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# ADVANCING AMERICA'S SPACE CHARACTERIZATION ECOSYSTEM

## An Organizational, Technological, and Data-Driven Approach to Addressing Tomorrow's Space Conflicts


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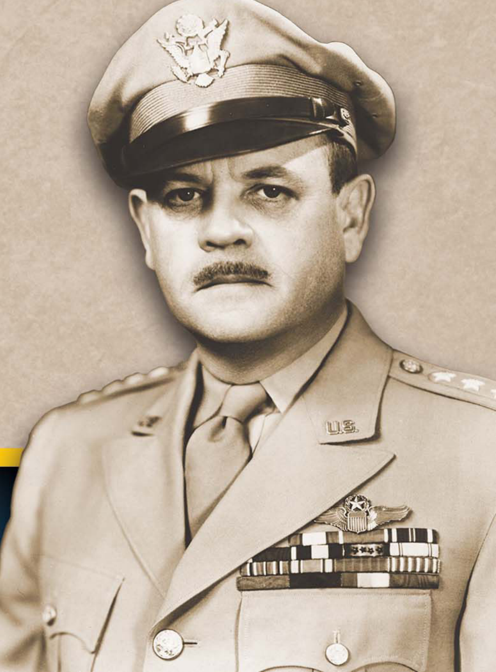

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# Advancing America's Space Characterization Ecosystem

## *An Organizational, Technological, and Data-Driven Approach to Addressing Tomorrow's Space Conflicts*

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## Abstract

This study aims to provide organizational and technological recommendations to the burgeoning problems associated with the congested and contested space domain. The authors contribute to the lexicon by offering a novel concept entitled the space characterization ecosystem to better define the nuances of relationships and responsibilities in the space domain while adding clarity to the global nature of the problem. The study also offers a space characterization ecosystem data architectural construct to address the complex data issues to provide leaders decision-ready information. Through a historical and contemporary analysis of the evolution of the space situational awareness and space domain awareness arenas, the authors establish the significant role that the new space characterization ecosystems plays in American space security interests now and in the future. This work contributes to the discussion with a broad investigation of relevant organizations in the military, commercial, and intelligence community sectors that capture historical context to provide various organizational and technical recommendations to the space community. Space scholars, enthusiasts, operators, engineers, and leaders may find motivation to address the problem of gaining and maintaining freedom of action and freedom of maneuver in a highly contested and competitive space threat environment. It is the wish of the authors to establish a twenty-first century space characterization ecosystem primer for future generations to assume the leading role in an unending race towards American and allied space security.

## Acknowledgements

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# Introduction

*Space is something that affects every American whether they know it or not.*

—Representative Mike Rogers, US Congress

## Background

The space domain is inspiring for those peering at the night sky. Yet, the wonderment and intrigue of space are matched with an equal measure of vulnerability and uncertainty. The nations, and presently commercial entities, that have begun to take advantage of space's vast benefits still face considerable problems. Despite American civil and military space endeavors' successes, the freedom of action and freedom of maneuverability in the domain are not guaranteed. At the foundation of space utility is awareness of the environment. The organizations, technology, and data required to act safely in the space environment are all intertwined and supported by what the authors label the Space Characterization Ecosystem. The complexity of the Space Characterization Ecosystem, and how the United States (US) should best utilize it to gain a competitive advantage in this environment, aligns with what the US Army Training and Doctrine Command Pamphlet 525-5-500 describes as an ill-structured, "wicked problem."[1] Wicked problems consist of professional disagreements with the problem structure, solution development, and execution of solution found through an iterative process.[2] The authors aspire to unpack the Space Characterization Ecosystem construct by assessing its historical, contemporary, and future implications to provide informed recommendations to space stakeholders.

## Hypothesis

Given the direction outlined in Space Policy Directive-3 and the 2021 national defense authorization act, the Department of Commerce (DOC) and Department of Defense (DOD) must pursue a new organizational structure and identify and implement novel technical approaches to what the authors describe as the Space Characterization Ecosystem to meet escalating mission requirements based on an evolving threat environment.

## General Definitions

Due to the complex nature of the space domain and the various operations conducted within, it is important to ensure the lexicon used in any analysis is well-defined. Before continuing into an in-depth analysis of the space domain and the organizations and tools tasked to monitor it, several terms require a definition to enable a common understanding. Joint Publication 3-14 defines the *space domain* as "the area above the altitude where atmospheric effects on airborne objects become negligible."[3] This definition is purposefully vague and does not draw a clear demarcation line between the space domain, the focus of this research, and the air domain. For this reason, the definition of the space domain used for the rest of this work, as defined by Joint Publication 3-14, is "the area surrounding the Earth at altitudes equal to, or greater than, 100km (54 nautical miles) above mean sea level."[4] This definition provides a precise boundary between the air and space domains at 100km and above. Furthermore, 100km is the altitude the US Space Command uses to establish the beginning of its area of responsibility as a geographical Combatant Command.[5] It is important to note that there is no end to the space domain according to the definition provided.

Any discussion of operations in the space domain requires an understanding of the two overarching terms, which sound similar but have different meanings. These two terms are Space Situational Awareness and Space Domain Awareness. The definition for *Space Situational Awareness* comes from Space Policy Directive-3 issued in 2018. Accordingly, Space Situational Awareness is defined as "the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities."[6] Joint Publication 3-14 also notes that Space Situational Awareness "is dependent on integrating space surveillance, collection, and processing."[7] Additionally, it is "fundamental to conducting space operations" because, without a sound understanding of what the space environment looks like or what activities are taking place, operations can be hazardous and difficult.[8] Space Situational Awareness provides the foundational knowledge of the location for all objects in near-Earth space. As seen in Figure 1, Space Situational Awareness is a critical function performed by the Space Characterization Ecosystem. It also enables Space Traffic Management and Space Domain Awareness functions, defined further in the following paragraphs.

It is best to view the Space Characterization Ecosystem by leveraging James F. Moore's concept of a "Business Ecosystem."[9] In his groundbreaking work, Moore defines the *business ecosystem* as "an economic community supported by a foundation of interacting organizations and individuals—the organisms of the business world. The economic community produces goods and services of value to customers, who are themselves members of the ecosystem."[10] As depicted in Figure 1, the Space Characterization Ecosystem can be viewed as a whole-of-nation network supported by certain key Space Situational Awareness stakeholders (Military, intelligence community, Interagency, Commercial, Civil, and Academia) aimed at collecting, distributing, and analyzing data to understand the space domain better. To borrow from the biology field, the more mutualistic the stakeholders, or organisms, are within the Space Characterization Ecosystem, the better the US can support all national space interests.[11] Mutualistic organisms are a specific variation of symbiotic relationships in an ecosystem. Mutualism seeks the benefit of each organism as opposed to commensalism where one species benefits and the other species is unaffected and is further removed from a parasitism relationship where one organism benefits at the expense of the other.[12] An American and Allied ecosystem that maximizes mutualistic gains and minimizes parasitic tendencies will promote the healthiest ecosystem to thwart predatory, adversarial, competitors.

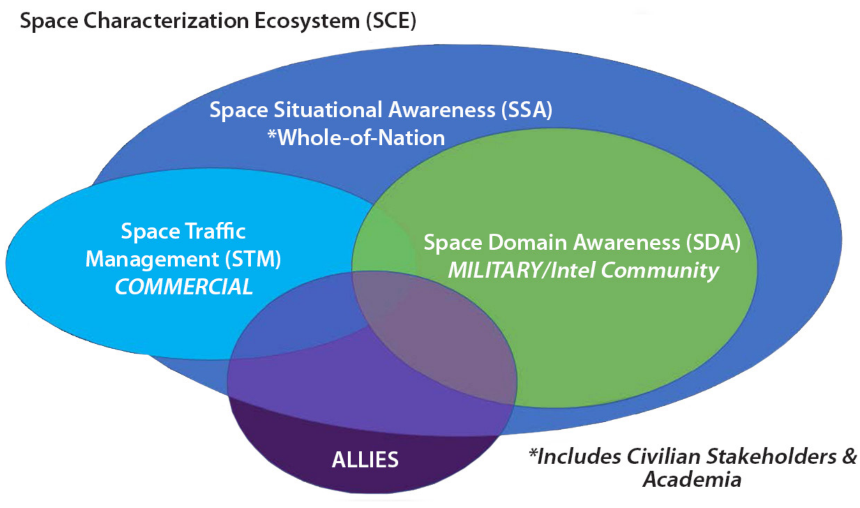


**Figure 1. Space Characterization Ecosystem Venn Diagram**

The Space Capstone Publication released by the Chief of Space Operations in June 2020 contains the first comprehensive Space Domain Awareness definition. The Space Capstone Publication defines *Space Domain Awareness* as "the effective identification, characterization, and understanding of any factor associated with the space domain that could affect space operations and thereby [impact] the security, safety, economy, or environment of our Nation."[13] Space Domain Awareness data is aggregated from intelligence, surveillance, reconnaissance, environmental monitoring, and other data sharing agreements to "provide operators and decision-makers with a timely depiction of all factors and actors—including friendly, adversary, and third party—impacting domain operations."[14] It is predictive, ideally intended to assess the probable future activities of objects in space.[15] Space Domain Awareness is the next step beyond Space Situational Awareness because it not only includes which objects are in the space domain—Space Situational Awareness—but what those objects are, where they are going, and what they are likely to do. As noted in the Space Capstone Publication, "complete Space Domain Awareness also includes mission-related details such as missions, intentions, system capabilities, patterns-of-life, and the status of consumables and expendables."[16] Space Domain Awareness is inherently a state's military and intelligence community's responsibility; therefore, this research confines Space Domain Awareness to those sectors.

The definition for Space Traffic Management also comes from Space Policy Directive-3. *Space Traffic Management* is defined as "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment."[17] The DOC is the organization designated to fulfill this function for the US per the Space Policy Directive-3. As is the case for all other space operations, Space Traffic Management is enabled by having a complete picture of Space Situational Awareness.

As each sector uses a different phrase, the authors needed a new term to describe the organizations, assets, and associated data that enable Space Situational Awareness, Space Domain Awareness, and Space Traffic Management and coined the term: *Space Characterization Ecosystem*. The Space Characterization Ecosystem, in essence, encompasses the organizations and assets that when combined form a holistic picture of the entire domain, enabling freedom of access and maneuverability within the space domain for the nation. For example, it is pertinent to understand that commercial providers within the Space Characterization Ecosystem collect and supply data supporting each of the following mission areas: Space Situational Awareness, Space Domain Awareness, and Space Traffic Management. Additionally, assuming a free market economy, commercial providers may sell the data they capture to many interested consumers, including other state governments. The terms covered in this section and their associated definitions are the basis for understanding the discussion and analysis that follow. Additional terms are introduced and defined in specific chapters or sections as required.

## Methodology and Analytical Criteria

This research aims to canvass the national organizations and associated architecture providing the previously defined Space Situational Awareness, Space Domain Awareness, and Space Traffic Management missions. The research team conducted interviews with the US DOD organizations currently conducting the nation's Space Domain Awareness mission. These organizations include the 1st Space Operations Squadron and the National Space Defense Center (NSDC) at Schriever Space Force Base, the 18th Space Control Squadron at Vandenbeurg Space Force Base, and the 20th Space Control Squadron at Eglin Air Force Base. The research team also conducted interviews with the DOC, to which the Space Traffic Management mission is assigned. The commercial company COMSPOC Corporation, a developer and provider of software solutions for spaceflight safety, also answered numerous questions about the commercial sector's thoughts and aspirations regarding Space Situational Awareness and Space Domain Awareness in the US. These interviews led to specific areas of common interests or concern. The authors used these common areas as the basis of research for this analysis. At a high-level, the themes common among all parties led to binning the research into two categories: organizations and technology. Each of these categories is explored in more detail in the following chapters. The authors make recommendations on areas the US Space Force (USSF), DOD, and DOC need to focus on in the coming years to sustain a secure operating environment and improve safety for all space operators as the environment becomes increasingly congested.

## Scope and Limitations

This work's scope is limited to providing the DOD and DOC recommendations based upon a whole-of-nation Space Characterization Ecosystem review. The recommendations provided focus solely on improvements needed in each of these two areas: organizations and technology. Additionally, from a national policy perspective, the research included only space policies and guidance from President Donald Trump's administration. As of this work's writing, it is unknown what policy changes are in store for the space domain under President Joe Biden. The organizational construct is current as of 1 March 2021. This work will focus primarily on US organizations and resources comprising the Space Characterization Ecosystem with little discussion of foreign and allied capabilities. To limit the breadth of this original scholarship, there is limited analysis of environmental threats, such as space weather, as it relates to the Space Characterization Ecosystem. The deliberate omission of these topics to appropriately scope this research are potential areas of study for future scholars.

## Roadmap

Chapter II provides the story of the Space Characterization Ecosystem, from the origin of the Space Situational Awareness mission to some of the early organizations involved in conducting this mission. Additionally, this chapter covers the initial sensors repurposed from a ballistic missile warning task standpoint to others developed specifically to conduct the vital Space Situational Awareness mission. The historical perspective lays the foundation for the presentation of the current Space Characterization Ecosystem, including its organizational structure and architecture, as it is has evolved to its present state as of the first quarter of calendar year 2021. Chapter II closes with a glimpse of what the future of the Space Characterization Ecosystem may hold as the US seeks to posture itself and its allies to flourish in the space domain as the domain grows increasingly congested.

Chapter III proposes poignant solutions to technical space characterization challenges, organizational hurdles, and data translation issues plaguing the DOD and DOC. References address the ecosystem's diversity of stakeholders, intrinsic relationships, and primary drivers in the Space Characterization Ecosystem problem set through extensive technical research and interviews with respected members of the field. The authors provide data-driven recommendations designed for leveraging current and expected capabilities in the space domain, enabling the Space Characterization Ecosystem to remain predictive, efficient, and accessible to the US and its partners.

Chapter IV describes historical and contemporary case studies relevant to the "wicked problem" of the Space Characterization Ecosystem that eventually led the US and other spacefaring nations to the precarious nature of future space domain conflict scenarios.[18] It reinforces the recommendations that place American spacepower in a position of military and economic advantage, which fall in line with US national security interests. Additionally, Chapter IV provides academia with specific and broad recommendations for further research regarding the complex nature of the Space Characterization Environment.

**Notes**

1. US Army TRADOC Pamphlet 525-5-500, Commander's Appreciation and Campaign Design, Version 1.0, 28 Jan 2008, 9.

2. US Army TRADOC Pamphlet 525-5-500.

3. Joint Chiefs of Staff, “Joint Publication 3-14: Space Operations,” 10 April 2018, Incorporating Change 1, 26 October 2020, vii.

4. Joint Chiefs of Staff, “Joint Publication 3-14: Space Operations,” vii.

5. Joint Chiefs of Staff, “Joint Publication 3-14: Space Operations,” vii.

6. Donald J. Trump, “Space Policy Directive-3, National Space Traffic Management Policy,” whitehouse.gov, 18 June 2018, https://trumpwhitehouse.archives.gov/.

7. Joint Chiefs of Staff, “Joint Publication 3-14: Space Operations,” ix.

8. Joint Chiefs of Staff, “Joint Publication 3-14,” II-1.

9. James F. Moore, *The Death of Competition: Leadership & Strategy in the Age of Business Ecosystems* (New York: Harper Business, 1996).

10. Moore, *The Death of Competition*.

11. Adam Augustyn, “Symbiosis,” Encyclopedia Britannica, 14 February 2020, https://www.britannica.com/.

12. Augustyn, “Symbiosis.”

13. “Space Capstone Publication: Doctrine for Space Forces,” (United States Space Force, June 2020), 38.

14. “Space Capstone Publication,” 38.

15. “Space Capstone Publication,” 38.

16. “Space Capstone Publication,” 39.

17. Trump, “Space Policy Directive,” 3.

18. US Army TRADOC Pamphlet 525-5-500, 9.

## The Space Characterization Ecosystem Story

*The first thing to do is make the invisible visible.*

—Jean-Luc Lefebvre, *Space Strategy*

### Chapter Overview

Chapter II establishes the past, present, and future of the Space Characterization Ecosystem, setting the stage for recommendations in both the organizational and technological areas. This chapter provides the story of the Space Characterization Ecosystem to help readers understand the problem the nation faces with increasing Resident Space Objects and their potential to limit or even prevent access to certain areas of the space domain. The chapter begins with a history of Space Situational Awareness to include the various assets used to conduct the mission, followed by the current Space Characterization Ecosystem organization and architecture, and finally, a look at the future of the Space Characterization Ecosystem.

### History - The Origins of Space Situational Awareness

The need to understand the operational environment of space is evident from the early days of human's venture into space. Initially, there were very few objects in the vast domain beyond Earth's atmosphere. Given that *Sputnik* and *Explorer 1* in the 1950s were separated by several hundred km in altitude, collision risk was negligible. This concept is analogous to the Big Sky Theory in aviation. The Big Sky Theory's "fundamental assertion is that the statistical odds of a midair collision between flying objects ought to be negligible since the sky is so big and airplanes are so relatively small."[1] Given that the space domain in cislunar space is significantly larger in volume than the airspace used in aviation, the Big Sky Theory is particularly applicable. Using the formula for finding the volume of a sphere, $\frac{4}{3}\pi r^3$, where r is the radius of the sphere, the significant difference in volume between the air domain and space domain is easily seen. The volume of the Earth, assuming it is a uniform sphere with a radius of 6,378 km, equates to approximately $1.09 \times 10^{12}$ $km^3$. Removing the Earth's volume from the air domain, ending at 100 km above the Earth's surface, results in a volume of $5.19 \times 10^{10}$ $km^3$. Performing the same exercise for the cislunar space domain, encompassing a distance out to the Moon of 384,400 km and removing the volume of the Earth and the air domain, results in a volume of $2.48 \times 10^{17}$ $km^3$. The volume of the cislunar space domain is therefore approximately 4.6 million times larger than the air domain, encompassing a vast area dwarfing the size of the terrestrial, air, and maritime domains. For perspective, over 227,500 Earths could fit into the volume comprising cislunar space. Additionally, space presents unique challenges not present in the air domain, specifically, speed and maneuverability.

Aircraft typically fly at speeds less than 2,000 kilometers per hour and can easily maneuver in three-dimensional space. On the other hand, satellites can move through space at many thousands of kilometers per hour relative to the Earth, with the minimum speed to maintain an orbit 240 kilometers above the Earth being over 27,000 km per hour.[2] Changing direction in space, while possible, requires significantly more energy than conducting a similar maneuver in the atmosphere. In space, there are not enough molecules for wings or ailerons to have any aerodynamic effect, so the force required to perform any maneuver quickly must come from onboard the satellite in the form of generated thrust. For these two reasons, the growing number of objects in Earth's orbit pose serious threats to each other. Coupling the speed and difficulties maneuvering in space with the lack of a central authority to monitor and control all satellites, analogous to the Federal Aviation Administration for the US air domain, creates an environment with a heightened risk of collision. The National Aeronautics and Space Administration (NASA) Orbital Debris Program Office keeps a record of the monthly number of objects in Earth orbit since the first artificial satellite launch in 1957.

The number of cataloged space objects greater than "10 centimeter[s] [in] diameter" continues to grow steadily, numbering over 20,000 objects in January 2019, as visually represented in Figure 2.[3] More recently, March 2021 catalog numbers rise to 22,650 tracked objects in orbit according to space-track.org, the US Space Command's Combined Force Space Component Command's public website.[4] The vast majority of artificial satellites orbit the planet in three orbital regimes, Low Earth Orbit, medium Earth orbit, and high Earth orbit. Low Earth Orbit encompasses altitudes of less than 2,000 km, medium Earth orbits comprise altitudes between 2,000 and 35,780 km, and high Earth orbits extend past 35,780 km in altitude.[5] There is also a special class of orbit within the high Earth orbit umbrella called the Geosynchronous Earth Orbit.[6] Satellites in Geosynchronous Earth Orbit have the unique characteristic of having the same orbital speed as the Earth's rotation. Therefore, the satellite remains over the same area of the Earth throughout its entire orbital period.

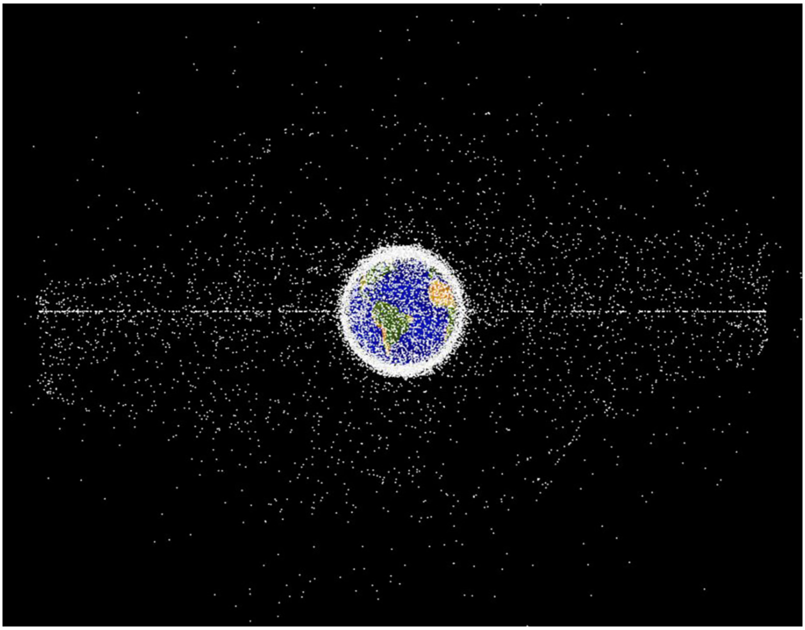

**Figure 2. A view of the current catalog of objects in Earth orbit as of 1 January 2019. (Adapted from NASA Orbital Debris Program Office.)**

Two additional orbit types require discussion to round out the various locations where satellites may be in cislunar space. Transfer orbits are a unique kind of orbit used to get satellites from one orbital altitude to another using a limited amount of satellite thrust. This method does not require the heavy launch vehicle to travel to the intended final destination. Rather, the launch vehicle drops off the satellite in one orbit, and through a burn or series of burns using the satellite's onboard capabilities, the satellite transitions to a different orbit.[7] During this process, as the satellite transitions through other orbital regimes, there are opportunities for collision. The final orbital regime is the Lunar Lagrange points. These Lagrange points are unique locations in a two-body system in which satellites can remain in a location nearly indefinitely.[8] If certain points are unstable, satellites located in those positions must be continuously monitored and controlled to keep them at desired areas. However, if the points are stable, a satellite can remain in one of these positions with minimal station keeping.[9] As these orbital regimes continue to fill with artificial satellites and any associated debris, the need to see or monitor activity in the space domain becomes readily evident.

The early years of artificial satellites led to the realization that space surveillance is a prerequisite to space operations. There were multiple entities brought together in the early 1960s to form an organization responsible for monitoring the space environment, later transitioning to be known as the Space Surveillance Network, the name given to the North American Aerospace Defense Command system in the late 1980s.[10] Upon realizing the necessity to have comprehensive Space Situational Awareness, three different elements were combined to provide a picture of the space environment. The three organizations included the Air Force's Spacetrack System, the Navy's Space Surveillance System, and the Canadian Forces Air Defense Command Satellite Tracking Unit. The Smithsonian Astrophysical Observatory provided additional data.[11] When all assets were combined, the complete network was called the Space Detection and Tracking System, operated by the North American Aerospace Defense Command in Colorado Springs, Colorado.[12] Therefore, the mission to acquire, operate, and maintain the Space Situational Awareness sensors became the duty of the DOD.[13]

Further Naval assets include the early Space Detection and Tracking System consisting of both optical and radar sensors providing data for tracking space objects. The sites capable of providing this data have expanded over the years since inception, even utilizing missile warning systems to provide the US DOD with necessary space domain information. The radar sites consisted of the "Cobra Dane located at Shemya Island, Alaska, the Milstone radar at Westford, Massachusetts, the AN/FPS-85 at Eglin Air Force Base, Florida, and the AN/FPS-79 at Pirinclik. . . Turkey."[14] The Cobra Dane was a radar system built primarily to support verification of arms limitation treaties with space surveillance being its secondary mission.[15] The Milstone radar was part of the complex owned by the Lincoln Laboratories at the Massachusetts Institute of Technology and is still a contributing sensor to space surveillance.[16] Similarly, the AN/FPS-85 phased array radar at Eglin Air Force Base was initially built in the 1960s to support the mission of submarine-launched ballistic missile warnings but transitioned to a dedicated space surveillance sensor in 1987.[17] The AN/FPS-79, built in 1964, also served a dual mission of tracking missiles and satellites but was decommissioned in 1997. Additional radar sensors, with a primary mission of ballistic missile tracking—such as the Ballistic Missile Early Warning System—also provided almost a quarter of observations for the early space surveillance mission.[18] The Ballistic Missile Early Warning System sensors were located at Thule Air Force Base, Greenland, Clear Air Force Station, Alaska, and Royal Air Force Station Fylingdales, United Kingdom.[19]

The Navy's Space Surveillance System was a fence designed to maintain continuous observation of space objects, reaching initial operational capability in 1961.[20] The fence used three transmit antennas and six receive antennas located along the US 33rd parallel to send a continual energy beam extending 24,000 km into space. When a satellite passed through the beam, it reflected energy and provided an accurate satellite position if the energy was received at two receive antennas. Control of the fence transitioned to the US Air Force (USAF) in 2004.[21] However, the USAF decommissioned this iteration of the space fence in the mid-2010s to be replaced by a newer, more capable version within the decade. Several other radar systems supported the Space Surveillance Network throughout its relatively young history, as covered in the following paragraph.

The Perimeter Acquisition Vehicle Entry Phased Array Warning System consists of two phased array antenna sites: one at Cape Cod Air Force Station, Massachusetts, and the other at Beale Air Force Base, California. The system's primary mission is missile warning but supports satellite tracking as a secondary mission.[22] Similarly, the Perimeter Acquisition Radar Attack Characterization System (PARCS) located at Cavalier Air Force Station, North Dakota, primarily provides missile warning data. Following its operational inception in 1977, the PARCS now supports both missile warning and space surveillance missions.[23] The Ascension radar is another primary radar used for the test and evaluation of ballistic missiles and space launch vehicles. When not conducting those missions, the radar supports the space surveillance mission.[24] The Kaena Point radar, which was located on the island of Oahu, Hawaii, started operations in 1978 and began supporting the Space Surveillance Network in 1986. However, the radar stopped supporting the space surveillance mission in 2006.[25]

The final radar system, Kiernan Reentry Measurements Site, consists of the Advanced Research Projects Agency Long-Range Tracking and Identification Radar, Target Resolution and Discrimination Experiment, Advanced Research Projects Agency-Lincoln C-band Observables Radar, and the Millimeter-Wave radar systems located on Kwajalein Atoll at the Reagan Test Site.[26] The Advanced Research Projects Agency Long-Range Tracking and Identification Radar's primary mission is supporting the test and evaluation of ballistic missiles and space launch vehicles but provides data for the space surveillance mission when not conducting its primary mission.[27] The Advanced Research Projects Agency-Lincoln C-band Observables Radar, the "first high-power, wide-band radar," and the Millimeter-Wave radar support the Space Object Identification mission by supplying radar imagery sets for analysis by the National Air and Space Intelligence Center to "improve US understanding of foreign satellite capabilities and to assess their health and status."[28] The Target Resolution and Discrimination Experiment became a contributing sensor to the Space Surveillance Network in 1998 and now "share[s] common algorithms for extended range processing" with the Advanced Research Projects Agency Long-Range Tracking and Identification Radar system to track new foreign launches.[29] Today, the number of radar systems supplying space surveillance data is numerous, but most sensors have primary missions other than Space Situational Awareness.

The second type of sensor supporting the space surveillance mission are the optical sensors. In the early days of space surveillance, the optical sensors providing Space Situational Awareness comprised of a system of Baker-Nunn telescopic cameras that could track an object the size of a basketball at 40,000 km.[30] These cameras were found at Sand Island in the Pacific; Jupiter, Florida; Harestua, Norway; Santiago, Chile; Mt. John, New Zealand; San Vito, Italy; Pulmosan, South Korea; St. Margarets, New Brunswick and Cold Lake, Alberta, Canada; and Edwards Air Force Base, California. While all ten sites were not in operation simultaneously, the cameras started operating at these locations between 1960 and 1977.[31] In the late 1980s, the Space Surveillance Network began an upgrade to a newer system: the Ground-based Electro-Optical Deep Space System, with sensors in Socorro, New Mexico; Choe Jong San, South Korea; and Maui, Hawaii starting operations in 1983.[32] The Ground-based Electro-Optical Deep Space System added a telescope in Diego Garcia in 1987, then later closed the South Korean site in 1993.[33] These optical sensors can track objects the size of basketballs in Geosynchronous Earth Orbit.[34] A more recent addition to the optical sensors of the Space Surveillance Network is the Moron Optical Space Surveillance system, added at Moron Air Base, Spain in 1998, to provide coverage of a critical area of the Geosynchronous Earth Orbit belt.[35] Additionally, all of the Space Surveillance Network optical sensors' primary mission is space surveillance, unlike their radar counterparts.

Although the Space Surveillance Network (SSN) performs a mission-critical to enabling Space Situational Awareness, many network sensors were not built to perform that specific mission. Instead, as Dr. T. S. Kelso notes, the sensors were "designed and built in the 1960s, 1970s, and 1980s . . . to track Soviet satellites and detect incoming ballistic missiles."[36] The SSN radar sensors were designed to detect objects 10 centimeters or bigger in Low Earth Orbit. The optical sensors were designed to identify objects one meter or larger in Geosynchronous Earth Orbit, a necessity to track Soviet satellites and potential incoming ballistic missiles.[37] However, tracking objects in orbit is only the first half of the Space Situational Awareness mission. The second half of the mission involved creating a catalog of the available data. To make the catalog, the SSN sensors sent the observation data they collected to the Space Defense Center inside Cheyenne Mountain, Colorado Springs, Colorado.[38] The Space Defense Center used the data to create catalogs of all the observable space objects, including operational satellites, defunct satellites, and trackable debris. These catalogs provided the ability to calculate close approaches, estimate where deorbiting debris may hit the Earth, and keep humans in space safe from possible satellite or debris impacts.[39] This information is a vital piece provided by the SSN for it assists in building a picture of the operating environment.

Throughout the short history of the SSN, there have been many sensors, including both optical and radar, used to provide observations for the conduct of Space Situational Awareness. These sensors were situated at numerous locations worldwide, some with a primary mission of space surveillance and others only supporting the SSN when not conducting their primary missions. These sensors, and the lessons learned by utilizing them throughout the years, provided valuable insight into the space domain's activities. The SSN's creation enabled many more satellites to safely orbit the Earth and cemented its need for the foreseeable future. These early sensors laid the groundwork for the current SSN architecture, covered in the following section.

## Current Space Characterization Architecture

The modern space environment is testing government, military, and commercial operators' capabilities to maintain situational awareness in the vast openness of the cislunar environment. With the exponential rate of satellite proliferation, deployment of mega-constellations which escalates the threat of space debris, and greater recognition of natural space hazards, challenges to even the most advanced and costly SSN systems arise daily. Still, the greater challenges to the Space Characterization Ecosystem are more nuanced than existing technological capabilities. For military purposes, it is impractical to retain a complete Space Domain Awareness sight picture all the time; instead, Space Domain Awareness must be produced deliberately for the right decision-maker at the right time.[40] Thus, the space characterization architecture for the US in the 21st century is mired in complex and often competing governmental priorities, burgeoning commercial partnerships, prioritization of space command and control functions, and a web of delicate bilateral agreements with international allies. It is not easy to find a way forward without addressing the existing state of affairs.

Currently, the US leads the world with the most advanced Space Situational Awareness capabilities and the highest level of Space Domain Awareness.[41] Success in this respect results from the US heavy investment in legacy and modern additions to the SSN architecture, missile warning and defenses development programs, and the steady growth of the domestic commercial space sector. SSN infrastructure is at the forefront of federal space expenditures considering the 10-year, $1.2 billion Maintenance of Space Situational Awareness Integrated Capabilities program intended to maintain the three primary Ground-Based Electro-Optical Deep Space Surveillance sites on the island of Diego Garcia in the Indian Ocean; at the White Sands Missile Range, New Mexico; and in Maui, Hawaii.[42] Furthermore, the C-band mechanical tracking radar located at US Naval Communication Station Holt, outside of Exmouth in Western Australia, is being joined in 2021 by the highly anticipated 3.5-meter Space Surveillance Telescope designed by the Defense Advanced Research Projects Agency, assisting and enhancing the S-Band phased array on Kwajalein Atoll.[43] Ballistic Missile Defense Systems, on the other hand, recently gained the Upgraded Early Warning Radars program, including the venerable Solid State Phased Array Radar Systems and PARCS.[44] Yet, upgrades to existing ground-based SSN sensor suites do not provide greater fidelity into deep space.[45] Moreover, missile warning and defense system designs, while proven and incredibly robust, come from an era with relatively few space objects and show their age considering the modern hardware and software requirements needed to conduct comprehensive Space Domain Awareness analysis.[46] Hence, the US supplements the ground-based telescopes and radars of SSN with multiple space-based optical sensors.

The US space-based SSN uses a meshed network of optical sensors to enhance Resident Space Object fidelity, without the disruption of terrestrial weather and atmospheric distortions that limit ground-based systems.[47] The major elements of the space-based satellite constellations are the Space-Based Space Surveillance (SBSS), Geosynchronous Space Situational Awareness Program (GSSAP), Operationally Responsive Space-5, Space Tracking and Surveillance System, and the Sapphire System from the Canadian Space Surveillance System. The SBSS project is the follow-on optical satellite to the Midcourse Space Experiment satellite, which was the first space-based sensor to contribute to the SSN and reached end-of-life in 2008.[48] While the Midcourse Space Experiment was originally designed to detect and track ballistic missiles during their midcourse flight phase, the SBSS satellite was established to provide enhanced space-based observation capabilities to the SSN. The SBSS satellite, located in Low Earth Orbit, uses a large, two-axis gimbled telescope to conduct surveillance, reconnaissance, intelligence, environmental monitoring, and data fusion and exploitation of multiple orbital regimes.[49] The 1st Space Operations Squadron, located at Schriever Space Force Base, Colorado, maintains Satellite Control Authority of the spacecraft, operating on a continuous cycle of operations.[50] Block 10 of the SBSS system has contributed more than 28 million observations of Resident Space Objects to the SSN since 2010.[51] Nevertheless, the SBSS satellite is resident to Low Earth Orbit limiting the effective range for the system to produce high-fidelity observations in deeper space. The exploitation of other orbits requires additional space-based assets in the SSN, giving rise to the GSSAP.

The GSSAP launched its first two satellites on 28 July 2014 to operate in near-geosynchronous orbit. The satellites' electro-optical sensors are designed for enhanced characterization of geostationary satellites.[52] Also managed by the 1st Space Operations Squadron, the four operational satellites maneuver above and below the Geostationary Orbit, gaining an unobstructed and distinct vantage point to produce timely and accurate observations of Resident Space Objects.[53] Additionally, the ability for GSSAP satellites to perform Rendezvous and Proximity Operations (RPO) on objects of interest to US Space Command is an essential national security and intelligence capability, providing close imaging, characterization and intelligence.[54] The GSSAP is unique in its ability to perform enhanced surveillance and anomaly resolution, but is expensive, large, and limited to exquisite tasking. US Strategic Command recognized this shortfall and authorized the Operationally Responsive Space Office, precursor organization to the Space Rapid Capabilities Office for the Air Force, to initiate a rapid acquisition of a new system in February 2014.[55]

The response to this identified shortfall is the Operationally Responsive Space-5 satellite. The Operationally Responsive Space-5 satellite provides more cost-efficient geosynchronous orbit observations compared to other space-based systems, demonstrates new sensor capabilities, and conducts autonomous operations using the Multi-Mission Space Operations Center ground system infrastructure.[56] Originally launched 26 August, 2017, Operationally Responsive Space-5 operates in Low Earth Orbit to scan outward to the Geosynchronous Earth Orbit, providing an essential perspective for the SSN.[57] Traditional satellite designs require larger optical sensor packages to gather the required detail, but Operationally Responsive Space-5 reduced the size of the detector utilizing an off-zenith imaging angle, permitting the target image to remain stationary for greater periods of time and increasing fidelity of distance objects.[58] Lieutenant General Stephen Whiting, Commander, Combined Force Space Component Command, highlighted the unique and essential nature of the Operationally Responsive Space-5 system stating, "The diverse viewing geometries enabled by sensors in different orbit regimes [GSSAP], combined with [Operationally Responsive Space-5] data, have greatly increased the reliability, responsiveness, and accuracy of the space catalog."[59] The modern space-based system's integration into the SSN architecture, in conjunction with supplementary systems such as the Missile Defense Agency's Space Tracking and Surveillance System and joint systems such as the Canadian Space Surveillance System Sapphire, produce a broad spectrum of orbital data. However, acquisitions and upgrades to existing ground-based and space-based systems, while effective, do little to overcome bureaucratic friction, data translation and distribution issues, and competing budgetary interests.

Leveraging commercial capabilities and signing more Space Situational Awareness data sharing agreements appear to be the only effectual directions the US is moving to enhance capabilities, while balancing limited financial resources.[60] Overall, the physical SSN, given its diverse access to characterization systems in both geography and ability, and the known satellite catalog, should enable an effective whole-of-nation approach to Space Situational Awareness, Space Domain Awareness, and Space Traffic Management.[61] The nature of the space domain is rapidly changing, and, in order to address the coming shortfalls, an evaluation of the current Space Domain Awareness paradigm is required.

The DOD is the military authority tasked with "coordinating and supervising all agencies and functions of the government directly related to national security and the U.S. Armed Forces."[62] The broad context of this mission statement as it pertains to the space domain should not be understated. Entities across the entire SSN architecture itself, including stakeholders with competing Space Situational Awareness and Space Domain Awareness priorities and functions, rely on the overarching DOD responsibility for the sustainment, operation, maintenance, and logistical support of the actual SSN assets. In effect, the DOD's national security and warfighting components must simultaneously track and maintain a catalog of an estimated 23,000 pieces of human-generated debris larger than 10 centimeters (four inches) in size, each of which could destroy an active satellite in a collision in addition to primary functions.[63] Moreover, personnel and SSN systems are also required to mitigate the additional risk posed by over 900,000 pieces of smaller orbital debris from causing devastating damage to existing satellites.[64] All ephemeris data for observed objects are screened for national security considerations and distributed to the public via the Space-Track.org website. This is an immense task for a bureaucracy that was never designed to engage in such activities. The Navy does not track and report sharks, nor does the Army track and report lions. The Air Force certainly does not track and report all birds, even though they are still a common cause of aircraft mishaps.[65] Intent as to why the DOD continues to track and report all celestial bodies is culturally tied to the "how" addressed below.

Potential conjunctions during analysis must be transmitted to satellite operators to make risk assessments if avoidance maneuvers are required. The sheer size of the DOD bureaucracy places tension on the small group of responsible agents by dependent stakeholders, even without accounting for variations in ephemeris data of known space objects. While the current capabilities of SSN architecture may theoretically exceed the true quantity of observable and traceable space objects, the effect of organizational friction towards attaining absolute Space Situational Awareness or absolute Space Domain Awareness makes the conversion of extensive data into usable information more difficult. However, Space Domain Awareness' rift from prioritization between space warfare and catalog maintenance due to rigid bureaucratic cultures is relevant. Reviewing organizational structure helps illuminate this pattern.

The DOD recently progressed through a rapid regeneration and restructuring of military space organizations to address the space domain's national security threats. Reestablished on 29 August 2019 as a unified Combatant Command, the US Space Command's mission is to "conduct operations in, from, and to space to deter conflict, and if necessary, defeat aggression, deliver space combat power for the Joint/Combined force, and defend U.S. vital interests with allies and partners."[66] It is currently structured with two subordinate field organizations: a Combined Force Space Component Command at Vandenberg Air Force Base, California and a Joint Task Force Space Defense at Schriever Space Force Base, Colorado. The DOD uses these entities to further hone US capability to employ military spacepower, preserving "the prosperity and security the US derives from the space domain."[67] However, any significant restructuring for strategic advantage does not come without compromising, competing interests, and intraorganizational contests for influence and control. This dynamic is an accurate portrayal of the delegation and responsibility of the Space Domain Awareness functions among the service components.

The DOD separated military space into a two-headed dragon. The Combined Force Space Component Command effectively oversees over 70 Air Force, Army, and Navy space units focused on support to the terrestrial-based global warfighter, while the Joint Task Force Space Defense is a new joint task force organization that operates within the national security apparatus to conduct space superiority operations.[68] The Space Capstone Publication defines space superiority as the "relative degree of control in space of one force over another that would permit the conduct of its operations without prohibitive interference from the adversary while simultaneously denying their opponent freedom of action in the domain at a given time."[69] In practice, space superiority operations by Joint Task Force Space Defense are based on their ability to sustain maximum Space Domain Awareness for the longest amount of time possible, monitoring potential threats, and actively defending satellites from attack. The Combined Force Space Component Command depends on Space Domain Awareness to enable lethality for other forces, whereas Joint Task Force Space Defense fights using Space Domain Awareness. Fostering accurate levels of Space Domain Awareness between the two subordinate commands is an internal, bureaucratic challenge in an already internationally competitive space domain.

Before reestablishing the US Space Command, the DOD restructured the Joint Functional Component Commander for Space and Global Strike in May 2005, embedding a single entity with authority over joint space assets creating the Joint Space Operations Center.[70] This move attempted to streamline communication between globally networked joint agencies. Originally located at Vandenburg Air Force Base, California, the initial iteration of the Joint Space Operations Center underperformed in its mission to "coordinate allies, and commercial and civil partners for defensive space efforts," forcing a secondary change in 2018 to the Combined Space Operations Center (CSpOC) by direction from US Strategic Command to improve mission execution.[71] Transforming the Joint Space Operations Center into the CSpOC separated Space Domain Awareness from providing space capabilities and preempted the greater organizational shift to US Space Command.

In addition to the organizational shift, the CSpOC's newly published mission to "[e]xecute operational command and control of space forces to achieve theater and global objectives" requires an even greater degree of interagency coordination.[72] Reporting to the Combined Force Space Component Command, the CSpOC "operates 24 hours a day, seven days a week; continuously coordinating, planning, integrating, synchronizing and executing space operations; providing tailored space effects on demand to support combatant commanders and accomplishing national security objectives."[73] Moreover, the CSpOC is the lead organizational node to provide a "multi-layered network of defense operations centers" in support of the Combined Force Space Component Command and the US Space Command operations, integrating the Joint Overhead Persistent Infrared Planning Center (JOPC), the Missile Warning Center, and the Joint Navigation Warfare Center (JNWC).[74] Additionally, the CSpOC works closely with the NSDC and the National Reconnaissance Office Operations Center, and hosts the Commercial Integration Cell, comprised of varying commercial partners, and Space Delta 5, USSF's Command and Control organization.[75] Each member of the CSpOC integrates their respective mission sets and capabilities for interagency and coalition partners, further expanding the vast network of space-centric agencies in the DOD.

Each joint center is dependent on data integration and space network support differently, subject to the nature of their customer base.

The JOPC is the joint component integrating the National Geospatial-Intelligence Agency into the CSpOC. Located on Buckley Space Force Base, Colorado, the primary mission of the JOPC is to "conduct integrated mission management to optimize the Joint Overhead Persistent Infrared Enterprise for national level decision-makers, warfighters, and the Intelligence Community."[76] The JOPC coordinates Joint Overhead Persistent Infrared operations and serves as the focal point for 24/7 Joint Overhead Persistent Infrared tailored support to their customer base, e.g., enterprise authorities across the DOD, the intelligence community, and Combatant Commands. Additionally, the JOPC coordinates with partner coalition centers, including the Australian Space Operations Center, Canadian Space Operations Center, and the United Kingdom Space Operations Center.[77] Management and coordination of their resident satellite constellations are at the forefront of their mission effectiveness, especially for Joint Overhead Persistent Infrared collection of high-interest assets across multiple Combatant Commands, requiring persistent and elevated levels of Space Domain Awareness. Culturally, the JOPC operates at the highest classification levels, prioritizes asset availability and sustainment, and is primarily concerned with reliable access for the terrestrial warfighter. The broader need for Space Domain Awareness is a subset of this mission, not a primary objective, relying on other organizational mechanisms to provide accurate, timely, and reliable information on space threats. Sustaining Joint Overhead Persistent Infrared functions' secrecy highlights the natural bureaucratic friction in coordination with allies, commercial and civil partners, and other agencies. In effect, minimizing adversarial Space Domain Awareness is an added benefit in providing clandestine support, thereby reducing transparency capacity. This dynamic results in public questions about the accuracy of the SSN's reported two-line element set data for JOPC disclosed satellites.[78] Whichever balance is required between transparency and secrecy for mission accomplishment, the JOPC has a vested national security interest in the distribution of sensitive data. However, other interagency components in the CSpOC may not require such levels of covertness in their integration and contribution to the Space Domain Awareness ecosystem.

The Missile Warning Center, located at Cheyenne Mountain Space Force Station, Colorado, supports decision-makers through a different joint operations center, providing global strategic and theater missile warnings and nuclear detonation detection capabilities 24/7. The enterprise customer base includes national, Combatant Command, and allied leadership levels, requiring sustainment of a vast network of legacy communication systems. Independent

Missile Warning Center sensors are incorporated in a worldwide $1.8 billion Integrated Threat Warning and Attack Assessment network (ITW/AA), combining information from both space-based and terrestrial systems.[79] The data is produced and disseminated to relevant nodes over the ITW/AA by the first sensor or associated ops floor that detects it, and the Missile Warning Center correlates, fuses, and assesses multiple reports within this complex layered network. Extensive and hardened, the ITW/AA can objectively pinpoint strategic nuclear threats with accuracy and persistence. However, ballistic nuclear delivery systems such as Intermediate-Range Ballistic Missiles and Intercontinental Ballistic Missiles exist in limited portions of space and are not necessarily Resident Space Objects.[80] Defending and deterring nuclear threats is paramount to the agency, allowing only supplemental usage of tracking assets to contribute to the SSN. Additionally, the necessary fidelity to conduct a comprehensive Space Domain Awareness assessment is limited due to the design nature of the missile warning systems. Proper Space Domain Awareness is an enabling element provided to the Missile Warning Center in CSpOC to conduct their mission with swiftness and clarity.

The JNWC specializes in Navigation Warfare to "enable positioning, navigation, and timing superiority for the [DOD], interagency and coalition partners."[81] Actions coordinated by the JNWC in space, cyberspace, and electronic warfare are vital to supply essential government, civil, commercial, and military warfighting capabilities to customers worldwide. For example, the Army is "highly dependent on the use of positioning, navigation, and timing data. The typical brigade combat team depends on over 28 different systems and 600 total systems that leverage positioning, navigation, and timing. The Army has over 250 thousand-dependent systems overall."[82] Furthermore, both the 2017 and 2019 US Department of Homeland Security "Report on Positioning, Navigation, and Timing Backup and Complementary Capabilities to the Global Positioning System" concluded that a sufficient disruption of the Global Positioning System (GPS) would cost the US economy $1 billion a day due to civil and commercial dependency.[83] Defensive and offensive measures taken by JNWC are impossible without sufficient levels of Space Domain Awareness. Warfighting in the space domain is dynamic by nature, requiring JNWC actions to be rapid and efficient, or network-wide fallout may occur. Significant organizational pressures to maintain and defend essential celestial lines of communication (CLOCs) are prevalent due to failure's dire consequences.[84] Any lack of dependable Space Domain Awareness within the CSpOC is debilitating to the JNWC, as the source of their space superiority over an adversary is resiliency to attack and in turn the ability to attack the source of an enemy's Space Domain Awareness. However, the CSpOC's joint functions intend to integrate DOD warfighting space enterprise components, not necessarily to improve sharing among the intelligence community components, who are increasingly dependent on Space Domain Awareness functions.

Formerly announced on the fifteenth anniversary of the 9/11 Attacks, the DOD established a Joint Interagency Combined Space Operations Center (JICSpOC) to work in conjunction with US Strategic Command, the US Space Command, and the intelligence community at Schriever Air Force Base in Colorado Springs, Colorado.[85] The JICSpOC's mission, similar to the CSpOC's (known as the Joint Space Operations Center at the time), was to facilitate information sharing across the DOD and Office of the Director of National Intelligence space enterprise, integrating previously autonomous organizations outside of the DOD enclave. While the JICSpOC was capable of providing backup support to the CSpOC, it was not considered a replacement and, as such, was purposefully given separation both physically and culturally. The JICSpOC was specifically designed for improving data fusion procedures and processes between the DOD, intelligence community, and commercial space entities, whereas the CSpOC's sole priority is DOD sub-organizations and allied partners. Considering the intelligence community organization's incredible breadth, including the National Reconnaissance Office and the National Geospatial-Intelligence Agency, the list of dependent and contributor stakeholders to the Space Domain Awareness organism formally expanded in complexity and density. However, even before the JICSpOC broke ground, informal relationships, memorandums of understanding, and formal agreements were tentatively established between the DOD and their intelligence community counterparts without a centralized joint structure constructed to sustain these relationships.[86] Relationships, especially informal in resource allocation and responsibility for both national and allied foreign partners, ultimately led to confusion among invested parties, adding to the bureaucratic web of capable assets producing ineffective information.

The US Strategic Command later determined in 2017 that the JICSpOC required a new name to reflect the organization's mission better, creating the NSDC.[87] This change helped reorient the new body and create more intent distinction between the NSDC and CSpOC. However, the renaming of the NSDC did not address the growing spread of authority and influence on the Space Domain Awareness ecosystem by the geographically separate organizations. Well-intended evolution in the space sensor architecture officially placed the NSDC and CSpOC into two parallel universes, individually mining information from shared data sources for their consumers. Despite the common fog and organizational friction these operation centers are tackling, the "wicked problems" of warfighter support (CSpOC) and the space protect and defend mission (NSDC) operate on a continuous basis.[88] The organizational changes do not stop at the operation center level; the USSF, as a whole, has decided to make widespread changes to their hierarchical structure.

Legacy military space organization and architecture was not designed for the rapid expansion of near-space and fell behind, leaving a vacuum following the establishment of US Space Command as a unified Combatant Command. Political inertia in Congress and cultural recognition within the Air Force space community led to the establishment of a sixth branch of service on 20 December 2019: the USSF.[89] Branch level concentration on space deterrence and counter threats within the USAF required additional authority to organize, train, and equip space resources as directed by Space Policy Directive-4.[90] The USSF accomplished this through a unique command structure that separates individual mission-oriented Delta components in an attempt to strategically align national objectives in space. Space Domain Awareness is the primary mission set assigned to Space Delta 2, activated on 24 July 2020 and headquartered out of the Peterson-Schriever Garrison at Peterson Space Force Base, Colorado.[91] Due to Delta 2's physical diversity in mission assets, personnel are distributed across Vandenberg Space Force Base, California; Eglin Air Force Base, Florida; Kirtland Air Force Base, New Mexico; Maui, Hawaii; Huntsville, Alabama; and Dahlgren, Virginia in addition to detached locations around the world including Australia, Diego Garcia, and the Marshall Islands.[92] Currently, this vast network of military functions is operationally controlled by the 18th Space Control Squadron, a globally impactful mission set for such a small team of experts.

The 18th Space Control Squadron is the tactical level unit under Delta 2 with operational control over the SSN itself, responsible for processing the raw data produced by the available network assets. This legacy Space Situational Awareness mission, now Space Domain Awareness, stems from the 18th Space Control Squadron heritage itself, previously the 1st Command and Control Squadron stationed at (then) Cheyenne Mountain Air Force Station in Colorado Springs, Colorado. The core functions of the 1st Command and Control Squadron, now the 18th Space Control Squadron, include physically maintaining the published catalog of known space objects, conducting space surveillance and updating tracking data received from the SSN, and "generating spaceflight safety data, and processing high-interest events such as launches, reentries, and breakups."[93] Public catalog maintenance consumes a significant portion of organizational bandwidth given today's current space environment containing roughly 17,000 on-orbit objects and approximately 6,000 on-orbit analyst objects (objects with insufficient fidelity for publication).[94] The 18th Space Control Squadron is effectively established as the US operational military component in the Space Characterization Ecosystem, finding and holding on to everything it can. However, the daily tasking needed to remain mission effective faces intense external pressures given an exponential propagation in space objects, a consistent threat of adversarial actions by foreign actors, and sheer volume of now dependent parties on orbital data analysis. Fortunately, limitations of the DOD's architecture were recognized by the National Space Council, prompting a dramatic shift in the future of the Space Characterization Ecosystem.

On 18 June 2018, President Donald Trump released Space Policy Directive-3, covering the new National Space Traffic Management Policy.[95] Advised through the National Space Council, Space Policy Directive-3 openly established the DOC as the future responsible government agency for administering and distributing the SSN data. Military space characterization and conjunction assessment was still considered essential to facilitate safe operations for private companies, at the time, but the intent for restructuring what the authors describe as the Space Characterization Ecosystem was federally mandated. Historically, it is no secret that the DOD prefers utilizing military assets of the SSN for employment of military spacepower. The DOD divesting responsibility for civilian data to a relevant federal agency better designed to communicate with the 70 state and commercial entities operating over 2,200 satellites is considered the optimal solution for all federal parties.[96] However, simply placing the entirety of the civilian Space Situational Awareness and Space Traffic Management responsibility outside of the DOD immediately highlights resource constraints and structural restrictions.

The DOC has a practical burden: it is small in manning and resources, with a broad area of responsibility. The DOC is one of the smallest cabinet-level departments, composed of 46,608 employees spread throughout all US states and territories, in addition to 86 countries.[97] Furthermore, the Office of Space Commerce, the department's principal unit for space commerce policy activities under the National Oceanographic and Atmospheric Administration (NOAA), has only three fulltime-equivalent employees, excluding the director.[98] While available manning can leverage up to 30 people from staffing personnel throughout the DOC, that contingent would be designated as part-time employees only, limiting capacity for human capital.[99] The Fiscal Year 2020 budget for the DOC was $15.2 billion, marked with a presidentially requested Fiscal Year 2021 drop of 48 percent due to the Decennial Census budgetary swell.[100] The Office of Space Commerce alone was allocated around $800,000 or 0.005 percent of the department's budget. Compared to the Federal Aviation Administration's Office of Commercial Space Transportation Fiscal Year 2018 budget of $22.5 million, retaining roughly 100 employees for licensing and approval of commercial space launches and reentries, the Office of Space Commerce is poorly funded for any form of expansion.[101] Even relative to their parent organization, the NOAA, the Office of Space Commerce's annual budget is only 0.018 percent of their overall allocation.[102] Ultimately, this budgetary crunch may be a byproduct of larger federal budget contests considering the DOC's Fiscal Year 2021 distributed budget of $12.2 billion is only 51 percent of NASA's, 20 percent of the Department of Homeland Security's, 14 percent of the Department of Transportation's, and a paltry 2 percent of the DOD's budgets, relatively speaking.[103] However, the explosive growth of space commerce has gained congressional recognition, as Dr. Brian Weeden warned the US House of Representatives Subcommittee on Space and Aeronautics on 11 February 2020, "Multiple commercial companies and governments have announced plans to develop and launch constellations ranging from 100 to more than 40,000 satellites each into Low Earth Orbit between 550 and 1300 kilometers (341 to 808 miles) in altitude."[104] Regulators simply can no longer ignore the mounting expanse of commercial satellite proliferation.

Given their current fiscal restrictions, the DOC has proposed restructuring using internal resources to fulfill its newly assigned Space Domain Awareness responsibilities under Space Policy Directive-3, establishing the novel Bureau of Space Commerce. The proposed legislation is structured to better address civilian space issues, incorporating a new civilian joint operations center and elevating the bureau's director to an assistant secretary, directly reporting to the Secretary of Commerce.[105] Additionally, the DOC is authorizing an additional $10 million for each Fiscal Year 2020 through 2024.[106] Restructure and consolidation of tertiary DOC offices in support of space commerce appears to be viable for the short term to create a favorable economic environment for commercial space activities in the US. Still, intraorganizational relationships, commercial memorandums of understanding, asset allocation and accountability, and data interpretation and distribution have yet to be finalized leaving more questions than answers. Alfred B. Anzaldua described the dilemma for the DOC under Space Policy Directive-3's direction briefly:

> The legislation proposed by the Commerce Department to create and fund the Bureau of Space Commerce is a major step in the right direction to consolidate executive space offices and facilitate commercial space activity in the US. However, other space offices are housed in Department of Transportation, the [NASA], the [Federal Communications Commission], and the Department of State. Therefore, even after the Bureau of Space Commerce comes into existence and receives adequate funding, further reorganization and coordination among executive space offices would be needed to adequately address the daunting national and international issues involved with fostering safe and

effective [Space Situational Awareness], orbital debris mitigation and removal, and [Space Traffic Management] worldwide.[107]

Bilateral relationships between DOD, commercial operators, civil organizations, and foreign partners continue to leverage past agreements to accommodate new challenges. However, the rate of satellite proliferation, aging infrastructure, diverse levels of investment and risk, and complex leadership paradigms place a measurable strain on the Space Characterization Ecosystem for all stakeholders. Organic transformation is required to create a safe, functional, secure, and mutualistic environment for the US and its allied partners.

## Future of Space Characterization and Commerce

The future of Space Situational Awareness and Space Domain Awareness is on the shoulders of the DOC and USSF, respectively. The next evolution of the Space Characterization Ecosystem must deliver a few key features for the US and its allies to flourish in the domain: safety and security through transparency. The safety and security of the domain enable the stability that the commercial sector needs to prosper.[108] Long-term investors require basic assurances that the investment of products and services they provide have protection, thus justifying their business venture's risk. Understanding the position of assets in the vastness of space is critical from a few different but linked perspectives: flight safety (collision avoidance), accountability, attribution, and threat protection. Real-time spatial location of adversarial and friendly assets in space provides information to enable decision-makers to avoid a collision, either intentional or accidental. Accountability of friendly, neutral, and enemy assets is significant as the space domain continues its congestion trend. Identifying possible threats, either adversarial or other environmental causes, is essential to attain space security objectives. Finally, preparation for conflict in the domain due to resource competition and territorial disputes requires a robust infrastructure to provide timely data to commercial or defense decision-makers.[109] This complex infrastructure is reliant on the Space Characterization Ecosystem organizational structure, technology, and data systems. Without the eyes and ears in and on space that Space Characterization Ecosystem provides, the considerable economic gains of space are uncertain.

Joshua Carlson's assertion that "Spacepower's decisive effects are through economic power" highlights the need to invest in an American-led and alliance-supported Space Characterization Ecosystem.[110] Expanding into and exploiting the moon's in-situ resources and gaining and maintaining CLOCs may provide tremendous economic potential and, in turn, a dominant strategic advantage.[111] John Klein, the author of *Understanding Space Strategy,* describes CLOCs as routes and locations that facilitate "the movement of trade, material, supplies, personnel, spacecraft, military effects, and electromagnetic transmissions."[112] The US status as the leading spacepower is at stake with the projected trillion-dollar space industry. Executing Klein's concept of "buying power" is at risk where the opportunity exists to "convert one form of national power into another; in this case economic capability into a military one."[113] Therefore, the authors believe it is time to shift from a brown-water, "high-ground," joint-warfighter strategy to a "blue-water," or Space Guard-like, organization enabled through a robust backbone of Space Domain Awareness.[114] The focus must be on gaining and maintaining CLOCs that enable economic growth.

Implementation of the CLOCs defense mission is not without a downside. Space actors may view American-led protection of strategic choke points as aggressive war posturing. American ambition to protect its space interests may clash with the interests of great power competitors and other spacefaring nations. These nations may be compelled to defend CLOCs thus creating a space security dilemma scenario preemptively.[115] The possibility of rising tension is great, but if the US can organize and develop technology in a transparent manner there is still hope for establishing a safe and secure space environment while minimizing escalation behaviors.

The goal is not to have complete and persistent domain awareness of infinite space but to have deliberate near-space (Low Earth Orbit to Geosynchronous Earth Orbit ) concentric coverage and fixed coverage of cislunar and translunar lanes that protect American and allied ability to access CLOCs and other celestial bodies of interest freely. Due to the vastness of space, Klein's view on persistent local command best aligns with the blue-water USSF analogy. In Klein's local command, the goal is to gain or exercise regional control of an area of interest.[116] Local command is best able to "protect economic interests, or gain a relative military advantage within a specific region of space."[117] Thus, using a local command structure to disrupt, degrade, or denyan adversary's capacity to use CLOCs is militarily efficient and economically viable.[118] It will be the military's accepted role and moral obligation to protect and defend these space assets, which are enabled via a robust Space Characterization Ecosystem. By serving this role, the domestic commercial market will have the best chance of success.

The commercial sector will flourish under American-led norms, behaviors, and values, which is advantageous for US national security. Using a maritime analogy is helpful to support this claim. For instance, Alfred Thayer Mahan offers that seapower exists through a powerful Naval force that sets the conditions for the sea's peaceful use for commercial purposes.[119] Without the security and stability of peaceful sea lanes, Mahan emphasizes that a state's commercial sector will never flourish or achieve its maximum extent possible. Application of the sea analogy to the space domain demonstrates that if the US does not control or contribute to the security and stability of celestial lines of communication , then another competitive nation or adversarial consortium will fill the void and set the terms of trade and commerce via their own "norms of behavior."[120] Commercial investors will acquiesce and support the first space actors to establish protection and stability for the vital CLOCs. Precedent in action and maneuver will be set by potential adversarial actors with customary law likely to follow.[121] Bottom-line, it is in the US best interests to lead a conglomerate of CLOCs guardians to dictate commercial market norms that best serve our economic and military objectives, which are underpinned by a robust and mutualistic Space Characterization Ecosystem capability.

## Space Characterization Ecosystem Story Conclusion

It is important to understand and appreciate the complexities of Space Situational Awareness's transformation into what is currently described as the Space Characterization Ecosystem. The current state of space characterization is a product of the needs and requirements of variable stakeholders in fluctuating organizational and technological environments. The transition from an organizationally dominated arena by military and government contractors has blossomed into a diverse ecosystem that includes civil, commercial, allied, and academic influence. Contextually, the environment from an economic and an adversarial threat perspective are significant contributors to framing the problem and shaping the solution. It is the opinion of the authors that the US must pay particular attention to the organizational and technical components of the space characterization problem to establish a path that best serves long-term national space interests instead of engaging in parasitic agendas that detract from the overall health of the Space Characterization Ecosystem.

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# Space Characterization Ecosystem Assessment and Recommendations

*To put it simply, we are trying to shine a light into the darkness of space.*

—Frank A. Rose, Former Assistant Secretary, Bureau of Arms Control, Verification and Compliance

## Chapter Overview

The following chapter provides an in-depth look into the organizational and technical components that are the primary drivers in the space characterization problem set. Based on extensive technical research and interviews with respected members of the field, the authors provide data-driven recommendations that aim to set the conditions for American space domain ascendancy now and into the future.

## Organizational Component

If the reader accepts the Clausewitzian axiom that "war is an instrument of policy," then the conduct of war is led by military commanders who must interpret a grand strategy developed by national civilian leadership.[1] Furthermore, accepting Barry Posen's claim that military strategy is a subcomponent of grand strategy is necessary to understand ties between democratically elected officials' decisions and their impact on the military instrument of power.[2] In the most general sense, US military strategy is the military means to achieve political ends.[3] The linkage between military strategy and policy is what Colin Gray describes as the "strategy bridge."[4] For space, at the center of the bridge is the ability to protect American vital space interests that provide the end users with critical capabilities. The ability to sustain and advance US space interests with assistance from allies and in a contested, degraded, operationally limited environment is why Space Domain Awareness must be a focus for the Space Force. Today, the USSF is responsible for providing service-level support towards space superiority efforts and providing warfighting capabilities to Combatant Commands, particularly, US Space Command. The USSF executes its charge through the standard service component requirements to organize, train, and equip, which are the essential ways and means to achieve space superiority ends.[5]

## Organize

Correctly shaping an agile fighting force to maximize military strength centers on organizing the appropriate construct to foster sufficient unity of command and clear authority lanes. The DOD and USSF are making great strides in these areas. The comprehensive organizational reform promoted by a bipartisan political effort in the 2019 National Defense Authorization Act set ambitious and expedient policy expectations. The establishment of the new geographical Combatant Command (US Space Command) and the USSF have shown signs that America's civilian leadership is serious about the space mission and is committed to and supportive of the organizational changes necessary to achieve US space priorities. For example, the USSF has eliminated two-levels of command structure typical of its Air Force heritage—the Numbered Air Force and the group command. The resulting flatter organization reduces superfluous administrative barriers indicative of overbearing corporate and bureaucratic structures. The new structure empowers the lower-level command echelons of the squadron and Delta to hold more authority and, in turn, more risk. The leaner structure also makes sense from a billet and bodies standpoint as the USSF military force structure of 16,000 at end strength, dictated by the National Defense Authorization Act, is almost 3% of the USAF end strength.[6] The comprehensive organizational reform shows that American leadership has an appetite for quick and impactful change.

Recent reform applies to the acquisition arm as well, where the Space Development Agency must pursue "Faster, Better, Cheaper" capabilities and systems to meet American space warfighting needs.[7] Other newly minted leadership positions and roles enumerated in the 2020 National Space Strategy further cement the DOD's determined nature to advance the American space agenda within a competitive strategic context. How the US organizes the growing Space Situational Awareness and Space Domain Awareness missions is paramount to the execution of national space objectives. Since the President Obama-era 2010 National Space Policy, the executive branch has used Space Policy Directives that carry the effect of law to publish and communicate actions and changes to America's space policy.[8] Under President Trump's administration, Space Policy Directive-3 placed the Space Situational Awareness mission onus on the DOC. The DOC must be ready to assume full Space Situational Awareness responsibilities by 2024. By law, the USSF is handing off the Space Situational Awareness mission to the DOC. The handoff specifically includes the safety of flight and satellite cataloging missions because the Space Policy Directive-3 intends to centralize Space Traffic Management and coordination within the DOC. As the lead for integration and collaboration of civil and commercial Space Traffic Management endeavors, the DOC unifies the US and allied Space Situational Awareness missions to support American prosperity. This unification frees the DOD to execute the defense-focused Space Domain Awareness mission of assessing and acting on allies and adversaries' intent to promote space security.

Unfortunately, the current Space Characterization Ecosystem is not sufficient to protect and support the proliferation of commercial and military satellites in space. The well-intended Space Policy Directive-3 and noble DOC efforts will allow for greater focus on the Space Situational Awareness problem set, but may not be the correct way forward. The American Space Characterization Ecosystem must ensure safety and security through transparency. There is merit in establishing the DOC's responsibilities of safety, focusing on commercial and civilian assets, and the DOD's responsibilities focusing on traditional military protect and defend missions. The DOC has the opportunity to be the central node for commercial strategic vision, data standardization, and system integration. The fresh-eyed focus will enable a whole-of-government strategic approach to matching capabilities (means), innovative procedures and processes (ways), to national goals (ends).[9] This strategy may set the conditions for more effective utilization of the space domain to further boost commercial endeavors. As safety and transparency become more commonplace in the domain, the American-led economic efforts will set the standards in "norms of behavior," translating to further military prowess in space and other domains.[10] Yet, the DOC seems to be an understaffed and underbudgeted organization and ultimately unprepared to fully execute this essential Space Situational Awareness mission in time.

The current Space Characterization Ecosystem's follies hinge on the DOC's limited budget and the institutional push-back customary with a significant reorganization. It is common for any organization to request more budget and, in turn, more personnel, but the DOC can genuinely call their budget insufficient.[11] The National Academy of Public Administration's 2020 report supports this claim. The limited financial backing inhibits the DOC's ability to stand on their own feet, which confuses who owns various commercial operations. For instance, the Federal Aviation Administration was previously a major governmental player in all commercial space activities. However, the Federal Aviation Administration's Office of Commercial Space Transportation is now solely focused on commercial space launch and reentry activities and all associated policies and regulations. Their charge, and number one priority, is to ensure public safety. On the other hand, the DOC Office of Space Commerce handles all other aspects of commercial space activities but prioritizes maximizing economic viability via whole-of-government integration. The distinction between the priorities of safety and profit are subtle but significant organizational shifts of focus, which deliberately inherits more risks for the sake of expedient growth. Unfortunately, the Office of Space Commerce is not fully operational, so through significant 18th Space Control Squadron efforts, the USSF must still provide the heavy lifting capabilities and resources until the DOC is sufficiently funded. The rushed and clunky hand-off has, and will, continue to inhibit the projected organizational and economic benefits expected from shifting the responsibility to the DOC. The necessary military involvement through a delayed hand-off also inhibits the DOC's maturation process. If the current paradigm is adequate enough, it will never mature into the fully capable organization initially envisioned. The delay may inculcate an undesired militaristic USSF culture and way of thinking into the DOC that may diminish the benefits of having a new and unbiased owner of the Space Traffic Management mission. The DOC's role may have unintended second-order effects like diluted or misunderstood command authorities.

Leaning on the definitions of Space Situational Awareness and Space Domain Awareness will help alleviate some of the confusion of authorities based on the division of mission. However, it will be incumbent on the DOC and DOD to ensure these lanes are understood inter and intra-organizationally as well as communicated to external stakeholders like Congress, the domestic commercial sector, and international partners. Thoughtful policy, strategic messaging, and identifying how each entity is organized and trained all have significant roles in understanding the new paradigm's authorities. Additionally, the DOD should retain Title 10 and G-series-level authorities and constructs. The Space Domain Awareness mission leader should remain the responsibility of the Delta 2 Commander, which will significantly elevate the position (potentially to a flag officer billet). Pushing more responsibility and risk to the Commander level is a must with this construct. This construct supports the Chief of Space Operations' vision of "mission command" and allows for proper identification of responsibilities.

The DOC must have complete authority over the commercial Space Situational Awareness and Space Traffic Management mission sets and work shoulder to shoulder with the Delta 2 Commander, including physical colocation of staff to encourage daily communication. The Space Characterization Ecosystem community must keep in mind Todd Greentree's statement that "traditional approaches to civil-military relations and resource management, institutional inertia, organizational friction, and divided authorities across multiple autonomous organizations hinder unity of effort and command."[12] If the DOD and DOC are able to strike the right balance of power in terms of organization and commands, and derive authority with the Space Characterization Ecosystem, then the US will set the conditions for generational space superiority.

**Recommended Way Forward**

By the US Government having several geographically separated, organizationally distinct ops centers serving their parochial institutions, the US will never fully realize its maximum domain awareness potential. Any hesitance to share information amongst defense or intelligence agencies, commercial partners, and international partners must be rejected to overcome great power competitors like China, which leverages militarycivil fusion techniques that completely integrate their military, civilian, and commercial sectors.[13] Prevalent and inherent institutional frictions must be squashed through decisive policy directives to overcome barriers.[14] A new national defense authorization act that directs unity of effort and unity of command in a centralized location and commensurate appropriations bills that sufficiently fund all aspects of the Space Characterization Ecosystem establish organizational success conditions. One potential construct would be to centralize control of the entire Space Characterization Ecosystem under the purview of the National Space Council. The National Space Council can ensure attainment of short and long-term visions while guiding whole-of-nation resources. Critics of this idea will cite the lack of solidarity of the National Space Council organization from one administration to another. The authors view the National Space Council's ownership of the Space Characterization Ecosystem mission as an opportunity to justify a permanent National Space Council presence given the critical nature of the Space Characterization Ecosystem mission. The National Space Council's explicit and tacit power derived from its cabinet-level sponsorship gives the Council the necessary influence in the space arena, which negates the need to create a new organization that would serve the same purpose but create redundant efforts. In addition to the elevated and centralized authority recommendation, centralizing all operations into the existing NSDC organization has many merits. For instance, feeding all Space Domain Awareness data to this hub in which all American and allied stakeholders can digest the data, attain a true sight picture, deconflict in real-time, and enact necessary strategic and tactical plans and operations takes advantage of existing or suggested constructs. One central location for defense operations and management allows for the unity of command when under the umbrella of a single organization. Under the purview of the National Space Council, the Space Situational Awareness and Space Traffic Management missions can be given to a senior civilian representative from within the DOC with appropriate civil authority while working alongside a senior member of the joint military force that leads the Space Domain Awareness mission. From a resiliency standpoint, the CSpOC and National Operations Center should be used as secondary and tertiary back-ups, respectively, in a warm or cold status.[15] The US and its allies have an opportunity to shape and influence the organizations, or organisms, that make up their Space Characterization Ecosystem to be as mutualistic as possible to have the best chance to counter the external predators. This organizational plan provides the unity of effort, unity of command, and clear lanes of authority required to more effectively protect and defend space assets at the national level undergirded by a centralized Space Characterization Ecosystem.

## Final Thoughts on Organization

As the authors write this work, President Biden's administration embarks on its first few months of policy directives through a complex global-pandemic context. President Biden's administration is departing from norms and does not intend to use Space Policy Directives to amend the National Space Policy guidance as President Trump's administration grew accustomed to doing. Reading between the lines may be ineffectual as this may be a political move to drive further distinction between the two administrations, but one could interpret other underlying motives. Perhaps the political policy tools elevate Space Policy Directives' strength that may rally stronger support than previously attained, or it may have the same amount of backing as any presidentially signed document. Regardless, the space community anticipates President Biden's administration stance on space security and space commerce and awaits clear signals of support through investment in Space Characterization Ecosystem organization, training, and equipment.

## Technical Components

The Joint Publication 1-0 notes that "the Services have a Title 10, [US Code], responsibility to organize, train, equip, and account for their personnel."[16] From a technical components perspective, this equates to acquiring the resources required to achieve a specific mission and ensuring that those operating the systems have the required training to use them effectively. For the Space Characterization Ecosystem, many technologies either perform the Space Situational Awareness or Space Domain Awareness missions or enable the sensors and operators to perform the mission more efficiently by reducing the number of unknowns attempting to locate and track objects in space. This section introduces the various domains where Space Characterization Ecosystem equipment is employed, to include the benefits and drawbacks of each and the different technologies used to perform the Space Situational Awareness or Space Domain Awareness mission. Additionally, this segment presents multiple existing or new technologies that enable more precise locations for friendly space assets, which, if used, could significantly reduce the burden on Space Characterization Ecosystem architecture. The authors' argument for this section is twofold.

First, a robust network of sensors must be acquired and maintained to provide the fidelity required to perform the Space Domain Awareness mission. Second, regardless of the Space Characterization Ecosystem hardware acquired to conduct the Space Domain Awareness mission, training and exercises must be planned and conducted routinely to prepare the operators to get the most out of the available Space Characterization Ecosystem resources. The Joint Task Force-Space Defense is currently spearheading this effort through its Sprint Advanced Concept Training series. This training series seeks "increased collaboration with sister component Combined Forces Space Component Command/CSpOC" to train to protect and defend the space domain.[17] The most recent exercise on 9 April 2021 included the Joint Task Force-Space Defense Commercial Operations Cell, which brings to bear numerous commercial sources of Space Situational Awareness and Space Domain Awareness information.[18] These exercises are a step in the right direction, but must continue expanding to include the entirety of the Space Characterization Ecosystem. Having an exquisite suite of sensors with a staff ill-prepared to use them is as unsatisfactory as having inadequate sensor capabilities limiting a highly trained staff's productivity. Both technology and training must be at the forefront of the Space Characterization Ecosystem to ensure the nation's best possible results.

## Orbit Determination

*Orbit Determination* is the process of determining a space object's motion relative to the Earth's center of mass.[19] Orbit Determination is a complicated process requiring inputs gathered from Space Characterization Ecosystem sensor observations and using the gathered data in equations to determine the satellite's current and future positions in space. However, "due to limitations in sensor capabilities, approximations in equations and models, and measurement errors, the true state of a Resident Space Object is rarely known."[20] This state of uncertainty is due to several factors. First, the physical constants and the mathematical representation of the forces used in the differential equations of motion to calculate a satellite's orbit are not precisely known.[21] Second, the observations made by each of the Space Characterization Ecosystem sensors inherently contains errors as no measuring device is exact. Combining all of these error sources and propagating the errors over time decreases the certainty of a satellite's location as the amount of time from the last good observation increases.

For this reason, the Strategic Directive (SD) 505-1 states, "for the most accurate orbit determination, observations should be taken at different positions on a satellite's orbital path . . . ideally, cover[ing] the full 360 degrees of an orbit."[22] As laid out in Chapter 2, the Space Characterization Ecosystem does not currently have the resources to cover all objects in orbit continuously. This limitation drives the need for efficient use of the limited Space Characterization Ecosystem resources and, if possible, augmentation by other means to reduce the burden on the already-restricted suite of Space Domain Awareness sensors. The Space Characterization Ecosystem uses the orbit determination data for satellite safety of flight to perform conjunction assessments. *Conjunction assessments* are the identification of a close approach between two or more objects in space. Conjunction assessments are a prerequisite for missions such as space launch, laser testing, orbital maneuvers, and day-to-day satellite operations to ensure satellites do not collide due to normal orbital decay.[23] After identifying a conjunction assessment, a Conjunction Assessments Risk Analysis is performed, which calculates the probability of collision. The probability of collision provides the "likelihood that the actual miss distance is less than what would cause physical contact (as described by the [hard-body radius]), given the uncertainty in the predicted object states (as described by the covariance)."[24] The final step in the process is collision avoidance. *Collision avoidance* is any step taken to mitigate a potential collision between two objects in space. It is significantly importance that the decision to perform collision avoidance rests solely with the owner or operator of a satellite.[25] Given two different operators or owners with two vastly different risk postures, the outcome of a close approach may very well be left to chance.

As discussed previously, errors in the end-to-end orbit determination process, from sensor-induced errors to mathematical uncertainties, drive the Space Characterization Ecosystem to achieve the most accurate observations possible. To achieve higher accuracy, "the whole Space Surveillance Network must be deliberately and routinely calibrated to achieve optimum performance."[26] This continual calibration ensures that the "quality of space object positional data meets operational performance requirements."[27] However, even with routine calibrations, the uncertainties involved in orbit determination lead to a covariance matrix which "characterizes the uncertainty in a satellite's state vector" with the state vector consisting of both position and velocity vectors.[28] This "uncertainty distribution is commonly referred to as the 'error ellipsoid' or 'uncertainty ellipsoid' for a three-dimensional state."[29] Figure 3 provides an example of a typical error ellipsoid, noting the in-track uncertainty is the largest, due to drag, with uncertainties in the cross-track and radial directions being less significant.

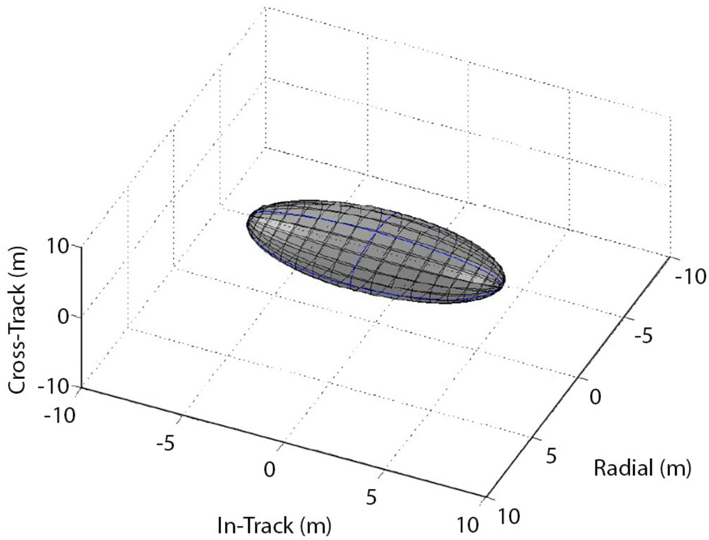


**Figure 3. An example of an error ellipsoid in three-dimensional space using the Radial, In-track, and Cross-track reference frame. (Reprinted from Jill Tombasco, "Orbit Estimation of Geosynchronous Objects Via Ground-Based and Space-Based Optical Tracking" (PhD. diss.), University of Colorado, 2011, 57.)**

As the amount of time increases from the last observation of an object, the error ellipsoid grows continually larger. If the amount of time between observations is on the order of several weeks, the "error can become so large that the space object becomes lost."[30] When it is projected that error ellipsoids of two or more satellites overlap, a collision is possible. However, because the satellite's exact location within the error ellipsoid is unknown, only a collision probability can be calculated. For this reason, reducing the error ellipsoid for all satellites also reduces the number of potential conjunctions. Reducing the number of potential conjunctions also reduces unnecessary maneuvers which diminish a satellite's life expectancy, to avoid a collision that likely would not have occurred in any case. Figure 4 illustrates a scenario where there is a high probability of collision due to the large error ellipsoids. If the yellow satellite is moving toward the right and the red satellite is moving toward the left, there is minimal risk of a collision given the satellite's actual location within the error ellipsoids. Because of all the unknowns, a worst-case scenario could lead to a satellite maneuvering into a position that increases the likelihood of a collision. For these reasons, the DOD, the US, and the international community must find ways to continually improve the ability to locate and track satellites persistently and more accurately.

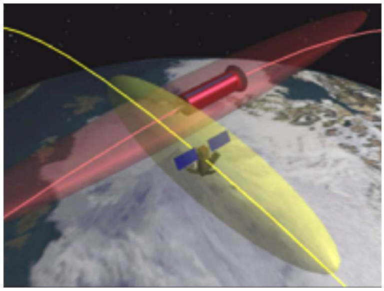

**Figure 4. Example of two error ellipsoids intersecting, triggering a high probability of collision. (Adapted from briefing, Office of Space Commerce Open Architecture Data Repository Industry Day, Image courtesy of the Aerospace Corporation, 23–24 November 2020.)**

## Space Characterization Ecosystem Sensors

The first, and most critical, pieces in the Space Characterization Ecosystem are the sensors. Without sensors painting a continually updated picture of the operational environment, operating in space is essentially like flying an airplane blindfolded. Things may go well for some time, but as the number of objects in the domain increases, so does the possibility of a collision. Any possibility greater than zero will eventually occur, given enough time. The sensors of the Space Characterization Ecosystem form its foundation and enable the Space Domain Awareness and Space Situational Awareness missions of the DOD and DOC, respectively. Because the types of sensors used for this mission set are agnostic to the agencies using them, they are discussed without delineation in the following paragraphs.

Optical sensors use visible light reflected off a Resident Space Object's numerous surfaces to locate objects in space and generate orbit determination data. These are passive sensors and require a source of illumination—in this case, the Sun. One drawback of optical sensors passiveness is the lack of range data available to the sensed Resident Space Object.[31] Because the optical sensors are sensitive to excessive light, the ground-based optical sensors, such as telescopes, cannot conduct their mission during daylight. This feature limits the optical sensors to collecting observations only during hours of darkness. However, even operating at night is not a given. For example, the observers at the Mount Lemmon Observatory in Arizona, conducting a Planetary Defense mission, only use the telescope approximately 24 nights a month, ceasing observations during a full or a near-full moon when the sky is too bright for successful observations.[32] Cloud cover or other inclement weather conditions such as fog or dust storms can also significantly hinder the sensors' ability to collect much needed observations. A study from 2014 indicated that the lack of cloud cover allowed collection from Socorro, NM over 50 percent of the time, just under 50 percent of the time for Maui, HI, and "less than 40 percent of the time" for the optical sensor at Diego Garcia.[33] Placing an optical sensor in space alleviates some of these limitations. However, on-orbit sensors still cannot point near the Sun or Moon to make observations due to the optical sensors' sensitivity to intense light. Inadvertently pointing an optical sensor at a bright object such as the Sun can temporarily or permanently disable an optical sensor. Baffles on the satellite can be used to block out some unwanted light, but an optical sensor intended for monitoring dim, reflective bodies is still unable to observe areas near the Sun or Moon. Additionally, there is still a requirement to be geometrically separated from the target satellite at an angle sufficient to gather an adequate amount of reflected light to enable orbit determination.

Optical sensors operate in one of two modes when performing Space Domain Awareness tasks. The first mode is the sidereal track mode. In this mode, the optical sensors stare at a night sky location with the stars fixed as the background and seen as points of light from the sensor's perspective. As satellites pass through the sensor's field of view, they generate a streak from light reflecting off the satellite's surface, as seen in Figure 5. After processing the streak, both endpoints are used to generate two observations with a minimum of three observations needed to compute an orbit.[34] In the second, rate-track mode shown in Figure 5, the optical sensor uses the predicted ephemeris of a Resident Space Object to slew the telescope and follow the object through the night sky. In this mode, the satellite appears as a point of light while the background stars appear as streaks. The rate-track mode requires prior knowledge of a satellite's expected orbit so that the sensor can maintain a fix on it. This mode is used to collect Space Object Identification data.[35] In general, Space Object Identification data is used to "determine satellite characteristics such as size, shape, motion, and orientation," and satellites' operational status and payloads.[36] As such, Space Object Identification data falls within the Space Domain Awareness realm. Because of these technological limitations, neither ground-based nor space-based optical sensors can provide all the details necessary for a comprehensive Space Characterization Environment alone.

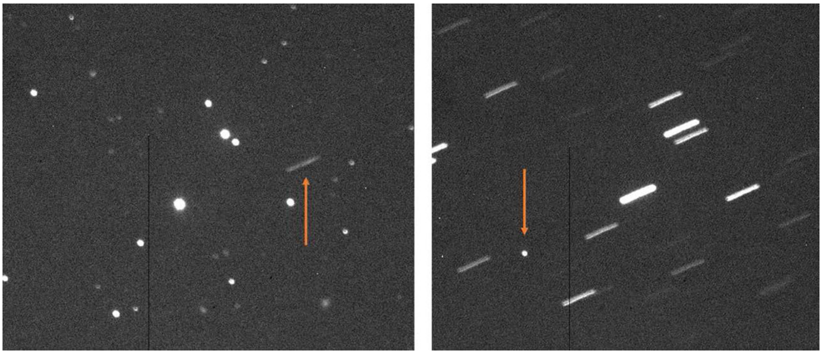

**Figure 5. A sidereal track example in the left image with the Resident Space Object identified as a streak with the stars as points and a rate-track example in the right image with the Resident Space Object identified as a point and the stars as streaks. (Reprinted from Michael Richmond, "Test of Non-sidereal Tracking on the Wiyn 0.9m Telescope,"13 November 2012, http://spiff.rit.edu/.)**

The radar sensors of the Space Characterization Ecosystem provide another active method to track Resident Space Objects. Radar sensors are "active" sensors because they transmit pulses of energy and then receive and process the energy reflected from Resident Space Objects to determine their orbits. Radar sensors have several advantages over their optical counterparts. First, radar sensors can conduct day and night operations, so there is never any downtime. Radar sensors are also able to perform their mission in all weather conditions. Because radars are active sensors, the range to a target can be calculated based on the time it takes the emitted energy to make it to the target and return to the sensor. However, as an active sensor required to transmit power to receive reflected energy, radar sensors' power requirements are significantly higher than optical sensors to track objects in the same locations in space. This significant power requirement limits Space Characterization Ecosystem radars' locations to areas with power infrastructures capable of handling this increased load.

Both optical and radar sensors can operate terrestrially or in space as Space Characterization Ecosystem sensors. There are several optical Space Characterization Ecosystem sensors currently in operation, such as the GSSAP and Operationally Responsive Space-5. There are no known Space Characterization Ecosystem radar systems on-orbit; however, "space-based radar capabilities exist for other purposes and in the future could be used" as part of the Space Characterization Ecosystem sensor suite.[37] As with their terrestrial brethren, optical sensors in orbit cannot point at, or near, extremely bright objects while conducting their mission due to the risk of damage to sensitive optical components.

Placing radars in space to perform a Space Situational Awareness or Space Domain Awareness role eliminates this restriction. It also reduces power requirements by locating the radar sensors hundreds or thousands of miles closer to their Resident Space Object targets, significantly reducing the amount of transmit power required to receive a useful return. Combining the observations from both terrestrial and space-based assets results in unique geometries by observing targets from different perspectives, resulting in higher accuracy covariance data. Using a diverse and dispersed sensor placement, both terrestrial and in space, provides the ability to overcome both the optical and radar sensors' limitations and deliver a more complete, near-real-time picture of the space environment.

With the Space Characterization Ecosystem radars able to operate continuously in all weather and lighting conditions, the sensors can act as a tipping mechanism for the rest of the Space Characterization Ecosystem sensors. When a radar notices an inconsistency in a Resident Space Object orbit or encounters a previously unknown Resident Space Object, it can tip other sensors to include the new Resident Space Object in their imaging queue to investigate the object further. Incorporating this tipping and queuing architecture among all sensors within the Space Characterization Ecosystem is paramount to enabling an orchestrated network. The tipping and queuing, while automated, should not occur out of view of operators. Notification to operators must occur immediately for any Resident Space Object exhibiting a new or uncommon behavior or any newly identified Resident Space Object. Constructing the Space Characterization Ecosystem in this manner enables the benefits of automation to combine with human operators' reasoning and decision-making abilities.

There are new sensor types, such as lasers, that may provide added fidelity; however, the narrow field of view requires precise knowledge of Resident Space Objects, limiting lasers to tracking well-known Resident Space Objects to reduce orbit uncertainties further. Additional sensors, such as radiofrequency and infrared, can be used to enhance Space Domain Awareness understanding.[38] Although none of these technologies currently reside in the Space Characterization Ecosystem architecture, their use and benefit should not be underestimated, particularly for the Space Domain Awareness mission. Monitoring the frequencies used during satellite operations and observing satellites' heat signatures at various orbit points helps understand its mission and potential future activities. The USSF must investigate the additional information provided by multiple phenomenology types to bolster its fledgling but critical Space Domain Awareness abilities. Finding the right mix of sensor types enables both the DOD and DOC to conduct their respective missions with added precision ultimately providing a safer space operating environment for commercial actors.

## Data, Information, and Location Aids

Regardless of the data source, the information gleaned from the data must be both useful and timely. The COMSPOC Corporation, a commercial provider of Space Situational Awareness information, exemplifies the need for timely and accurate data. For example, a Chinese SJ-17 satellite in Geosynchronous Earth Orbit orbit drifts West, performs a maneuver, then begins to drift East. The COMSPOC Corporation can estimate the commercial solution, the legacy SSN solution, and the actual location of the SJ-17.

The US government's SSN architecture's legacy solution fails to identify the maneuver for nearly two days. Applying the commercial sector filter to the same data yields an almost immediate indication that the SJ-17 maneuvered and is heading in a different direction. This disparity is significant. Assuming the SJ-17 maneuvered every day, the legacy system would likely never catch up to the satellite's actual location. The risk is abundantly clear for other satellites in the same region of space planning their own maneuvers. Based on the legacy architecture, it may appear there is no danger to perform a maneuver. However, using the same data interpreted through a commercial filter lens presents an entirely different perspective. Where it once appeared safe to maneuver, the SJ-17 now occupies a similar area in the Geosynchronous Earth Orbit belt as the satellite preparing to maneuver. While this is likely a rare occurrence, the magnitude of the associated risk is abundantly clear—a catastrophic collision between two or more satellites.

To attempt to minimize the risk of such a collision, the SSN uses both General Perturbation and Special Perturbation orbit propagation models to determine satellite location based on input data from the vast array of available sensors.[39] The General Perturbation is a low-fidelity model, and the Special Perturbation is a high-fidelity model providing a more accurate satellite location solution at the expense of additional computations, computational power, and time. The Special Perturbation data is maintained by the DOD and "is not widely available."[40] Making this higher fidelity data available to all users will diminish the likelihood of a catastrophic collision and enable more complex RPO for things such as on-orbit refueling.

The RPO behavior exhibited by the SJ-17 satellite further magnifies the importance of a clear space domain picture. RPOs require a precise understanding of the target satellite's location, regardless of whether it is a cooperative satellite or not. RPOs occur thousands, hundreds, or tens of meters from the target satellite and promptly require accurate orbit information. Updating the Space Characterization Ecosystem architecture with newly developed algorithms to process the significant amount of orbital data more precisely and timely is paramount. This example is not meant to indicate the COMSPOC Corporation solution is the correct one, merely that a trade study among the various commercial algorithms available must occur. If the study indicates a better solution than the current instantiation, the architecture must be updated accordingly; orbital safety depends on it. As Theodore Muelhaupt et al. notes, "the timelines of the current catalog process and automated maneuvers for a large constellation are fundamentally incompatible."[41] Constructing a Space Characterization Ecosystem architecture that is responsive to a rapidly changing space environment is paramount to the conduct of the Space Situational Awareness, Space Traffic Management, and Space Domain Awareness missions. Having a suite of sensors providing copious data yet processing it in a manner that does not produce fast or accurate results hinders the ability to execute the Space Traffic Management and Space Domain Awareness missions efficiently and effectively.

Objects in Earth orbit are continually changing location within their orbit because of orbital perturbations such as gravity, atmospheric drag, or any number of other challenging-to-model external forces. Resident Space Objects can also change orbit due to a planned or unplanned maneuver. Both scenarios require continually updated knowledge of the Resident Space Object to maintain an accurate picture of the orbital environment, maintain Resident Space Object safety, and enable RPO if desired. For example, there are two critical concepts for Space Domain Awareness. The first concept reveals the commercial sector's capabilities using unclassified algorithms to determine Resident Space Object locations. While a commercially derived Resident Space Object position could be projected within 190 meters on average, a current, publicly available solution averages over 5.5 km from the truth data—i.e., data known to be accurate. Although the commercial position situation may not regularly occur, as identified earlier, not pursuing a change to the Space Characterization Ecosystem presents a serious, increased risk of collision and unnecessary maneuvers.

The second concept highlights the importance and benefits of having orbit determination data provided by sensors onboard the satellite. Having well-known ephemeris data for a satellite provides a set of truth data to compare against other sensing and processing methods. Without truth data, a comparison of alternative methods of orbit determination may yield vastly different results. Additionally, having truth data for multiple satellites aids in fine-tuning the calibrations of Space Characterization Ecosystem sensors. Continually collecting on these known quantities allows identification and suppression or removal of any Space Characterization Ecosystem sensor errors and biases. Although an ideal solution would be a stand-alone GPS transponder on every satellite to supply near-real-time ephemeris data, there are many other methods to enhance the Space Characterization Ecosystem architecture via on-orbit location aids.[42]

All on-orbit location aids fall into either a passive or active category. The passive measures do not require any power from the host satellite and are low-weight options that minimalize the satellite's mass. Active on-orbit location aids rely on power, either self-supplied or obtained from the host satellite, to generate data and transmit it to the ground. Active on-orbit location aids are also larger in size and mass than their passive counterparts, which need to be accounted for early in a satellite's acquisition and design process. Both the active and passive on-orbit location aids are compatible with satellites ranging in size from the largest satellites down to the smallest CubeSats.[43]

There are several variants of passive on-orbit location aids. They consist of low-cost, low-weight radar and laser reflectors attached to the spacecraft body or high-albedo paints and tapes, increasing host satellites' visibility to the Space Characterization Ecosystem's sensors.[44] The radar or laser reflectors reflect radar energy or laser light back in the direction from which it was received.[45] Using a different number of reflectors on a satellite enables the ground system to differentiate between satellites.[46] Another type of passive tracking aid is high-albedo paint or tape, reflecting more light or radar energy than the untreated satellite surfaces making it easier to find and track.[47] Van Atta arrays are another type of passive device that, when interrogated by a radio frequency signal of the right wavelength, "radiates radio frequency energy back toward the source of that energy."[48] A drawback of the Van Atta arrays is that two satellites carrying the same array will return the same signature, making differentiating multiple satellites difficult.[49]

Actively emitting visible light, Light Emitting Diodes (LEDs) and diode lasers make it easier to find, identify, and track satellites. The LEDs or diode lasers are mounted externally on the host satellite and "blink in a prescribed sequence that uniquely identifies the satellite" when viewed by optical or specialized photon-counting Space Characterization Ecosystem sensors.[50] Another similar method involves colored LEDs placed in a distinctive pattern on a satellite's surfaces and then blinking in a unique pattern to identify a particular satellite.[51] These on-orbit tracking aids are simple, low-cost, and lightweight, making them an ideal addition to all satellites, especially micro-satellites in large constellations being launched and deployed simultaneously. These tracking aids help quickly distinguish one satellite from another and can be especially useful for large constellations of small satellites deployed from the same rocket. However, since these aids do not provide ephemeris-type data, their use is limited to making it easier for the Space Characterization Ecosystem to find, identify, and track satellites instead of increasing the covariance data's fidelity.

The first type of active on-orbit tracking aid uses a radio frequency interrogation receiver. Similar to the Van Atta array, when interrogated by a specific wavelength of radio frequency energy, it "responds with a short burst of information."[52] However, a drawback of the radio frequency interrogation receiver is that it requires a large ground antenna array "to interrogate the system and successfully acquire the low-power response."[53] As previously mentioned, the ideal orbit tracking solution is a GPS transponder attached to each Resident Space Object. This solution is ideal because it places no burden on the current Space Characterization Ecosystem sensors, freeing them to focus their efforts on non-cooperative Resident Space Objects—making numerous observations to reduce their covariances further. The only added requirement for the Space Characterization Ecosystem architecture is to have the capability to receive the data broadcast from these transponders. GPS transponders "provide the most complete data on a satellite's position."[54] Small, lightweight GPS transponders designed to last three to four decades, well beyond the average life of a satellite, and with both self-powered and host-powered modes could be used "as a supplemental (even primary) navigation unit for the host [satellite]."[55] The ability to stand alone, without the need for host satellite power or input data, allows the transponder to continue to function in a host satellite failure event. Some of the other tracking aids mentioned also share this ability. However, none provide the highly accurate ephemeris of a GPS transponder, making this aid more valuable to long-term Space Traffic Management. Additionally, GPS transponders have become "so small that their impact on size, weight, and power is negligible, while the additional benefit is significant."[56] Levying a requirement on all DOD, civilian, and commercial satellites to incorporate a GPS transponder enables the size, weight, and power trades to be conducted early in the design phase, minimizing the impact on the overall satellite design and maximizing the information available for the Space Characterization Ecosystem architecture to conduct its critical mission successfully.

Collecting data from the Space Characterization Ecosystem sensors and location aids is only the first action in a multi-step process needed to get useful information promptly to decision-makers. The data needs to be transported, analyzed for useful information, and stored for decision-makers access. To perform the data storage piece, the USSF and the DOC have two separate databases. The USSF uses the Universal Data Library (UDL), and the DOC is standing up an Open Architecture Data Repository. Both options provide a digital solution via cloud-based technology to host and access Space Domain Awareness or Space Situational Awareness data, respectively. These are intended to be central repositories of data and information to provide operations centers quick and easy access. For example, the UDL provides data to the CSpOC, NSDC, and National Operations Center with additional data provided by commercial and allied assets for the space protect and defend missions. Unfortunately, more data does not necessarily translate to a better characterized domain. The authors recommend that the USSF continue noteworthy UDL efforts and pursue complete integration of joint, intelligence community, and commercial capabilities into one central location. Figure 6 depicts a suggested Space Characterization Ecosystem data architecture that proposes to connect the DOC's Open Architecture Data Repository with the DOD's UDL to share and compare data. When there is a discrepancy between the two databases, indicating a satellite is found to be in two different locations or nonexistent in one database, stakeholders in both the DOD and DOC must be notified to resolve the issue. Additionally, agreements must be put in place to allow commercial, civil, allies, and academia access to the appropriate databases, depending on need. These users can provide valuable operator ephemeris data and have transparent access to the most accurate US Space Situational Awareness data to better enable the continued safety of flight. This is an area for further focus and study as there is work to be done to ensure a standardized data format as well as determining when new data is out-of-family with previous, similar inputs. However, with a proper, whole-of-nation approach in the context of an information-age conflict, the nation or alliance that has the fastest information flow to inform combat decisions in the space domain will maintain space superiority. Ideally, this architecture will evolve over time into a single, cloud-based database shared by all space operators.

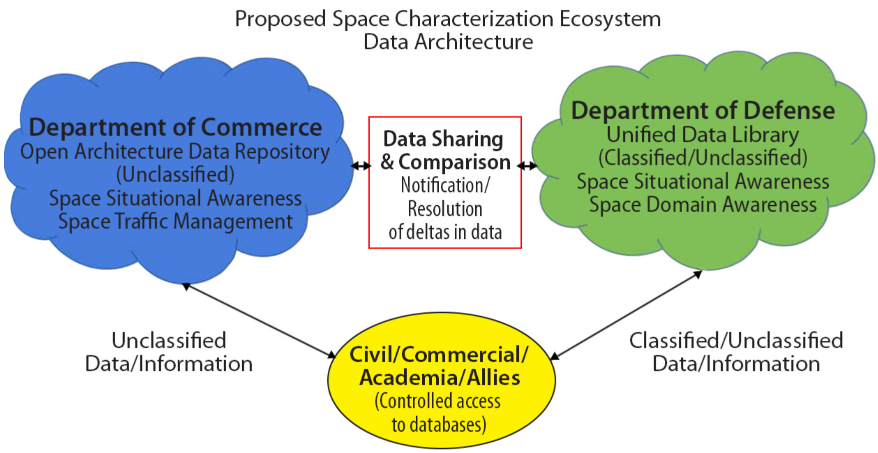


**Figure 6. Proposed Space Characterization Ecosystem data architecture**

## Recommended Way Forward

This section introduced many sensors that collect Space Characterization Ecosystem data and other devices that augment the Space Characterization Ecosystem with onboard sensors or passive measures to simplify the orbit determination and identification problems prevalent in the space domain. Gathering data from multiple sensor types and sensor locations supplies a clearer picture for Space Domain Awareness and Space Situational Awareness.[57] Additionally, creating a Space Characterization Ecosystem data architecture incorporating a whole-of-nation approach is imperative to continue safe access and operation in the space domain. What follows is a series of recommendations to pursue with further research and action.

The first recommendation is for the DOD and DOC to work together to develop, acquire, and maintain a suite of sensors beneficial to both organizations and their overlapping missions while continually looking for new technologies across the commercial sector to enhance the Space Characterization Ecosystem architecture. As part of this effort, the DOD and DOC must ensure the sensors currently employed, both terrestrially and in space, have a replenishment plan as they age or become obsolete. As sensors need replacement, the commercial sector should be leveraged to provide viable solutions. As technologies are proven, they should be incorporated into the Space Characterization Ecosystem architecture to reduce the cost of acquiring exquisite, government-owned sensors. The Space Characterization Ecosystem sensors must continue to be distributed worldwide and in space to supply a deterrent to adversaries wishing to destroy or degrade the US ability to see in space. Dispersing the many sensors limits the ability to blind only a single location or a handful of locations forcing a nefarious actor to take significantly more complex and costly actions to deny the US a view of the space domain.

A second related recommendation is that the US must continue to add allied and commercial Space Situational Awareness and Space Domain Awareness sensors into the Space Characterization Ecosystem to enhance sensor fidelity. Creating an integrated Space Characterization Ecosystem architecture with many partner nations and commercial suppliers provides a robust system with diverse perspectives. It promotes burden sharing among the participating nations and drives innovation within the commercial sector while also creating a greater deterrence to destruction by a great power competitor. This diverse Space Characterization Ecosystem will maximize the mutualistic gains for all organizations within the ecosystem, from cost reductions to greater security and more rapid innovation.

The third recommendation is to invest in a robust training program for sensor operators and continue to build on the Sprint Advanced Concept Training exercises currently planned and executed by the Joint Task Force-Space Defense. It does not matter how good the network of sensors performs if the sensors are not used by well-trained operators who are getting the correct data, transforming it into useful information, and transferring it to decision-makers at the speed of warfare. Along with this training regimen, the Space Characterization Ecosystem architecture must be fully automated and architected so that sensors tip-and-cue each other to collect data on Resident Space Objects that behave abnormally. The Space Characterization Ecosystem sensors must swiftly alert operators to Resident Space Object maneuvers or potential collision events while monitoring the offending Resident Space Objects to ensure adequate data is made available for transformation into useful information for decision-makers. This automation shifts the operators' focus from the day-to-day maintenance and upkeep of satellite operations to a more active role in determining the best course of action and focusing only on the data and information that are non-nominal or out-of-family with regular daily reports.

The fourth recommendation is to conduct a trade study between the General Perturbations, Special Perturbations, and commercially available propagation methods to determine the best or an appropriate mix of methods to analyze collected data and turn it into useful, accurate information in the most timely and efficient manner. If the US is committed to safety of flight in the space domain, withholding the most accurate satellite location information from many users of the domain does not clearly signal this desire. The commercial sector continues to find innovative technologies and techniques that can rapidly adapt to the constant changes in the space domain. Finding the best algorithms commercially available and comparing their performance to the current government baseline is the first step to ensuring a modern Space Characterization Ecosystem that can keep up with an ever-increasing demand for timely, accurate information.

The fifth recommendation, related to the last proposal, is to make the data from both classified and unclassified systems available for the general public. The Special Perturbation catalog uses a high-fidelity propagator and its resulting data held by the DOD is not widely available to the detriment of satellite operators worldwide.[58] By withholding this valuable data, satellite owners and operators seeking to ensure safe space operations may be driven to develop their own independent methods of collecting the data or may look to other countries such as China or Russia in pursuit of the data. Providing greater transparency is key to maintaining the lead as the Space Situational Awareness data provider and limits the drive for other competitors to develop comparable, or superior systems, negating any secrecy the US currently invokes. The means and methods used to gather the data do not need to be disclosed for the data to be useful. There are likely unique military missions for Space Domain Awareness that require exquisite, classified systems which can continue without hindering the essential Space Situational Awareness and Space Traffic Management missions at the same time. However, any data available from those classified missions that may also reduce Resident Space Object location errors must be shared with the space community, independent of the means used to collect it. Additionally, "the concern about disclosing sensitive information about the location of military assets is likely to be rendered moot over time, if it has not been already, as more and better commercial sources of [Space Situational Awareness] data become available globally that allow the surveillance and tracking of objects independent of the [Department of Defenses'] sensor network."[59] Any collision in space affects all spacefaring nations, and withholding information that may help prevent a collision is not worth the increased risk of degrading the operating environment.

Muelhaupt et al. state that "existing catalog and collision avoidance processes have no effective way of dealing with frequent or continuous maneuvers."[60] Inserting a satellite into Low Earth Orbit for operational checkout and using a series of burns or a continual thrust to raise the satellite to its operational altitude creates numerous collision opportunities throughout the process.[61] Using the current process of external tracking and observation results in a high number of collision avoidance warnings. However, that number can be "drastically reduced by using more accurate owner-operator information."[62] Muelhaupt et al. note that "obtaining more accurate data is perhaps the most cost-effective safety improvement within the current framework of collision avoidance."[63] For this reason, the sixth recommendation is to establish a process and behavioral norm for satellite owner-operators to continuously furnish their operational ephemeris and covariance data to the Space Characterization Ecosystem. Providing this data must be a mandatory step for all Government-procured satellites, and the DOC must work with the US commercial sector to make this an accepted best practice. Additionally, the Department of State (DOS), DOC, and DOD must work with their international counterparts to establish this as a norm for all space actors. This simple practice of sharing high-fidelity, owner-operator data will significantly reduce the number of collision avoidance warnings and subsequent costly maneuvers satellite operators conduct. In a scenario where two satellites have a high probability of collision due to insufficient covariance data, using "Global Positioning System-quality owner-operator data for both systems makes the problem vanish."[64] The US and the rest of the international space community must make it a priority to make the problem vanish using transparent data sharing.

The seventh recommendation relates to the air and sea domains and the international agreement on the data format and use of signals to track and monitor aircraft and vessels, respectively.[65] However, this is not the case for the space domain. The DOC, DOD, and DOS must work with the international community to establish a standard data format for satellite tracking and expand the opportunity to contribute owner-operator data to the Space Characterization Ecosystem through agreements with satellite operators worldwide. The first step is to define what the standard data format must include to supply useful information to the ecosystem. The next step should be to establish a norm of behavior to provide data in this standard format, but later work to capture this norm in an international treaty such as the Outer Space Treaty. The US Government must use lessons learned in the air and sea domains and lead the effort to set up international regulations for the international space community's conduct of Space Situational Awareness and Space Traffic Management.

The eighth recommendation involves the need for Space Situational Awareness and Space Domain Awareness collection assets for cislunar space. The current Space Characterization Ecosystem suite of sensors, particularly the radar-based sensors, are limited to a range out to Geosynchronous Earth Orbit. As the US and other nations continue their outward expansion into cislunar space, the Space Characterization Ecosystem sensors need to be ready and provide an accurate and useful picture of the cislunar domain. These assets should be procured in conjunction with NASA as these assets can perform a dual, civil-military mission of Planetary Defense and Space Situational Awareness. NASA is tasked with the Planetary Defense mission, requiring it to "detect, track and characterize . . . 90 percent of all asteroids and comets that pass within five million miles of Earth."[66] In the NASA-USSF Memorandum of Understanding, NASA acknowledges it needs future technical capabilities to meet this requirement.[67] Therefore, NASA and the USSF must partner to develop and acquire systems to add to the Space Characterization Ecosystem that supports cislunar space and beyond for both civil and military needs.

The ninth recommendation is to establish a policy that all US Government acquired satellites, DOD or civil sector, have an active, stand-alone GPS transponder incorporated into the design for satellites below medium Earth orbit and a passive orbit tracking aid incorporated for satellites above medium Earth orbit. The current GPS satellite constellation limits the usefulness of the GPS signal for satellites above medium Earth orbit. However, through further study and potentially additional higher altitude GPS satellites, this limitation may be overcome. Mandating that these government systems have a tracking aid is a step toward establishing the behavior as a norm for the community. One cannot expect other states to accept new international norms if the proposing state is unwilling to adopt them as well. The DOC must also work with the commercial space sector to incorporate active or passive orbital tracking aids on their satellites. An aviation corollary is the Real-time Automatic Dependent Surveillance-Broadcast. The Real-time Automatic Dependent Surveillance-Broadcast is currently transforming all segments of aviation and Air Traffic Control, providing a comprehensive shared situational awareness for all equipped aircraft.[68] Aircraft equipped with Automatic Dependent Surveillance-Broadcast versus a traditional Mode-C Transponder allow the pilot to see the location of surrounding aircraft on their cockpit displays that provides information similar to what air traffic controllers observe. Automatic Dependent Surveillance-Broadcast transponders link to Traffic Information Service–Broadcast, which provides "altitude, ground track, speed, and distance of aircraft flying in radar contact with controllers, and within a 15-nautical mile radius, up to 3,500 feet above or below the receiving aircraft's position."[69] This functionality creates an environment of mutual situational awareness and provides a crucial see-and-avoid capability. The technological efficiency provided by Automatic Dependent Surveillance-Broadcast improves safety, reduces congestion and costs, and diminishes the task loading on the air traffic management system as a whole. Mimicking this concept in space provides the same benefits already being realized by the aviation community.

The tenth, and final, recommendation is to conduct a study of the US complete Space Characterization Ecosystem architecture as it is today and, based on projected launches in the coming years, determine if the Space Characterization Ecosystem architecture can keep pace with the thousands of expected new Resident Space Objects. Deciding what the Space Characterization Ecosystem needs to be capable of in 50 years is a crucial first step to putting a plan in place to achieve this desired end state. Additionally, a study should be conducted that seeks to determine the optimal Space Characterization Ecosystem architecture. This study must focus on the mix of terrestrial and space-based assets and what locations supply the most persistent and accurate coverage of the near-Earth space domain. Furthermore, the types of sensors must also be factored into the study and the resulting needed architecture shared among all interested parties: government, commercial, and international allies. Working together to provide the required Space Characterization Ecosystem architecture for future needs is of interest to all.

## Final Thoughts on Technology

The need for accurate and persistent satellite location information is evident given the rapidly growing number of Resident Space Objects. The current Space Characterization Ecosystem architecture uses a combination of terrestrial and space-based sensors to provide the nation with Space Situational Awareness and Space Domain Awareness data. The Space Characterization Ecosystem sensors are aging, and the commercial sector is continually innovating new technologies and techniques to provide enhanced Space Situational Awareness and Space Domain Awareness data. The current Space Characterization Ecosystem architecture paired with the future demands of an ever-increasing Resident Space Object population led to ten recommendations the DOD, DOC, and DOS must undertake through a whole-of-government approach. These recommendations seek to posture the US Space Characterization Ecosystem to provide essential data for the safe access and operation in the space domain that the nation requires now and into the future.

**Notes**

1. Carl von Clausewitz, *On War*, Edited and Translated by Michael Howard and Peter Paret (Princeton: Princeton University Press, 1976), 610.
2. Barry R. Posen, *The Sources of Military Doctrine: France, Britain, and Germany Between the World Wars* (Ithaca: Cornell University Press, 1986), 13.
3. Posen, *The Sources of Military Doctrine*.
4. Klein, *Understanding Space Strategy*, 3.
5. "Strategy can also be described as the art and science of determining a future state/condition (ends), conveying this to an audience, determining the operational approach (ways), and identifying the authorities and resources (time, forces, equipment, money, etc.) (means), necessary to reach the intended end state, all while managing the associated risk." Joint Publication 5-0, xii.
6. The FY21 request for USAF end strength is 505,666 (total incl AD, ANG, AFR). For FY21 USSF is 6,434 (AD because no National Guard or Reserve components). Even if calculated at the max 16,000 mil billets for USSF, USSF is just over 3 percent of the USAF size. https://comptroller.defense.gov/.
7. Paul D. Spudis, *The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources* (Washington, DC: Smithsonian Books, 2016), 56.
8. "Presidential Directives are a specific form of Executive Order that state the Executive Branch's national security policy, and carry the force and effect of law, stating requirements for the Executive Branch. Over time, Presidents have used different names for Presidential Directives. The table below shows the types and abbreviations that appear on this webpage." https://www.phe.gov/.

9. Antulio J. Echevarria II, *Military Strategy: A Very Short Introduction* (Oxford: Oxford University Press, 2017), 5.

10. Klein, *Understanding Space Strategy*, 10.

11. Wing Commander Milburn Lecture, Organizational Accounts of War & Strategy Lesson, ACSC.

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## Case Studies

*It's like all of us are driving on a highway in a dense fog and I have no idea if I'm about to hit something in front of me, and so maybe I decide to change lanes, but do I know what's beside me?*

—Moriba Jah, CNN Interview

### Case Study #1: First Collision

The first collision between two orbiting satellites occurred on 10 February 2009, almost 52 years after Russia launched the first artificial satellite into Earth orbit.[1] This collision occurred between Iridium 33, a functioning US commercial communications satellite that was part of a 66 satellite constellation, and Cosmos 2251, an inactive Russian communications satellite.[2] The collision occurred at an altitude of approximately 800 km and produced nearly 2,000 pieces of space debris "at least ten centimeters in diameter" as well as thousands of smaller pieces.[3] Because of the altitude of the satellites at the time of collision, the debris produced will remain in orbit "for decades or longer, posing a collision risk to other objects in [Low Earth Orbit ]."[4]

The satellites "collided at almost right angles to each other, and at a relative speed of nearly 10 km/s."[5] The extreme speeds associated with Earth orbits reveal that any two or more objects can create significant amounts of debris if their paths cross at the wrong moment. The debris fields are the result of the quick spread of fragments within and around the satellite's respective orbital planes within the first 180 minutes following the collision.[6] It is evident that the inadvertent pollution of an orbital plane from a devastating collision can render that region of space useless until the debris is either actively removed, which is not currently technologically feasible, or the debris reenters the Earth's atmosphere after a slow orbital decay.

The Cosmos satellite was not functional at the time of the collision and could not maneuver. However, the Iridium satellite being active, did have the ability to maneuver if the operators chose to use its fuel resources. This incident further highlights the need for accurate satellite location information. With limited fuel onboard to perform maneuvers for both mission utility and collision avoidance, the decision to move a satellite to avoid a collision must be made using the most accurate information available. The public system used to screen for close approaches, the Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space, predicted this close approach, but it was not the closest approach predicted for the week.[7] The Satellite Orbital Conjunction Reports

Assessing Threatening Encounters in Space predicted the two satellites would pass each other at a distance of 584 m, but "at the time of predicted close approach (16:56 UTC), Iridium 33 suddenly went silent."[8] In the week leading up to the collision, the close approach between Iridium 33 and Cosmos 2251 ranged from 117 m to 1.812 km.[9] This variability in information makes it difficult to determine when a close approach poses an actual risk to a satellite's safety and when it is a false alarm. From a priority perspective, the Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space report ranked the Iridium 33-Cosmos 2251 conjunction at 152 at the time of the collision.[10] This meant there were 151 other conjunctions with a higher ranking that the Iridium operators had to determine whether or not to maneuver before they would get to the one that collided. The ambiguity in data coupled with numerous potential conjunctions each day significantly hampered the ability to smartly manage satellite fuel resources and maintain safe operations.

As the number of on-orbit satellites continues to increase, this incident is a stark reminder of the need for a robust Space Characterization Ecosystem architecture providing accurate and transparent information to prevent a duplicate event or even worse the chain reaction of the Kessler Syndrome. The Kessler Syndrome is essentially a nightmare scenario where one collision sparks a domino-effect of other collisions that perpetuate space debris until complete orbital regimes are unusable.[11] This first-ever collision remains a warning signal for the US and the rest of the spacefaring nations and emphasizes the necessity of investing in a more robust Space Characterization Ecosystem architecture paired with transparent, accurate, and timely communication.

**Case Study #2: Present Event**

In June of 2017, a "space apparatus inspector" was deployed by the Russian Ministry of Defense. Observers were baffled by its design as the only publicly reported information was a ". . . space platform which can carry different variants of payloads."[12] Later designated Cosmos-2519 (2017-037A, 42798), the moderately sized satellite made only a series of small maneuvers for months, confirming suspicions that it was indeed a remote sensing platform. However, on 23 August 2007, Russian officials shocked the world with the public announcement that a small satellite, designated Cosmos-2521 (2017-037D, 42919), had separated from the mysterious mothership and was "intended for the inspection of the condition of a Russian satellite."[13] General Raymond described the system ". . . like Russian nesting dolls."[14] For purposes unknown, Cosmos-2521 continued small maneuvers in late August and early September 2007 until 26 October 2007; Russia reported Cosmos-2519 had returned to the host satellite after completing a series of suspected RPO experiments on Cosmos-2486 (2013-028A, 39177).[15] Less than a week later, Russia announced that another small satellite, Cosmos-2523 (2017-037E, 42986), had separated from Cosmos-2521 to conduct other satellite inspections, but, to date, other RPO approaches were never publicly confirmed.[16] As curious as this new space system was, many experts and military analysts considered the deployment of Cosmos-2523 to have been an anti-satellite weapons test, given its relatively large deployment velocity.[17] The security community was alarmed at the perceived capabilities, unknown threats posed, and intent by the Russian Federation. Its behavior on-orbit was inconsistent with anything overtly seen before "from on-orbit inspection or Space Situational Awareness capabilities, including other Russian inspection satellite activities."[18] Security experts and analysts were delayed in providing any sufficient Space Domain Awareness at the time as there was very little intelligence on the system and no effective way to verify those assumptions immediately. Russia had officially launched a mystery box into space.

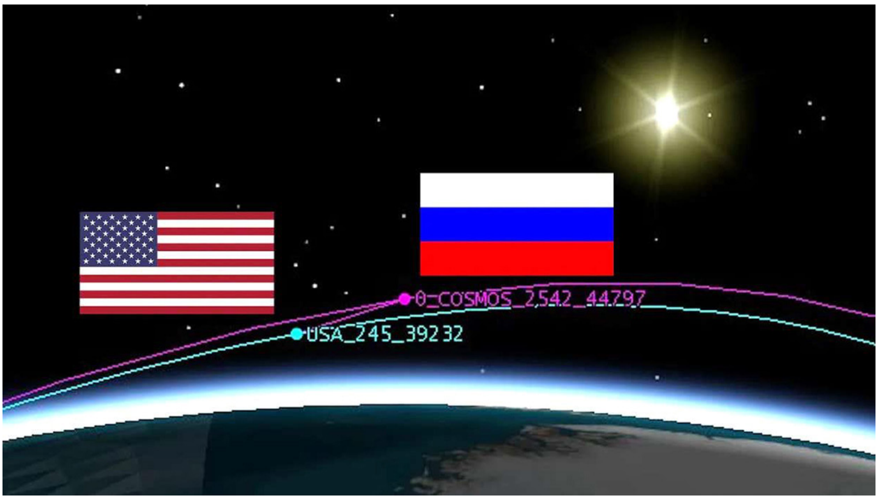


**Figure 7. Graphical representation of the position of Cosmos 2542 with regards to USA 245 in January 2020 (Reprinted from Joseph Trevithick, "Space Force Boss Says One Of Russia's Killer Satellites Fired A Projectile In Orbit," The War Zone, 23 July 2020, https://www.thedrive.com/.)**

Shortly after launching the mysterious "inspector," Russia accelerated prototyping of on-orbit weapons testing, conducting a total of two space-based anti-satellite weapons tests in three years.[19] The Commander of US Space Command and now Chief of Space Operations for the USSF, General John Raymond, warned that "Russia [was] developing on-orbit capabilities that seek to exploit our reliance on space-based systems."[20] His statement could not have been more accurate with the launch and subsequent test of Cosmos-2542 and Cosmos-2543.

Launched on 25 November 2019 from Plesetsk, Cosmos-2542 (2019-079A, 44797) was placed into orbit by a Soyuz-2-1V. The Russian space agencies reported that its military payload onboard was designed to conduct space surveillance as well as Earth remote sensing.[21] However, space security experts quickly assessed that the optical satellite was the second satellite in the Nivelir 14F150 series, countering reports by *Interfax*.[22] This event indicated that the satellite would have "orbital inspection capabilities" attracting increased scrutiny in the operations of the satellite considering the performance of Cosmos-2519. On 6 December 2019 around 0800 UTC, after two weeks of stable orbit, Cosmos-2542 ejected a sub-satellite later labeled Cosmos-2543 (2019-079D, 44835). Military analysts again were bewildered that Cosmos-2542 ejected Cosmos-2543. General Raymond recognized the new threat posed by the nesting technologies that ". . . exhibited characteristics of a weapon system when one of those satellites launched a high-speed projectile into space."[23] He explicitly declared "[t]his is further evidence of Russia's continuing efforts to develop and test space-based systems, and consistent with the Kremlin's published military doctrine to employ weapons that hold US and allied space assets at risk."[24] Additionally, the separation shocked many in the space community for the lack of transparency displayed by Russia's Ministry of Defense for another orbital separation, which the US previously decried at the United Nation's 2018 Conference on Disarmament as "Russia's hypocritical advocacy of outer space arms control."[25] Cosmos-2542 was reminiscent of the Cosmos-2519 launch, considering it was not until the public announcement later on 6 December 2019 by the Russian News Agency, that the Russian Defense Ministry confirmed the two had, in fact, separated, claiming a "small sub-satellite" was detached from "the multi-functional platform in orbit."[26] Clandestine operations are nothing new for the Russian Defense Ministry, but the subsequent overt events challenged previous assumptions on acceptable norms and behaviors in the space domain.

Considered another "experiment," the new Cosmos constellation—Cosmos-2543, whose purpose was to "continue work on assessing the technical condition of domestic satellites,"—remained within 2 km of Cosmos-2542 until 1100 UTC on 9 December 2019 when US radar detected that it began raising its apogee from 368 km to arrive at 590 km by 16 December.[27] Amateur analysts using optical observations suggested that those maneuvers were to conduct RPO inspections of the National Reconnaissance Office's KH-11 or USA 245 (2013-043A, 39232) satellite, but there was little consensus with some even reporting that the "similarity in orbital planes is probably a coincidence.[28] However, considering that Cosmos-2543 had entered orbit within one degree of inclination from the USA-245, intercept and inspection of the US satellite seemed logical. According to Nico Janssen, another satellite observer, during 9-10 December, USA-245 left its "272 by 985-[km] orbit and maneuvered somewhere else, possibly attempting to prevent a close encounter with the newly released Cosmos-2543," which had moved from a 590 by 859-km orbit.[29] However, subsequent analysis observed both Cosmos-2542 and Cosmos-2543 making precise maneuvers in an orbit where it could observe USA 245, remaining synchronized such that Cosmos-2543 periodically extended up to 300 km and ultimately came within 20 km several times throughout January 2020.[30] Michael Thompson, an amateur satellite tracker, wrote, "the relative orbit is actually pretty cleverly designed, where Cosmos 2542 can observe one side of the KH11 when both satellites first come into sunlight, and by the time they enter eclipse, it has migrated to the other side . . . This is all circumstantial evidence, but there [is] a hell of a lot of circumstances that make it look like a known Russian inspection satellite is currently inspecting a known [US] spy satellite."[31]

Speculation surrounding the event, including the true intent, only highlighted the international community's delayed response to recognizing what was occurring. The international Space Domain Awareness complex was now mired in political signaling between the US and Russia, revealing technical challenges between competing space observation systems, and exposing an active disinformation campaign by the Russian Ministry of Defense to protect their new assets. The RPO by a foreign adversary on any US system is considered "unusual and disturbing," noting the RPO maneuver alone to inspect a satellite is indistinguishable from a kinetic attack.[32] The potential intelligence gained from such an orbital maneuver could offset the diplomatic signal posed by such an act. Furthermore, the Russians are paradoxically at the forefront of international efforts to ban such systems.[33] The purpose of the maneuvers may not have ever been observed nor explored without robust Space Domain Awareness assets available to US Space Command and public engagement of non-government organizations, intergovernmental organizations, and amateur satellite observers. The implications to the international order have yet to be determined.

Russian journalist Igor Lissov argued that the orbital parameters published by the US Space Command of Cosmos-2542 and amateur observations of

USA-245 by Janssen and others were unable to correlate "confirm(ing) with certainty only one maneuver of the American satellite since December 2019."[34] Additionally, he noted that Janssen's method in radio-tracking provides accurate measurement of the orbital period but is ill-suited for determining the shape of the orbit. Official data was not available for USA 245 either as its operations are classified and had not been seen by hobbyists since early December 2019, preventing any detailed orbital comparisons by any public or partnered entities.[35]

Regardless of interpreted accuracy of published data, amateur observations, and public announcements, the contest threatened vital US national assets' safety and security. That threat resulted in an unprecedented event for the US DOD: the first public confirmation of a malicious, foreign threat to a US satellite.[36] Furthermore, classification levels and adversarial conduct left many lingering questions. The US may have had the fidelity to respond to the event in an appropriate and timely manner but did not respond overtly. Events like the shadowing of USA 245 shook the bureaucratic system and test doctrine, but what changed? US policy changed in 2010 to broaden the Air Force's Space Situational Awareness mission due to the Iridium-Cosmos collision.[37] Are collisions required to progress the Space Domain Awareness architecture further? Transparency with partners and adversaries may be the only path forward as proliferation of nested systems continues.

## Case Study #3: Future Possibilities

Within the scope of the next 30 years, the proliferation of satellite assets and activity in the Low Earth Orbit, medium Earth orbit, and Geosynchronous Earth Orbital regimes point to inevitable issues with congestion and, ultimately, the likelihood of a collision. Whether the collisions are nefarious or accidental, the threat of destruction is increased if there is an inaccurate understanding of satellites' locations and future trajectories. The air domain's "Big Sky" theory applied to space will not always hold true, as proven by the 2009 Iridium and Cosmos collision. Even more worrisome are the prospects of the pollution of certain orbital regimes if the Kessler Syndrome's effects occur. Regardless of the unitary or cataclysmic effect of on-orbit collisions, space actors' remote and unforgiving environment places an extra burden on space actors to act responsibly. The first step in conducting safe and secure operations is to understand one's space objects' spatial location. The burden of accurate and timely Space Situational Awareness data is placed on the actor or actors that rely on the space domain's advantages, particularly as the economic markets drive more government and commercial interests. From an economic standpoint, the better characterized the domain is, the more likely investors are to proliferate the market. Assuming the likelihood of accidental collision is greater than the likelihood of hostile acts, the Space Situational Awareness infrastructure plays a foundational role in the burgeoning domain.

The Space Characterization Ecosystem architecture must be robust enough to identify accurate ephemeris data and derive information on space actors' intent and activities. The discovery of the intent of allied, neutral, or adversarial activity falls on the capabilities and resources of the US military and intelligence community. The security of space will be placed on the forces and agencies charged to protect and defend the domain: namely the USSF. Both organizations play critical roles in enabling security for American space assets, commercial or military. The ability to thwart hostile activity from space Global Power Competitors is the paramount focus of what military and intelligence planners would call the "Most Dangerous" scenario.[38] Findings in recent space threat assessments highlight China and Russia as the near-term and long-term threats. For example, China's SJ-17 co-orbital capabilities, aggressive pursuit of directed-energy weapons, and overall Chinese space investment prospects are urgent concerns.[39] Compared to China's capabilities, Russia's co-orbital Cosmos activities, disruptive jamming, and electronic warfare exploits are significant but less pressing.[40] Providing Space Domain Awareness for a scenario where China decides to control vital celestial lines of communication around the Moon that denies American space assets freedom of access and freedom of maneuver is critical to national security. If China attains local command of the CLOCs before the US and its allies, the Chinese can control the most relevant space real estate and "sinify" the norms of behavior in space to favor their own national objectives.[41] Simply put, this places future American prosperity and security at significant risk.

Threats from other sources like Near-Earth Objects are also of concern.[42] The *Armageddon* scenario, although less likely than all previous cases, is a concern for global safety. The 1998 summer blockbuster dramatized a story of a motley crew of oil rig roughnecks who saved Earth from an asteroid collision. As sensational as the storyline was, the need for Planetary Defense is not farfetched, as NASA Planetary Defense Officer Linley Johnson attested.[43] Manpower and resources, although limited, are being put towards this problem set. The role of Space Situational Awareness and other deep space characterization technology is significant towards the success of a mission of this nature. Gambling with the entire nation's safety and security by avoiding this unlikely but highly impactful scenario is a dangerous gamble. While some argue that a Planetary Defense mission belongs as part of the military mission, the authors' position is that, at this time, the mission should stay with

NASA. However, inherent military and commercial Space Situational Awareness capabilities should continue to augment the need for deep space characterization. There may be a time in the future where a whole-of-government and global solution is necessary to defeat a Near-Earth Object's threat, so it would be prudent to support contingency plans and exercises to walk through, and war game, these events.

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# Conclusion

*What we see of the real world is not the unvarnished real world but a model of the real world, regulated and adjusted by sense data— a model that is constructed so that it is useful for dealing with the real world.*

—Richard Dawkins, *The God Delusion*

## Chapter Overview

This chapter provides a consolidated view of the recommendations found throughout this work. Additionally, work remaining that was not covered as part of this research is highlighted as an opportunity for further analysis. Finally, this chapter closes with a few parting thoughts meant to prompt current and future space professionals to take action to solve the work's identified "wicked problems" via organizational and technical solutions that should also posture the US-led Space Characterization Ecosystem to confront problems yet to be uncovered.[1]

## Recommendations

There are various recommendations interspersed throughout the work based on the research on past, current, and potential future Space Characterization Ecosystems. This section attempts to capture these recommendations, in no particular order, to supply a succinct, high-level view of the outcome of this body of work. More in-depth analysis is found in the preceding chapters. While the subsequent section offers areas of remaining work in this field, the recommendations in this section are meant to spur near-term actions to resolve the identified issue or deficiency within the Space Characterization Ecosystem. These recommendations are not meant to shine a negative light on the current organizations or architectures of the Space Characterization Ecosystem, but rather highlight areas where applying thought and resources will pay dividends well into the future.

The first recommendation is for the DOD and DOC to work together to develop, acquire, and maintain a suite of sensors beneficial to both organizations and their overlapping missions, continually looking for new technologies across the commercial sector to enhance the Space Characterization Ecosystem. The Space Situational Awareness component of both the Space Domain Awareness and the Space Traffic Management missions is common ground for both organizations. Collaboration between the DOD and the DOC in seeking and acquiring new technologies, sensors, data storage, data fusion, and data analysis techniques will limit the possibility of duplicating similar efforts while reducing costs to each organization through resource sharing.

A second and related recommendation is that the US must continue to add allied and commercial Space Situational Awareness and Space Domain Awareness sensors into the Space Characterization Ecosystem to enhance sensor fidelity and ecosystem robustness. This diverse Space Characterization Ecosystem will maximize the mutualistic gains for all organizations within the ecosystem through burden sharing and a larger knowledge base with varied perspectives. The multi-organization, multi-nation Space Characterization Ecosystem is resilient and creates a greater deterrence to interference by a Great Power Competitor through sheer numbers of participants and a more robust network of sensors.

The third recommendation is to invest in a robust training program for sensor operators and continue to build on the Sprint Advanced Concept Training exercises currently planned and executed by the Joint Task Force-Space Defense. Acquiring exquisite sensors while neglecting proper training has the potential to leave capabilities unused and opportunities missed. In tandem with a robust training regimen, the Space Characterization Ecosystem architecture must be fully automated and configured so that sensors tip-and-cue each other to collect data on Resident Space Objects that behave abnormally. This construct focuses well-trained operators on the Resident Space Objects that potentially pose the greatest risk, allowing the full brunt of their cognitive processes to be directed toward finding solutions to the difficult problems inherent with space operations.

The fourth recommendation is to conduct a trade study between the General Perturbations, Special Perturbations, and commercially available propagation methods to determine the best or an appropriate mix of methods to analyze collected data and turn it into useful, accurate information in the most timely and efficient manner. The commercial sector continues to find innovative technologies and techniques that can rapidly adapt to the continual changes occurring in the space domain at a much faster pace than the government is able to respond. Finding the best algorithms commercially available and comparing their performance to the current government baseline is the first step to ensuring a modern Space Characterization Ecosystem that can keep up with an ever-increasing demand for timely, accurate information.

The fifth recommendation, related to the last proposal, is to make the data from both classified and unclassified systems available for the general public. To ensure safety for all actors within space domain, the US cannot continue to keep the most accurate location information hidden behind various classifications. Withholding this information will likely drive other owners and operators to develop their own architectures or compel near-peer competitors such as China or Russia to gather more accurate Space Situational Awareness information on their own. The means and methods used to gather the data do not need to be disclosed for the data to be useful for those seeking to ensure safety within the space domain. Supplying greater transparency is key to the US maintaining the lead as the Space Situational Awareness data provider and limits the drive for other competitors to develop comparable, or superior systems, negating any secrecy the US currently invokes.

The sixth recommendation is to establish a process and behavioral norm for satellite owner-operators to continuously furnish their operational ephemeris and covariance data to the Space Characterization Ecosystm. Satellite owners and operators know the location of their satellite better than any other organization and continually providing this information for the Space Characterization Ecosystem allows the sensors of the network to focus more time on rogue or unknown objects. The US Government must make this a mandatory step for all Government-procured satellites, while the DOS and DOC work to establish this norm of behavior with other countries and the commercial sector, respectively. The sharing of high-fidelity, owner-operator data will greatly reduce the number of collision avoidance warnings so the US and the rest of the international community must make transparent data sharing a priority to minimize the risk of a collision between space objects.

The seventh recommendation relates to the air and sea domains and the international agreement on the data format and use of signals to track vessels in each domain. The DOC, DOD, and DOS must work with the international community to establish a standard data format for satellite tracking and expand the opportunity to contribute owner-operator data to the Space Characterization Ecosystem. The first step is to define the standard data format and establish a norm of behavior among all participating parties to provide data to the Space Characterization Ecosystem in that format. To ensure future compliance, this format must be codified in an international treaty such as the Outer Space Treaty.

The eighth recommendation addresses the need for Space Situational Awareness and Space Domain Awareness collection assets for cislunar space. The current Space Characterization Ecosystem suite of sensors, particularly the radar-based sensors, are limited to a range reaching to Geosynchronous Earth Orbit. As the US and other countries continue the outward push into cislunar space, assets capable of providing the needed Space Situational Awareness and Space Domain Awareness data need to be developed and fielded. These assets should be developed and procured in conjunction with

NASA as these assets can perform a dual, civil-military mission of Planetary Defense and Space Situational Awareness.

The ninth recommendation is to establish a policy that all US Government acquired satellites, DOD or civil, have an active, stand-alone GPS transponder incorporated into the design for satellites below medium Earth orbit and a passive orbit tracking aid incorporated for satellites above medium Earth orbit. Mandating that these government systems are equipped with tracking aids enables further discussion with other nations about accepting this as a new international norm. The DOC must also work with the commercial space sector to establish a norm of behavior to incorporate active or passive orbital tracking aids on their satellites. This recommendation reduces the burden on the Space Characterization Ecosystem to find and track all space objects on a continual basis as more groups implement the new international norm.

The tenth and final recommendation is to conduct a study of the U complete Space Characterization Ecosystem architecture as it is today and, based on projected launches in the coming years, determine if the Space Characterization Ecosystem architecture can keep pace with the thousands of new expected Resident Space Objects. Determining where the Space Characterization Ecosystem needs to be in 20–40 years is a crucial step to put a plan in place to achieve the desired end state. Additionally, a study should be conducted that seeks to determine the optimal composition among all of the various sensor types and sensor locations for the Space Characterization Ecosystem architecture. Furthermore, the authors recommend empowering the National Space Council to take the lead in managing the Space Characterization Ecosystem mission and that the DOC and DOD work in a centralized location to facilitate unity of command of the entire ecosystem, but higher fidelity study and input from the field is necessary to address the feasibility of that recommendation. Taking action on these recommendations is a vital next step to posture the US as a continued leader and norm establisher in space for the foreseeable future.

## Work Remaining in the Field

This section provides recommendations for areas relating to this research but were either out of the scope of this work or were omitted due to time constraints. From a data storage, data processing, and data access perspective, the connection and interaction of the currently planned Open Architecture Data Repository of the DOC and the Unified Data Library of the DOD must be further studied, perhaps by a research team at the Air Force Institute of Technology. This study should tackle items such as how the two systems can seamlessly interact as well as the potential to combine the databases into a single, cloud-based architecture. This new architecture should address all the security layers and tools needed to provide usable data collection, data storage, and information sharing to users from all echelons of the government and private sector, while still being scalable to meet increasing demand.

Throughout the interview and research process, it is clear to the authors that different terms used within the Space Characterization Ecosystem lexicon have various meanings depending on the organization or country using them. As noted in Chapter I, a standard lexicon is needed before further discussion ensues. Because the field of space safety transcends many borders, languages, and cultures, a further look at the lexicon needed to communicate effectively is required. Much as the International Civil Aviation Organization promotes a standard lexicon for aviation, a similar organization and lexicon must be developed for the space community. The rapid speeds of satellites in orbit require equally swift communication by operators and decision-makers on the ground to stay in front of developing problems in space. A misstep in communication may be the difference between continuing a mission and a collision. Ensuring the words used in the communication of a problem mean the same to all parties will be a small, yet significant step in the right direction. The authors attempt to contribute to the lexicon through coining a new higher-level term such as Space Characterization Ecosystem and settling on pragmatic and relevant contemporary definitions to build the foundation and highlight important nuance in the space community. The authors hope that healthy debate on the exactness of terminology will contribute to advancing the doctrinal and theoretical conversation for eventual practical use.

## Parting Thoughts

The Space Characterization Ecosystem is an essential component for the US as it continues to grow and expand operations in the space domain. The influx of satellites from academia, civil, commercial, and other nations continue to grow rapidly with no slowdown in sight. Now is the precise time to focus a whole-of-nation effort on finding a unique organizational and technological solution to provide the US with a robust and mutualistic Space Characterization Ecosystem that is not only affordable but will also stand the test of time through ease of update and scalability. Tomorrow's "wicked problems" call for a resilient Space Characterization Ecosystem that is adaptive, agile, and transparent amongst its diverse stakeholders to combat multifaceted threats.[2] Attainment of this resilience must be a security priority for the US and its allies to gain and maintain the competitive edge in space. To neglect this obligation is to allow our known and unknown competition the advantage in space. It is humankind's history to find conflict in new frontiers; to lose the advantage in this relatively new frontier is to place the safety and security of American and allied citizens at risk. The burden of thinking and leading through these wicked problems is placed on the shoulders of the men and women charged to protect and defend the domain of space—we are ready to take on the challenge.

**Notes**

(Notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. US Army TRADOC Pamphlet 525-5-500, 9.
2. US Army TRADOC Pamphlet 525-5-500, 9.

## Abbreviations

| | |
|---|---|
| CLOC | Celestial Lines of Communications |
| CSpOC | Combined Space Operations Center |
| DOC | Department of Commerce |
| DOD | Department of Defense |
| DOS | Department of State |
| GPS | Global Positioning System |
| GSSAP | Geosynchronous Space Situational Awareness Program |
| JICSpOC | Joint Interagency Combined Space Operations Center |
| JNWC | Joint Navigation Warfare Center |
| JOPC | Joint Overhead Persistent Infrared Planning Center |
| LED | Light Emitting Diodes |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanographic and Atmospheric Administration |
| NSDC | National Space Defense Center |
| PARCS | Perimeter Acquisition Radar Attack Characterization System |
| RPO | Rendezvous and Proximity Operations |
| SBSS | Space-Based Space Surveillance |
| SSN | Space Surveillance Network |
| UDL | Universal Data Library |
| US | United States |
| USAF | United States Air Force |
| USSF | United States Space Force |

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