijan, Belarus, and Tajikistan (Vallado, David A., and Jacob D. Griesbach. n.d.). Russia SSA data primarily supports government-owned satellite operators and likely supports Russian-owned commercial operators. Russia does not manage a publicly available SSA sharing program; therefore, does not share SSA information with other

nations on a routine basis. These relationships are represented by the solid lines connecting the Gov/Civil and Commercial Partners Block. The dotted lines connecting Russia with the U.S. and other entities represents the ad hoc SSA coordination that likely exists when it is in their best interest to ensure the safety of their own spacecraft. For instance, Russia called on the ESA for support in attempts to detect and recover the failed Phobus Grunt Mars probe. The probe was launched on November 8, 2011, but technical issues caused the probe to be stuck in LEO. The Russian Space Federation worked with ESA to recover the satellite, but was unsuccessful (David 2011). The probe later deorbited in January 2012. Since that time there has been a SSA sharing agreement between the U.S. and Russia in which the JSpOC sends CSM alerts to Russia. Even before the Phobus Grunt event, the JSpOC had been sending CSMs to Russia without the agreement. During 2010, Russia received 252 of these messages warning of close approach conjunctions (Chow 2011, 6).

The U.S. also provides China with SSA data even though there is no formal SSA sharing agreement in place. During 2010, the U.S. sent 147 CSM messages to China (Chow 2011, 6). According to an article, the U.S. has been sending SSA data to China via CSMs for quite some time through the State Department, but they were never acknowledged (Clark 2014). It wasn't until recently, when the U.S. received a formal request from China to provide the information directly to the military that the U.S. got confirmation that the Chinese were indeed receiving it and wanted more. It is unclear exactly how the Chinese used this information. The article postulated the information could have been used to compare the accuracy of U.S. SSA information to the accuracy

of their SSA data or to enhance their own data. This ad hoc relationship is represented by the dotted line connecting China to the U.S.

The solid lines from China to the Gov/Civ, Foreign Partners, and Commercial blocks represent the STC managed by China. The People's Liberation Army is the organization responsible for Chinese SSA program, which does not release information publically. Little information is available on the radar sensors of China's SSN, but a study assessed that it likely consists of nine phased array radars that are all located within China's borders (Becker 2012, 6). China also uses four optical sensors, managed by the Purple Mountain Observatory, that are also within China's borders, which limits observation of satellites in the GEO belt to those within in the field of view of China. China possesses the capability to populate a respectable SSA database consisting of LEO and possibly MEO. GEO information is likely incomplete due to the lack of global sensor coverage. As mentioned, China does not publicly release SSA data, so it is likely that China has not signed formal SSA sharing agreements with other nations. Also, there was no indication that the PLA currently exchanges SSA data with China's commercial space operators. China could be a significant contributor in the current STC system; however, the closed nature of their SSA program deters their participation in a more open construct. Much like Russia, their participation would likely only come when it is in their best interest or during an emergency.

Current Space Traffic Control Process

From the results previously mentioned, it is apparent that the U.S. has inherited the preponderance of responsibility with regard to the current STC system. It has the most transparent process even though it is run by the U.S. military. Therefore,

determining the process the U.S. military uses to improve safe space operations was not difficult to discover due to the fact that quite a bit of information resides on the internet. A review of the U.S. process follows.

There are three ways to gain access to U.S. SSA information. The first way is to start an account at Space-Track.org which is overseen by the U.S. Strategic Command and managed by the JFCC Space's Joint Space Operations Center (JSpOC). This site allows access to basic satellite catalogue information and reentry predictions without cost. The information can be used to enhance the space operator's collision avoidance processes. The second way to gain access to U.S. SSA information is through JSpOC's emergency broadcasts via CSM, which was also discussed in the previous section. When the JSpOC detects a close approach of satellites, it attempts to send CSMs messages to the affected space operators regardless of the existence of an agreement. The CSM information can then be used to conduct conjunction analysis and collision avoidance in accordance with the operators' operational plan. JSpOC will provide assistance to the satellite operators as required. These two options are provided at no cost and without agreements in place; however, it may not include the most accurate information the U.S. has access to. Furthermore, there is no obligation for the effected operator to reciprocate in any way. The third way to gain access to U.S. SSA information, however, involves acquiring an agreement with the U.S. to access more advanced and routine support, such as launch, deorbit and disposal of spacecraft, from the JSpOC. With an agreement, two-way information exchanged is allowed. The information or support received by the U.S. is likely dependent upon the space operator

and the parameters of the agreement. Figure 2 below represents the STC process after a space operator acquires an agreement with JSpOC.

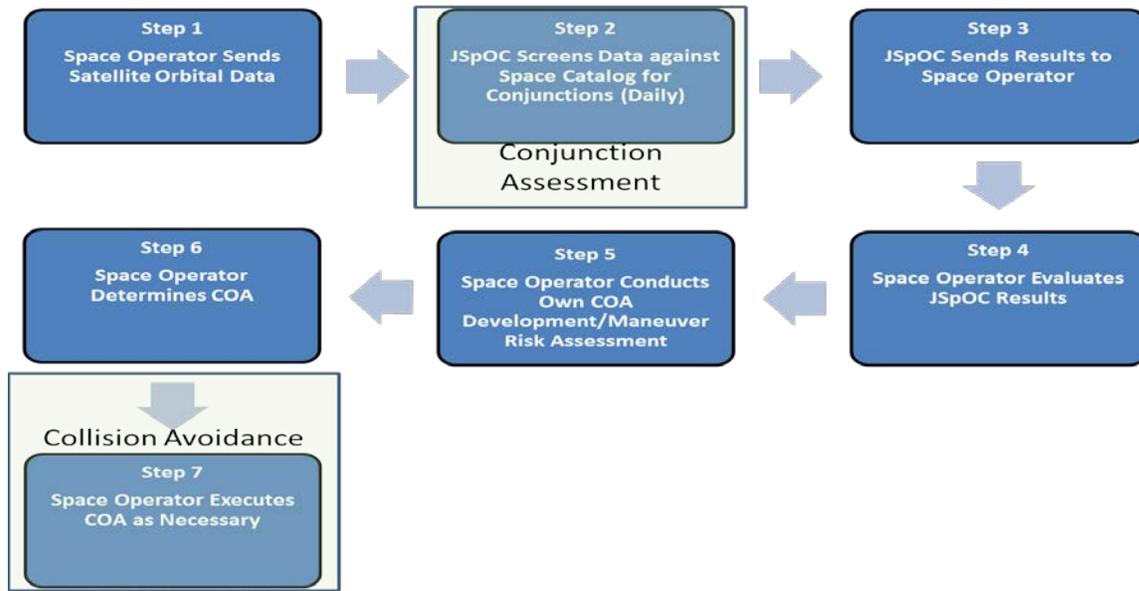


Figure 2. Current STC Process

In Step 1, the space operator provides the JSpOC with the information needed to acquire and track the satellite or satellites. This information consists of the satellite Two-Line Element (TLE) set, which details the last known position, time, and other pertinent information. There are different versions of element sets; however, JSpOC has the ability to translate the different variations into a format required by their systems. Step 2, the JSpOC screens the data against the information already in their satellite catalogue to look for close approaches or conjunctions. This process is known as conjunction assessment. A close approach or conjunction may be declared if an object is predicted to fly through a pre-established boundary placed around the subject satellites. JSpOC may assign additional SSN tasking in order to more precisely track the intersecting

satellites. Step 3, the space operator is notified of the results that JSpOC has produced. Along with the results, JSpOC offers additional support to include collision avoidance support. Step 4, At this point, it is up to the space operator as to whether or not JSpOC continues to support. The space operator evaluates JSpOC's results to determine if it meets criteria for further evaluation and collision avoidance planning. Step 5, if further planning is required, the Space Operator could continue to work with JSpOC for further support or determine the course of action on its own. In this step the risks of conducting different maneuvers are assessed. Maneuvers to save the spacecraft from colliding with another space object could result in reducing the lifespan of the spacecraft or even loss of the spacecraft. This is an important time where a STC could provide critical support by assisting in the selection of the best COA. Today, JSpOC assumes this role for its partners; however, a GSTC could assume the role in JSpOC's place. Step 6, once the risks are carefully weighed the space operator chooses the best COA that ensures spacecraft safety. Step 7, the space operator executes the COA, which may or may not entail a maneuver, depending on the satellite owner's best interest. Either way this part of the process is call collision avoidance. There is no obligation for the space operator to maneuver once notified. Depending upon the agreement, the space operator may follow-up with JSpOC to inform them of the maneuver. This may not be the case, if no agreement exists with the space operator as there is no other obligation to inform JSpOC of a maneuver.

The review of the current STC may seem biased in favor of the U.S system. The review is simply a reflection of the transparency of the U.S. system and the lack of information available on the processes of other elements of the current STC structure. It

is possible Russia and China, follow a similar process; however, that information is not readily available. From this review, it is evident that the U.S. process is the most robust and it attempts to cross international lanes to ensure safe space operations. However, it is not without its flaws, which will be covered in the gap analysis later. The next section will provide an overview of the GSTC concept.

A Look at the Global STC Concept

Figure 3 depicts the proposed GSTC concept. The diagram is a simplified representation of what would likely be an intricate construct involving the integration of the STC capabilities that already exist. The primary challenge; however, would be convincing the major space-faring elements discussed in the previous section to cooperate on an agreeable construct.

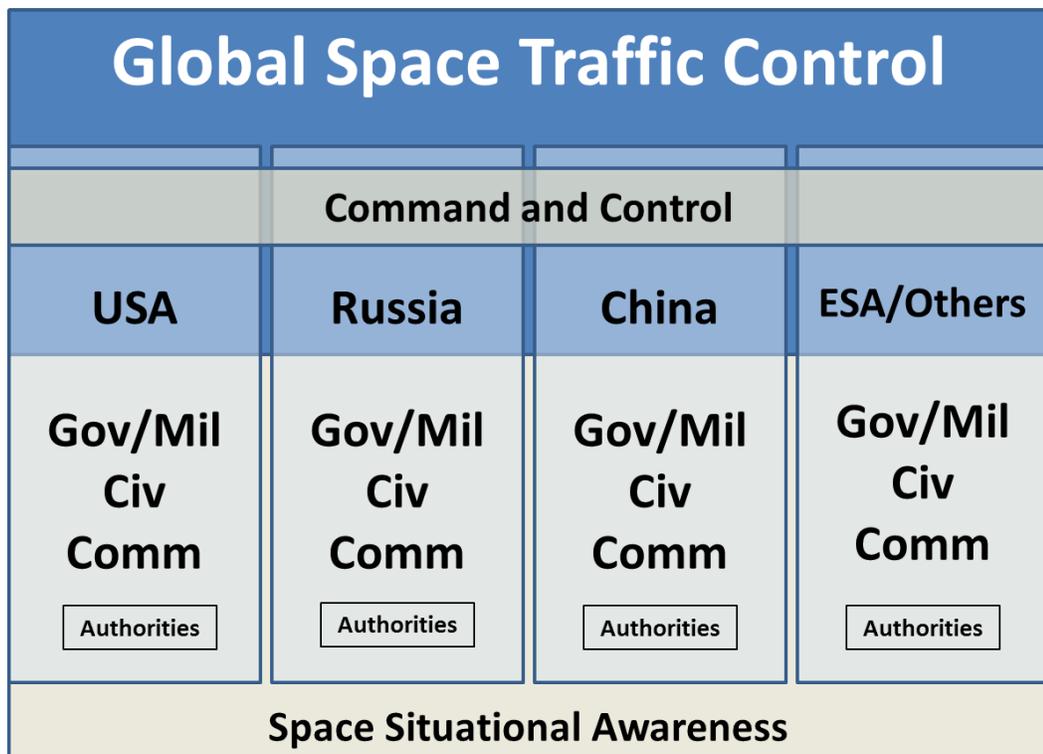


Figure 3. Global STC Concept

There would be several requirements involved in instituting such a concept. First, a GSTC would need a space situational awareness process in order to perform conjunction assessments. This would entail acquiring satellite information from a global SSN to develop a satellite catalog and possessing the computer processing capability to perform conjunction assessments. The capability and technology exists today within different elements of the current STC construct. The nation-states and civil and commercial organizations that perform these actions today could provide support to the GSTC and could expect to take advantage of its capabilities as well, to ensure the safety of their own space operations. Second, a command and control (C2) network would need to be established to allow the GSTC to have immediate communications with satellite owner-operators. This C2 network would allow the GSTC to provide warning to all effected satellite owner-operators at one time and provide an avenue for further coordination such as conducting avoidance maneuvers. Third, authorities would need to be granted by satellite owner-operators to the GSTC to enable the utilization of owner-operator information and to be able to direct satellites during times of crisis. There are limitations and constraints to each of these areas, which would be discussed throughout the thesis. The next section will provide the results of the gap analysis conducted to identify the gaps that exist in the current STC structure.

Gap Analysis – STC vs. GSTC

For the following discussion refer to Table 5, GSTC vs. Current STC (STC) Gap Analysis, which provides the results of the gap analysis. This analysis assessed three processes of the current STC that would be required for a GSTC; SSA, command and

control (C2), and authorities. For each process, the state of current STC was determined based on information gathered from reviewed documents. This was compared to aforementioned requirements and objectives that would need to be accomplished within a GSTC construct.

The gap analysis methodology described in Section III, Methodology, was followed to provide the scores listed in Table 5. The Objective Assessed Scores, column five, provide insight into the current accomplishment of the respective GSTC objectives within each process. A score of 0 (zero) reflects no issues and objectives are being achieved. The larger the number, the more severe the issues are that affect objective accomplishment. The Process Assessed Scores, column one, provide insight into overall performance of the current STC process. Figure 4 below is a radar chart, which provides a visual representation of the assessed scores received by the objectives. The following discussion provides further detail discovered during the gap analysis.

Process Name	GSTC Objective	Issues with current STC	Issue Weighted Score	Objective Assessed Score
SSA	S1. SSN capable of global coverage	Lack of Sensors in S.H.	2	5.0
		Sensors are antiquated	1	
	S2. HAC available for conjunction assessment	Space operators use different satellite catalog datasets	1	3.3
		JSpOC HAC accuracy issues	1	
	S3. SSN able to track all objects 1cm+ in LEO	Can't track objects continuously	1	6.7
		Can't track objects <5cm	3	
C2	C1. C2 Structure promotes info sharing	No clear lines of Command	2	5.0
		Reliance on US military provider	1	
	C2. Comms System enables immediate contact with Space Operators	No mass notification process	2	5.0
		CSM/Email notifications are not dependable	1	
Authorities	A1. Ability to share data amongst space operators	Data sharing agreements are not standardized	1	3.3
	A2. Ability to direct space operators during emergencies	No authority to direct space operators	3	10
No obligation for space operators to obey STC		3		
<i>Weighted Score Scale:</i> 0 = Issue(s) do not prevent objective achievement, 3 = Issue(s) prevent objective achievement				
<i>Assessment Score Scale:</i> 0 = Objective(s) achieved, 10 = Objective(s) not achieved				

Table 5. GSTC vs. Current STC Gap Analysis

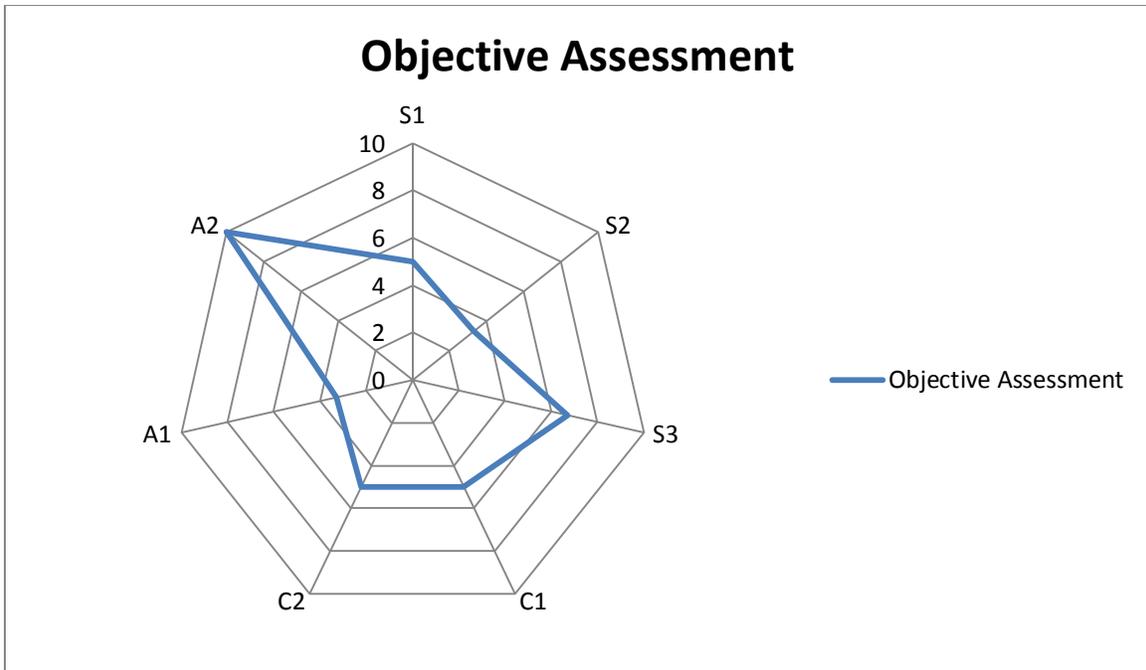


Figure 4. GSTC Gap Analysis Radar Chart

Space Situational Awareness Process

The current SSA process was evaluated based on three GSTC objectives. Referring to Table 5, GSTC vs. Current STC Gap Analysis, objective S1 was evaluated, which states: GSTC SSN is capable of global sensor coverage in order to fully characterize LEO and HEO. Analysis of the current STC, based on this objective, revealed significant issues. The first issue deals with identified sensor capability gaps in the U.S. SSN. As mentioned earlier, the U.S. possesses SSN sensors all over the world; however, the majority of the radar sensors are concentrated in the U.S. and oriented toward the north. Additionally, most of these radars are located in the northern hemisphere. This is an issue that is the result of the Cold War era, when the initial objective for the deployment of most of these radars was to defend against ICBMs. Though this does not seem to have had a negative effect on characterizing GEO, it has

resulted in reduced effectiveness in characterizing the HEO satellite population (Becker et al 2012, 5). Another issue that adversely affects the SSN ability to detect objects is the sheer numbers of objects that need to be tracked. The SSN has cataloged and can track over 22,000 objects larger than 10cm. However, the SSN is not able to continuously track each object. The system checks each object periodically and uses a predictive methodology that enables the sensors to reacquire them at a later time.

A GSTC would need to be able to fully characterize LEO and HEO orbits (HEO may intersect LEO orbits at perigee). Objects in these orbits pose the most significant threat to spacecraft and human life that operate in LEO. Referring to Table 5, objective S1 regarding global SSN coverage received an assessment score of 5 based on the issues discussed. This is reflective of significant issues effecting the achievement of this objective. Therefore, the GSTC SSN would need to be modified in order to improve coverage in the southern hemisphere and increase the number of observations per object. One way to accomplish this would be to upgrade or replace antiquated ground-based radar and optical sensors to handle a larger workload. Another way would be to establish new sensors (ground-based or on-orbit) in locations that would enhance current tracking capabilities. Additionally, a GSTC could augment the current U.S. SSN data with data collected from other sources, such as ESA's burgeoning space surveillance system or even China's or Russia's space surveillance systems. Referring to Figure 4, GSTC Gap Analysis Radar Chart, the recommended SSN modifications would allow the S1 value, currently set to 5, to slide closer to 0 (zero) as the accomplishment of the relative objective improves.

Obviously, these recommendations would not be without limitations. Upgrading current sensors or establishing new sensors may be cost prohibitive, but when you consider the cost of losing several spacecraft or losing the use of an orbit all together due to the debris population, these solutions may be worth the cost. Convincing China or Russia to share SSA data would be a challenge as these nations are not known to share their space surveillance data readily. However, in due time, these two nations may determine sharing SSA data may be in their best interest due to the increasingly dangerous space traffic environment.

If a GSTC were able to consolidate the disparate SSA data collected by the different STC entities, the number of sensors would increase by over 100%. The number of ground-based sensors would increase from 29 to 60 with the addition of 13 Chinese and 15 Russian sensors. On-orbit sensors would increase from 1 to 3 with the addition of Canada's and the ESA's on-orbit SSA sensors capabilities. The number of sensors would grow even more if the GSTC were to garner the support of organizations like International Scientific Observation Network (ISON), which is a network of 18 scientific observatories equipped with optical sensors. ISON consists of 18 academic and scientific organizations located in 9 different nations that are focused on characterizing the space debris environment. Currently, the U.S. SSN accomplishes over 380,000 observations per day (Becker et al 2012, 4). A GSTC network that consolidates the aforementioned systems would greatly increase the number of observations improving the accuracy and number of objects tracked for a SSA catalog.

Next, objective S2 in Table 5 was evaluated, which states: A High Accuracy Catalog (HAC) would be available for conjunction assessments. One of the issues with

the current STC is the different space operators use different SSA data sets due to lack of access to the JSpOCs HAC. The U.S. SSA website provides only basic data to its users unless a formal agreement is signed to access more sensitive information. Any entity can access the website, but will only be able to retrieve the simplified TLE data set, which is good enough to maintain good situational awareness, but not accurate enough for conjunction assessment and follow-on collision avoidance processes. On the other hand, the U.S. JSpOC uses a TLE data set that utilizes a special perturbation algorithm that corrects atmospheric and gravitational perturbations to generate a HAC and subsequently conduct precise conjunction analysis. This HAC is not publicly available and can only be accessed by acquiring an agreement with the U.S. (Becker et al 2012, 29). Those not able to qualify for this advanced data service are relegated to utilizing the standard TLE. This data disparity in information could result in a space operator's conjunction assessment conclusion being slightly different than the JSpOC's and may lead to miscalculation.

According to an article, in 2012 the Space Data Association (SDA), which is an organization that gathers spacecraft SSA data directly from satellite operators, claimed that the many of CSMs the JSpOC produced were wrong and some close approaches were missed by the JSpOC (Morrison 2012). This has led to organizations not trusting the accuracy of CSM data and finding other solutions to providing more precise SSA data. One example is the aforementioned Space Data Association, which is a consortium of satellite providers that use positional data provided by satellite operators, vice radar or optical sensors, to populate an automated SSA catalog of over 340 satellites in LEO and GEO and conduct conjunction assessments. Another example is

Celestrak, which is an online SSA data provider that utilizes the JSpOC's Space-Track.org data. According to the site owner, the orbital prediction source code that was initially publically available was changed by the DoD and subsequently not released. The site owner claims to have corrected for these modifications to ensure accuracy and compatibility with DoD source code (Kelso n.d.).

The evaluation of these issues resulted in an assessed score of 3.3 for the S2 objective regarding an HAC available for conjunction assessments, referring back to Table 5. This score is indicative of issues that reduce the accomplishment of the objective. On the radar chart, Figure 4, the S2 objective received the lowest score, which reveals that the issues impact the achievement of this objective the least compared to the other objectives.

To improve upon the achievement of this objective, it would require the utilization of a standardized method of generating SSA data that is accurate enough to conduct conjunction assessment and collision avoidance. Ideally, a GSTC would utilize the most accurate method currently available at least as a starting point. However, considering there is uncertainty in the accuracy of the special perturbations technique used by the JSpOC, as previously mentioned, the establishment of new international process would likely be the solution for a GSTC. Besides, the likelihood of the DoD's special perturbations methodology being released to the GSTC is doubtful. Perhaps even a hybrid system that combines the JSpOC general perturbations data set with satellite operator provided positional data, such as the SDA model, would be a reasonable substitute for the current system.

The third SSA objective, S3 in Table 5, was evaluated, which states: The SSN is able to track all objects equal to or greater than 1cm. There are well over 370,000 debris objects in LEO measuring 1cm or more (NASA Orbital Debris Office, n.d.). There are also hundreds of thousands of debris objects smaller than 1cm, but most satellites are shielded to protect components from this threat. Space objects greater than 1cm can cause serious damage to satellite components, while objects measuring 10cm or more can result in destruction of satellites. The current SSN, with the U.S. providing the preponderance of capability, has the ability to track objects as small as 5 cm in LEO (NASA Orbital Debris Program n.d.). There are SSN radars that can detect objects smaller than 5cm, but they do not have the ability to track these objects on a continuous basis. Because these smaller pieces of debris are difficult to detect and track, they are significant threat to space traffic safety.

These issues covered above, resulted in a 6.7 assessed score of the S3 objective in Table 5, which indicated that there are significant issues that would prevent the accomplishment of this GSTC objective. This is also depicted on the radar chart, figure 4, which shows that this objective has the most room for improvement within the SSA process. Therefore, serious effort must be exerted to improve the capability to detect and track objects measuring in the 1-10cm range. This might be done by increasing the number of sensors capable of detecting and tracking objects below 5cm. Examples of sensors with this capability are the U.S. Haystack Auxiliary radars, which is capable of detecting objects down to 5mm in LEO; and the U.S. JPL Goldstone radars that are capable of detecting objects 2-3mm in size (Becker et al 2012, 6). Deployment of many of these radars may be cost prohibitive for a GSTC, however, this cost may be

defrayed by the deployment of additional space-based sensors to augment ground-based capabilities and by focusing sensors on the most populated regions of LEO.

Command and Control Process

The next step in this gap analysis consisted of a review of the command and control (C2) processes of the current STC. Objective C1 in Table 5 was first evaluated, which states: The communications structure must promote information sharing amongst space operators. Issues regarding this objective didn't emerge until the Iridium-Cosmos collision in 2009. This collision was the first between two satellites and not only exposed the space debris problem, but also revealed to the world that no one was in charge of controlling space traffic. Though space operators around the world turned to USSTRATCOM, through JFCC Space/JSpOC, to provide collision warnings, this event also proved that the military is not without its faults.

According to a study, tracking of the two satellites before the collision was available to the U.S. and Russia. In fact, Socrates, a conjunction analysis tool hosted on Celestrak.com, which utilizes the TLE data sets available on JSpOC's Space-Track SSA tool, predicted a close approach of 584 meters less than two hours before the collision (Kelso n.d., 1). Iridium had access to the SOCRATES information, but failed to act on it. JSpOC had previously provided collision warnings to Iridium, but discontinued this service due to the excessive number of warnings generated by the Iridium constellation. Additionally, there was no direct SSA communication lines established between Russia and the U.S. during this time. Though the conjunction assessment information was available, without a clear designated STC, no party was obligated to take control of the situation. After this collision, the JSpOC began disseminating

conjunction warning messages to all satellite operators, causing a 300 percent increase in the potential number of satellite operators that could be contacted (Ferster 2012). However, there was still no organization assigned the responsibility, by international law or otherwise, to provide collision warning notifications or similar duties.

The U.S. has taken the opportunity to be a leader in providing SSA to space operators; however, many non-government entities have questioned the reliance on a military organization for this service. Studies cited that space operators were concerned with the timeliness and accuracy of the information available on JSpOC's SSA website. Others were concerned with the possibility of the U.S. government shutting down the SSA program without warning and that the U.S. government could not be held accountable for the information it distributed (Chow 2011, 8). Certainly, there were security concerns from all sides participating in a SSA sharing program regarding the compromise of sensitive program information.

The lack of a designated STC authority and the reliance on the U.S. military for information has contributed to an uncertain environment regarding information sharing. These issues contributed to the C1 objective assessed rating of 5, which indicates that these are major issues that would hamper the accomplishment of this objective. The establishment of a GSTC would alleviate these concerns, but it will take a concerted effort from all parties concerned with the current space traffic problem to construct a model that is agreeable to all. There is some debate within the space community as to what type of organization would best be suited to conduct such operations. Some studies suggest the best choice would be a space traffic management organization that would be subordinate to the United Nations, similar to the International Maritime

Organization or the International Civil Aviation Organization. This has some merit; however, these are regulatory bodies that would primarily be concerned with ensuring nation-states operated within established international law. A GSTC could certainly be a smaller part of larger governing body; however it would be technical in nature and would likely assume the STC operational responsibilities managed by the U.S. military.

One option would be to assign these responsibilities to an international inter-governmental organization. An example of this is the European Space Agency (ESA), which has a 22-nation membership. The ESA is a non-military organization that is focused on peaceful cooperation in space and possesses a sizeable budget of which each member is responsible for contributing funds (What is ESA? n.d.). An organization such as ESA could elevate many of the concerns regarding the military being responsible for STC. Another option would be to shift the services that the JSpOC provides over to a non-governmental organization such as the Space Data Association (SDA). SDA is a consortium of satellite operators who share satellite positional data to improve safety of operations. The SDA provides a SSA database, similar to the JSpOC, which is managed by its Space Data Center (Space Data Association n.d.). Though there'd be issues with either of these options, they would accomplish the same goal, which would be to allow the U.S. military to relinquish responsibility of ensuring space traffic safety of all the world's space activity and focus on protecting DoD space assets.

The next objective, C2 in Table 5, was evaluated, which states: The communications system enables immediate contact with space operators. Referring back to Figure 1, which depicts the current STC process, Step 1 consisted of the space operator conveying the initial data concerning the spacecraft of interest to the JSpOC.

This information would be integrated into the JSpOC's conjunction assessment process. The space operator would later receive warnings via a CSM from the JSpOC if a probable collision was detected. Follow-on communications could involve email exchanges, if the space operator chose to work with JSpOC, to avoid a collision.

This notification process is conducted primarily via email, which can be cumbersome and slow. Also, transporting CSM data from one system to another could be time consuming and may lead to data corruption. In instances where a collision seems imminent or the space operator has little time to make a decision, such as break-ups or satellite anomalies, a more immediate form of communication is required to ensure all parties involved are notified and follow-on actions can be discussed. A mass notification system that broadcasts warnings via voice or data networks should be used as the primary means of notification to ensure contact. Contact via CSM and email should occur simultaneously or following initial voice contact. It will be important for a GSTC to ensure the availability of communications capabilities that enables immediate contact with space operators. Having adequate time to assess the situation and make sound decisions would provide a means for the space operator to protect their expensive equipment and contribute to the preservation Earth's orbits by avoiding collisions.

Authorities

This next section addresses the gaps noted regarding authorities between different space operators within the current STC structure. The first objective, A1 in Table 5, was evaluated, which states: Agreements must promote data sharing among space operators. Again, this is an area where the U.S. has been very transparent and

seems to be leading the charge in establishing solid SSA sharing partnerships around the world. As of 2013, the USSTRATCOM's SSA sharing website had over 88,000 users spanning 185 countries (Florick and Cashin 2013). To gain access, a user acquires an account on Space –Track.org and agrees to a simple digital terms and conditions agreement that demands non-proliferation of the information without permission (User Agreement n.d.). The site also mentions that members could be charged or services can be terminated at any time without prior warning, which is cause for operators' concern regarding continued availability of future services. The space operator is provided basic service access that consists of the satellites catalog and satellite decay data, which can be used for its own purposes. However, as pointed out earlier, there is some concern as to the accuracy of this data. This contributes to some uncertainty for space operators who must use this information to make self-determined conjunction assessment or collision avoidance measures. Nevertheless, all space operators are eligible to receive JSpOC's emergency service, which provides warnings when a conjunction is expected, without agreements in place.

JSpOC's SSA program also provides advanced services, such as launch conjunction assessment, collision avoidance, disposal support and more. This service is more exclusive and requires a formal agreement between the U.S. and the requesting space operator. All space operators, including commercial and foreign partners, are eligible for the service; however, these agreements are subject to approval based on whether it is in the best interest of the U.S from national security perspective (Florick and Cashin 2013). As mentioned earlier, only around 60 SSA sharing agreements have been signed as of 2015. This is one-third the amount of basic service recipients in 2010.

This disparity reveals the number of entities that could be operating on slightly different data, which could potentially lead to miscalculation and increase the risk to safe space operations.

Referring to Table 5, the A1 objective, regarding the agreement to promote data sharing, was assessed a score of 3.3. This score denotes the issue would have a lesser effect on the achievement of the objective. On the radar chart, Figure 4, this objective is one of two objectives that require the least amount of improvement. Within the construct of a GSTC, agreements would be standardized allowing all space operators to access the same types of services. Agreements would be based on the GSTC's goal of international cooperation to ensure safety of space operations in the peaceful uses of outer space and only make exceptions for those wishing to protect certain data such as sensitive military data. Referring back to the Command and Control section, the recommendation to assign an intergovernmental or non-governmental organization as the lead agent for a GSTC would be most appropriate to ensure political or national security interests don't skew the implementation of agreements and the availability of information. Since the GSTC would not be responsible to any one government, it would not have to impose constraints or restrictions on space operators, since the same services would be available to all. A structure like this may also attract increased participation from nations like Russia or China that may have security concerns.

The last objective, S2 in Table 5, was evaluated, which states: Agreements allow the direction of space operators during emergencies. The first issue discovered dealt with the current STC's lack of authority to direct spacecraft. The current STC, namely the JSpOC, provides services to enhance the safety of space operations; however, they

are restricted from directing space operators outside the U.S. on any maneuvers. The basis for this omission is to ensure the U.S. is not held accountable for any incidents that may occur as a result of space operator actions. By law, the JSpOC cannot be held responsible for any issues resulting from the use of SSA information (User Agreement, n.d.). Additionally, once a conjunction assessment warning is received, there is no guidance that obligates the space operator to take evasive actions. Any actions by the space operator are voluntary. These issues could make it very difficult to resolve an incident where one or more spacecraft have the ability to maneuver, but chose not to do so. As a result of this analysis, this objective, A2 in Table 5, receives a 10 due to the issues would likely prevent the achievement of the objective. This objective is rated the highest of all, which is also displayed in Figure 4. It can be recognized by its prominent spike at the A2 line. Unfortunately, this also means, it will require much work to resolve the issues.

It would be beneficial to all space operators if the GSTC integrated the ability to direct spacecraft into agreements to properly deal with events that reach a predefined threshold that could result in catastrophic effects. The GSTC would construct agreements that would enhance its ability to provide direction to space operators without eroding the space operators' freedom of space access. Agreements could be worded in such a way to guarantee space operators' freedom during non-crisis and only be subject to direction when an imminent emergency is predicted. In this situation, GSTC orders would become priority and failure to follow through with GSTC orders could result in possible fault judgement against the space operator in accordance with international space law. Obviously, convincing government space operators of the

importance of allowing the GSTC to have this authority would be difficult. However, as the space traffic safety problem becomes a more prominent issue, a concept such as this may become more acceptable.

V. Discussion

The space traffic environment is predicted to worsen even though many nations have adopted the IADC's recommendations intended to reduce mission-oriented debris. The most prominent space debris danger exists in LEO orbit (800-1000km), which is popular for remote sensing, Earth observation and communication satellites. Studies have concluded that LEO has reached a critical state in which orbital debris will be self-generating due to the amount of debris that currently exists and the cascading effect of predicted catastrophic collisions. Some studies recommended more aggressive measures, such as active debris removal, will be required to remove large debris and stabilize LEO. However, other studies reveal that remediation is not a viable option at this point in time due to the associated deployment costs of the different techniques and the lack of urgency by the international space community. The problem with both approaches is that the best that could be expected from such operations is a stabilized LEO in which a debris threat to space operations still exists.

LEO is also the orbit where the majority of new space actors will be operating, adding to the space traffic. In particular, commercial space is continuing to solidify its role in space industry with companies like SpaceX and Orbital establishing footholds in the space launch arena; and companies like Virgin Galactic making progress in the space tourism market. Not only would their success increase the number of space launches, but the human presence in outer space would also increase. Considering the

growing threat of debris in LEO, protecting the human space population will have to be factored into any STC plan. Additionally, the advent of SmallSats could prompt a significant increase in satellite deployments by non-state entities resulting in additional space traffic. Since SmallSats are normally inexpensively designed, there could also be concern that these satellites may contribute to the space debris problem; or, in the wrong hands, could possibly be used to threaten other satellites.

The above issues support the continued requirement for STC measures, such as conjunction assessment and collision avoidance, as space debris mitigation and remediation processes will be not enough to ensure safe space operations. It is evident that many of the major space-faring nations currently perform STC processes or plan to in the near future. However, several organizations are attempting to improve the safety of their space operations by developing their own SSA. This development has been in response to the growing space traffic problem and a need by some organizations to move away from military processes. For example, consortium endeavors such as SDA, have come up with innovative ways of accessing, consolidating, and disseminating existing SSA information to space operators. ESA has plans to develop an SSA program in the future and provide SSA data to its members.

The U.S. possesses the most mature SSA sharing program that encompasses conjunction assessment and collision avoidance processes and offers its services to any satellite operator. The U.S. SSN is second to none and it contributes to a very accurate satellite catalog. The U.S. also provides a transparent SSA sharing program, via its online service, Space-Track.org, which provides basic to advanced SSA services to those willing to sign a SSA sharing agreement. This has resulted in the JSpOC

accumulating a large clientele that consists of foreign, domestic and commercial space operators.

JSpOC will also send conjunction assessment warning messages to the satellite owners so they may determine avoidance measures. Due to its robust SSA program, which by-the-way is free, the U.S. has become the de facto STC for much of the space-faring community. However, it was also evident the current STC structure is disparate with gaps in SSA, command and control and authorities processes that need to be improved to provide continued safe space operations.

The gap analysis performed for this study resulted in several areas within the current STC structure that require improvement when compared to the proposed GSTC. In general, the SSA findings were related to a lack of space surveillance capabilities to characterize objects in HEO and objects smaller than 5cm in LEO. Also, space operators require a more accurate process for predicting conjunctions. Recommendations were to increase the number of SSN sensors in the Southern Hemisphere to be able to detect HEO satellites through LEO transit; and increase the number of sensors capable of tracking objects smaller than 5cm in LEO to improve the capability to avoid small space debris. Additionally, an international special perturbations process, similar to JSpOC's process, should be developed to ensure a GSTC is able to conduct accurate conjunction predictions.

For the C2 requirement, findings were related to space operator SSA data accuracy and access concerns due to the U.S. military's control of the information. Additionally, the CSM and email coordination processes JSpOC used were not efficient

enough for emergency situations. The recommendation to improve C2 was to assign an intergovernmental or non-governmental organization as the GSTC to alleviate concerns with the U.S. military. This would also alleviate any liability concerns the military may have with regard to use of its information for avoidance maneuvers that resulted in mishap. Additionally, add a voice/data mass notification system as the primary means of providing conjunction alerts to ensure timely notification.

Lastly, issues with authorities dealt with the disparity of information being used by space operators, due to bilateral agreements that grant access to different levels of data. Also, agreements lack provisions to obligate space operators to execute collision avoidance recommendations within the current STC construct. The recommendations were to standardize agreements to grant the same services to all GSTC members to avoid miscalculations; and to integrate provisions into GSTC agreements that provide authorities to direct space operators during emergencies.

This study revealed that the need for a GSTC is evident mainly due to two reasons. One, the space traffic environment will likely deteriorate due to the predicted increase in the space debris population, especially in LEO. Debris mitigation efforts by current space operators have produced only minimal results in the reduction of orbital debris. Any aggressive mitigation efforts, as recommended by some experts, will only result in stabilizing LEO debris environment, but not remove the threat of orbital debris will remain. To add to the problem, new space entities currently carving out niche services in the space industry will pose significant safety challenges regarding protecting their material and human capital. In order to maintain safe space operations some sort of STC will be required.

Two, STC functions are currently being conducted by disparate organizations. Although the JSpOC is attempting to satisfy the role of a “global” STC, it is doing so by default due to its superior capabilities. Considering the SSA, C2 and authorities issues experienced by the current space control structure, it may be time for these responsibilities to shift to a non-governmental or inter-governmental entity. This will allow the JSpOC and other STC elements to focus on protecting their own assets; possibly even become provider-customers to the new GSTC. Additionally, a non-military affiliated GSTC could have less issues garnering support from currently non-participative space operators, such as Russia and China. With this added support and political-military issues aside, a GSTC could be more effective in ensuring safe space operations, than the current JSpOC pseudo-led STC.

There would be quite a few things to consider in establishing a GSTC that would need further research. For instance, research is needed to determine how SSA information from each of the current space control elements could be consolidated to provide one information source from which a GSTC could conduct operations. Further research is needed to determine whether an all new organization that represents the different elements of the current space traffic control construct or an existing one, such as ESA, could assume JSpOC’s role. Also, this study did not address funding issues, so more research would be required to assess the cost of another organization assuming the role of a GSTC taking into account that the goal would be to use current systems as a baseline.

Throughout the research for this study the requirement for a “global” or “international” STC was recognized by several studies, however, it is likely there won’t

be much urgency on creating one because of the aforementioned issues. This is unfortunate as a reflexive response to the space traffic problem will surely lead to further damage to Earth's orbits. This affects all space stakeholders world-wide; therefore an early, measured approach to a global solution, such as Global STC, by the international community is required.

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